Inverter Technology

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Please read "Direct and Alternating Current" and "Inverter History" articles prior to this article. This is not meant to be a precise discussion for electrical engineers, but rather an attempt to help the majority of consumers have a better understanding of inverters.

Inverters have become an important adjunct to the RV electrical system allowing RV owners to choose from a variety of electronic inverters varying in capacity, technology, and price. In order to make good purchase decisions, consumers need to be aware of the different types of inverters available as well as optional features.

Inverter types can be broadly categorized as mechanical or electronic. The mechanical type is the early motor generator, which consists of a DC motor that powers an AC generator. The output waveform is a sine wave with low harmonic distortion. The overall efficiency is between 50% and 70%, idle power consumption is high, and surge capability is poor. DC voltage and current ripple caused by the production of AC is minimal. This type of inverter is no longer used in RV applications, but modern versions are popular in utility, trade, and emergency applications.

Electronic inverters can be further categorized by output waveform, switch type, switching technology and frequency. In order to create alternating current from direct current, the straight line 12 VDC is put through an oscillating circuit, which creates 12 volt alternating current. Other control circuits regulate the frequency of the oscillating AC current to 60 cycles per second. The AC output may be square wave, modified square wave (modified sine wave), multi-step sine wave, or sine wave. A special waveform described as semi sine wave is also possible, but it is not usually seen in RV applications.

The earliest switches used to oscillate 12 VDC were mechanical vibrators. Essentially oscillating mechanical relays, they were inefficient and unreliable, but there were no alternatives until the development of semiconductors (transistors) in the 1960s. Silicon Controlled Rectifiers (SCRs) were the first solid state relays and functioned as electronic latching relays. Next, Darlington transistors were used. SCRs and Darlington transistors were far more reliable than the mechanical vibrator but had their own disadvantages. The Metal Oxide Semi-conducting Field Effect Transistor (MOSFET or FET) was the answer for switching problems. FETs have a number of advantages such as low "on" resistance, and ability to handle high current. They are easy to connect in a circuit, and they work well in parallel connections. The parallel connections increase the current carrying ability and lower the "on" resistance even more. One manufacturer describes them as ideal for medium power applications (1,000 watts to 5,000 watts). Some inverters use IGBTs (Insulated Gate Bi-Polar Transistors). These are newer, high power, low loss switching transistors.

Switch Types

There are two main types of switching topologies: Push-Pull and H Bridge.(Note: the term "topology" refers to design layout or landscape). The Push-Pull ***(Figure 1)*** uses a transformer with a center tap attached to the battery positive. Two transistor switches connect the windings of the transformer to the battery negative. The transistors alternately close in a flip-flop pattern every 8 milliseconds. This changes the direction of the current 120 times per second and creates 60-cycle alternating current. This type of circuit is suitable for a square wave inverter. When used in a modified sine wave inverter, a special transformer with an additional winding to provide "off" time shorting must be added. In addition, an extra transistor switch is needed to activate the shorting winding. Heart Interface products do not use this tertiary winding. Off time is accomplished by shorting the primary winding. According to Heart, this results in measurably higher efficiency when running an inductive load than an inverter that uses a separate tertiary winding. The disadvantage is that the inverter has less tolerance to transient voltage spikes or AC miswired to the output.

The H Bridge design (***Figure 2***) has four transistors that turn off and on in pairs. Since transistor pairs are used in series, current flows through two transistors and power loss doubles. This design was not used until high efficiency FETs were available. Efficiency was further improved by using FETs in parallel. With improved transistor efficiency, the H bridge offered significant advantages over the older push-pull design. The transformer requires only one primary winding and no off time shorting winding is needed. Off time shorting occurs by switching on the bottom pair of transistors. The oscillating AC is created by switching diagonal pairs. ***Figure 3*** displays the H Bridge switching sequence. The H Bridge design is used with either FET or IGBT transistors and in both high and low frequency, multi-step sine wave, MSW, and sine wave inverters.

Frequency

When we describe inverters as using high or low frequency design, we are referring to the switching frequency used to oscillate the 12 VDC. Low frequency inverters create 60 cycle AC and then step-up transformers create 120 VAC, however, low frequency transformers are large and heavy. High frequency inverters oscillate the DC at frequencies ranging from 25,000 to 200,000 Hz (cycles per second). The transformers used to create 120 VAC in high frequency applications, on the other hand, are small and light weight.

Like the starter-headlight example in "Direct and Alternating Current," an inverter draws high amperage from the battery bank; however, the draw fluctuates between zero and the maximum current. This fluctuation occurs <u>120 times every second</u>. An ammeter can not reflect these rapidly pulsating changes and deceptively shows a steady draw. The pulsating draw with high transient spikes cause a corresponding voltage ripple ***(Figure 4)*** in the DC electrical system, and can cause buzzing in audio equipment, interference in radio and television reception, and interference with other electronic equipment.

High transient current spikes and ripple voltage also occur on the low frequency charger side and, based on our testing, appear to be significant factors in the increased battery temperature elevations often encountered during charging. Reliable high output chargers with high frequency design are difficult to engineer. However, once accomplished, the high frequency chargers offer the possibility of ripple-free charging One of the major advantages to the high frequency sine wave design is the presence of a DC energy storage bus. The bus stores the high voltage DC used to create the 120 VAC and reduces ripple current, and therefore, the ripple voltage from the DC system. ***(Figure 5)***

Square Wave Output

As mentioned previously, square wave inverters by Tripp Lite were the first electronic inverters ***(Figure 6).*** The mechanical vibrator used a push pull circuit to oscillate the current. When SCR (Silicon Controlled Rectifier) became available, they replaced the mechanical vibrators but still used the push pull design. This design essentially consists of two transistors that alternately switch on and off ***(Figure 7).*** As one switch opens, the other closes, and the current through the transformer changes direction. This cycle continues and the result is a square wave alternating current ***(Figure 8).*** In a square wave inverter, peak voltage equals RMS voltage and varies directly with battery voltage. Therefore, when the battery voltage is low, the peak AC output voltage and RMS voltage are also low. This type of inverter has high harmonic distortion (50%) and marginal efficiency (60% to 80%). A square wave inverter often cannot properly power electronic equipment and motors tend to run hotter. Surge capability ranges from poor to good depending upon other design features.

Modified Sine/Square Wave-Low Frequency

Low frequency design means that the switches operate at 60 cycles per second (60 Hz). Present day inverters use FETs (Field Effect Transistors) or IGBTs (Insulated Gate Bi-Polar Transistor) in the oscillating circuit. For the most part, the H bridge design has replaced the push-pull method. However, there are still some inverters currently manufactured with the push-pull design. As mentioned previously, a push pull circuit uses an extra transistor to short the transformer between current oscillations. With the H bridge design, transistors are switched off in a particular pattern to produce each part of the waveform. The 12 volt modified sine wave AC is then fed to a step up transformer which converts it to 120 volts modified sine wave AC ***(Figure 9).*** An advantage of the MSW type inverter is that the RMS (Root-Mean-Square) voltage can be regulated and maintained over a range of battery voltages by varying the duty cycle ***(Figures 10 & 11). Note: Figure 11 is exaggerated to illustrate the concept.*** The peak voltage, however, is not regulated and varies with battery voltage, typically from 174 VAC when battery voltage is 16 VDC to 114 VAC when battery voltage is 10.5 VDC. For this reason, MSW inverters may not be able to supply full power to devices that require peak voltage for optimum performance like microwave ovens. They have excellent surge capabilities and efficiency (80% to 95%). Idle power consumption is rated at low to medium. Harmonic distortion ranges from 15% to 35%. MSW inverters exhibit some incompatibilities with various types of electronic equipment. Timers, digital clocks, bread machines, and rechargeable power tools or flashlights may be incompatible. These appliances often use modern switching type battery chargers and power supplies that only draw current at the peak of the sine wave, making them susceptible to overheating which results in premature failure. Modified sine wave inverters, commonly used in motorhome applications, range in output from 1000 watts to 3600 watts. Using inverters of this size can quite easily discharge house batteries, so provisions for recharging must be available.

We still have some not-so-fond memories of trying to recharge batteries with a ferroresonant converter. A major advancement in the motorhome electrical system was the integration of a high powered 3-stage charger in the inverter package by Heart Interface. Most of the other major manufacturers have now incorporated similar chargers into their products. When grid voltage is present, either from a generator or shore power, a transfer switch inside the inverter disconnects the unit's output circuit from the inverter output and connects it to grid AC. In addition, grid voltage is supplied to the transformer. A separate winding allows the output transformer to step down the 120 VAC grid voltage to 16 VAC. It is then rectified to DC (12-16 volts) by using a part of the FETs as diodes. Control circuitry provides automatic 3-stage charging: bulk, absorption, and float, plus a manual equalizing stage. 3-stage charging can rapidly recharge house batteries. These chargers range in output from 100 to 130 amps. Charging at 100 amps or more requires 21 to 25 amps of AC power, so it is important to have 120 VAC with a peak voltage of 169 VAC. Low campground voltage or a low capacity generator may not be able to supply the power required for full output charging. Unlike the old ferroresonant converters, even when DC loads are present, these chargers can maintain battery voltage either at the bulk/absorption set point or the float set point, whichever is in use.

It is also important to use temperature compensation when using modified sine wave technology. Low frequency MSW inverter/chargers superimpose AC current fluctuations on the DC wave and thereby produce ripple effects. We have found that this voltage and amperage distortion can produce undesirable elevations in battery temperature during high output charging. Temperature control circuits reduce charger output in order to limit temperature elevations but do not alter the fact that the temperature rises with high output charging. Personally, we would never use a modified sine wave inverter/charger without some method of determining battery temperature and a way to control charging output to limit the temperature elevation. These inverters and the high output chargers are less expensive to build than sine wave units and, to the consumer, this translates to more watts of power per dollar.

Modified Square/Sine Wave Output-High Frequency

High frequency design means the switches operate between 50,000 and 200,000 cycles per second. The transformers are much smaller and lighter in weight than the low frequency transformers. Therefore, MSW inverters using high frequency design, weigh a fraction of their low frequency counterparts.

Battery voltage (12 VDC) is converted to high frequency alternating current using Pulse Width Modulation (PWM) which is then stepped up to high voltage AC ***(Figures 12 & 13).*** The high voltage AC is then rectified to high voltage DC. An H bridge with low frequency transistor switches produces modified sine wave AC. Off time is done on the AC side of the H bridge ***(Figures 14 A, B, & C).***

According to one of our sources, through the years, various high frequency MSW inverters have produced peak AC outputs of 155, 165, and 170 VAC. A major advantage of high frequency MSW inverters is the peak voltage produced is not dependent on battery voltage and remains constant through varying levels of battery discharge. As discussed previously, in square wave output, peak voltage equals RMS voltage. In low frequency MSW inverters, the length of off time is varied to regulate and maintain RMS voltage through varying levels of peak voltage, which varies with battery voltage. Because peak voltage is constant in high frequency designs, the off time is calculated to give 120 VAC RMS. The result is an inverter that produces consistent peak AC and RMS voltage. When inverter peak voltage is 155 or 165, microwave ovens, which depend on peak voltage, will operate at reduced power for a selected setting as compared to operating on shore power. However, this reduced level does remain constant for various states of battery discharge.

Total harmonic distortion is 15% to 35%, typical efficiency is 85%-90%, and idle power consumption is medium. Surge capability ranges from poor to good, but generally is lower than low frequency MSW inverters. The zero volt transistors on the H bridge are not isolated from the AC line and are susceptible to voltage spikes. There is also a possibility of TV and radio interference because of the high voltage switcher.

Semi-Sine Wave Output

Adding a ferroresonant transformer to a MSW inverter makes a semi-sine waveform ***(Figure 15***). The harmonic distortion remains at 15% to 35%. Typical efficiency is 50% to 70%, idle power consumption is high, and surge capability is poor. This type inverter is not commonly used in RV applications.

Sine Wave Output

We believe that sine wave inverters will become the inverters of choice for RV applications. As more sophisticated and sensitive electronic equipment is added to the chassis, there will be a greater need to reduce electronic noise on the DC circuits. It is conceivable that some of the problems with the early electronic engine controls for diesel engines were associated with interference from inverter/chargers. These problems were seen in RV applications and not seen in trucks. Currently automotive manufacturers are moving toward a 36-42 volt system. One of the reasons cited is to reduce the effects of electronic noise, which can interfere with various engine and chassis computer controls. As more sophisticated equipment is added to the house side of the RV, the seamless performance and excellent load compatibility of a sine wave inverter will become more desirable to the consumer.

Each technology used to make a sine wave inverter has advantages and disadvantages. The three main technologies are high frequency, multi-step low frequency, and hybrid, which is a combination of the high and low frequency designs. Statpower and Exeltech use the high frequency topology. The Exeltech unit is an inverter only and does not have a charger. Trace Engineering uses multi-step low frequency design; Vanner, Inc., and Heart Interface use the hybrid approach. To date, only Trace Engineering and Statpower sine wave products have been used extensively in the RV market. Both are combined with high output, 3-stage chargers.

High Frequency with DC energy Bus (Statpower)

The AC waveform of a sine wave inverter is nearly identical to the waveform of grid AC so incompatible loads are rare.***(Figure 16***). It has the potential to offer better frequency and peak voltage control than a generator. A reliable source from the utility industry tells us that even utility power now looks worse than that coming from a good sine wave inverter. A utility's Total Harmonic Distortion frequently exceeds 3%. Generally, sine wave units are more expensive to produce. High charger output is not only more difficult to achieve but more expensive to manufacture.

Figure 17 shows a block diagram and schematic for the high frequency technology. Direct Current from the battery is oscillated through the center tap of a high frequency transformer(s) using unidirectional switching transistors. The switch frequency is approximately 120,000 to 200,000 cycles per second. This creates an alternating voltage that can be stepped up by the high frequency transformers to approximately 215 volts-slightly higher than the peak voltages that will later be seen on the AC side. The alternating voltage is then rectified using an "H" bridge of unidirectional switching transistors back to DC. There is now approximately 215 volts stored in the DC bus energy storage section. **The bus serves three purposes. It stores DC power irrespective of the state of charge of the battery bank; it allows continuous transfer of ripple-free power to and from the battery bank; and it shields the DC system from the ripple effect created by the production of 60 cycle AC.** The next stage converts the 215 VDC to sinusoidal AC using a second "H" bridge of unidirectional switching transistors. This creates oscillations at twice the AC frequency (120 Hz for 60 cycle AC). Pulse Width Modulated (PWM) switching is used to switch the four transistors in the "H" bridge. Diagonally opposite switches function as switch pairs, each pair being turned on or off simultaneously. Whenever the circuit is active, one pair is on while the other is off. The result of the PWM switching is AC produced at 40 kHz and at 60 Hz. The switching technique for the DC-AC "H" bridge is difficult to explain. It involves a carrier frequency of 40 kHz and a reference frequency of 60 Hz. The resulting AC waveform is sinusoidal and has major components at both 60 Hz and 40 kHz. A simple low pass filter network is used to remove the 40 kHz component, leaving only 60 Hz sinusoidal wave AC available at the AC terminals of the inverter. In the high frequency design, 12 VDC is elevated to 215 VDC and then inverted to 60 Hz AC. This high frequency design, coupled with a DC bus, uniquely separates the AC from the DC system. Voltage and current ripple in the DC system is markedly reduced from that seen in low frequency designs. Total harmonic distortion ranges from 1% to 5%, typical efficiency is 84% to 88%, and surge capability is in the medium range. Although this inverter does not offer the higher efficiency and surge capability seen in low frequency inverters, the Statpower Prosine series has captured the elusive high output, 3-stage charging using high frequency design. In this product, reduced efficiency on the inverter side is compensated by a charger that has a power factor approaching 1. This attribute makes the Statpower charger significantly more efficient than typical chargers with a power factor of 0.7 and elevates the combined efficiency of this inverter/charger package. Since high frequency transformers are lightweight, the Statpower Prosine series inverter/chargers weigh just 32 pounds.

Multi-Step Sine Wave Output (Trace Engineering)

To combine the efficiency and surge capabilities of the low frequency design with high output, 3-stage charging in a sine wave package, Trace Engineering developed a multi-step design ***(Figure 18).*** The SW series from Trace Engineering significantly alters the modified sine wave technology. By strict definition, this multi-step inverter is not a true sine wave. However, with 34 to 52 stair-steps per cycle, the output waveform approaches a sine wave. The number of steps increases as battery voltage becomes lower or power requirements become higher. Trace creates this waveform by using three low frequency transformers with the secondary windings wired in series ***(Figure 19).*** This allows for 27 possible voltages. Power MOSFETs (Metal Oxide Field Effect Transistors) switch the primary windings. Harmonic distortion of this waveform is typically only 3% to 5%. The typical efficiency is 85% to 95%, the idle power consumption is low, and the surge capability is good.

This sinusoidal waveform has significantly fewer incompatibilities when compared to the modified sine wave. This model has a sophisticated generator/shore power transfer relay, which allows a seamless transfer between the inverter and AC sources. There is an automatic generator start feature and three extra user programmable, voltage controlled relays for accessories, (e.g., to control solar panel charging). When using the auto-generator start feature, consumers should be aware of the perils of starting a generator indoors in regard to the possibility of carbon monoxide intoxication, and the need for proper safety interlocks so there is no danger of electrocution. Two units can be stacked to provide 240 volt service. This product is primarily intended for remote off-grid housing, but is frequently used in bus conversions. The 12 volt model is finding its way into high end Class A motorhomes.

When AC from shore power or a generator is present, the transformers reduce the AC voltage and rectify the low voltage AC to DC, which is then available for charging the batteries. The integrated 3-stage charger is temperature compensated, is more efficient, and has lower AC current distortion when compared to the modified sine wave units. This technology increases the power factor and lowers the AC current distortion in the charge mode. Large pulsating currents remain at the DC port in both inverter and charger modes. Since the low frequency transformers are heavy, the Trace SW series inverter/charger weighs approximately 105 pounds.

Hybrid, High-Low Frequency

12 VDC from the battery is switched using a high frequency transistor H bridge to 12 V sine wave AC. It is then stepped up to 120 volts sine wave AC using a step-up transformer. The 120 volts sine wave AC is used to supply AC loads. ***(Figure 20).*** This method yields the high efficiency, surge capabilities, and high output, 3-stage charging of the low frequency design, plus the low harmonic distortion of the high frequency design. THD ranges from 1% to 5%, efficiency is 85% to 90%, reliability and surge capability are good, and there is medium idle power consumption. Brutus and IT Series by Vanner, Kenetech from Trace Engineering, and Heart Interface use this approach.

CONCLUSION

Inverter-chargers must fit the needs of the individual RV owner. Needs range from none or little to an absolute necessity for high capacity, pure output units. Sine wave inverter-chargers may cost up to 50% more than MSW inverter-chargers, but for our application, we believe the added performance more than justifies the added expense. When we contemplate investing in a new inverter-charger, we first estimate our present and future needs. If future plans include trading up to a new RV, we would seriously consider investing in an inverter-charger with a higher capacity than currently needed and then plan to move the inverter to the new RV. We would then order the new RV "inverter ready" but without a standard model installed. A manufacturer's willingness to comply with this plan would be a determining factor in which RV to purchase.

Most inverter/chargers used in RV applications offer standard or optional remote controls. The remote units provide a means to activate/deactivate the inverter/charger from within the RV. They also offer monitor and display features. Most models offer some form of a search feature that allows the inverter to "sleep" and thereby reduce power consumption in standby mode. It then "wakes up" when it detects a load. Almost all chargers have "power sharing" although the protocol varies among manufacturers. Generically, power sharing limits the amount of power used by the charger so some power is available for other AC loads. This is a valuable feature when shore power is limited to 30 amps or less.

Acknowledgments:

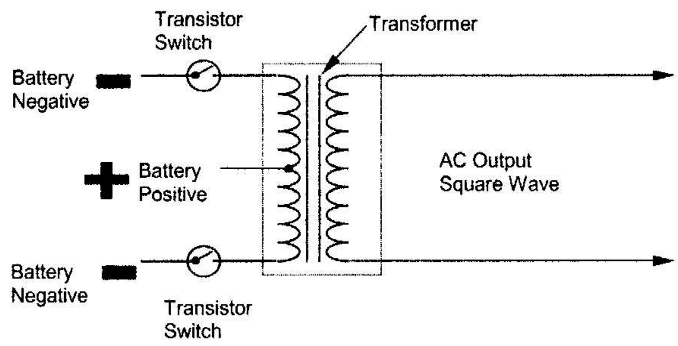
We accept all responsibility for any errors contained in this article. The subject is complicated and the process of accumulating information and data has been long and difficult. The manufacturers and individuals listed below have contributed equipment, technical data, illustrations, and advice. We are grateful to all. If we have omitted any company or individual from this list, we are sincerely sorry. Any omission is purely unintentional.

Ample Power, Inc.: David Smead
Exeltech
Heart Interface, Inc: Warren Stokes, Mike Hirata, Smitty Ovitt
Redi-line, Inc.
Statpower, Inc.: Konrad Mauch, Derek Pettingale, Fred Dennert
Trace Engineering: Mike McCoy, Gary Baxter, Ray Barbee, Craig Lang, Eldon Wharton.
Tripp Lite, Inc.
Vanner, Inc: Greg Woeste.

For more information, visit the web sites of the contributing companies. Trace Engineering maintains many technical articles on their web site in their "Document Depot."

Figure 1, ***Courtesy of Trace Engineering***

A common circuit topology referred to as "push-pull" is used to produce a square wave output



Push-Pull Topology - Square Wave Output

Figure 2, ***Courtesy of Trace Engineering***

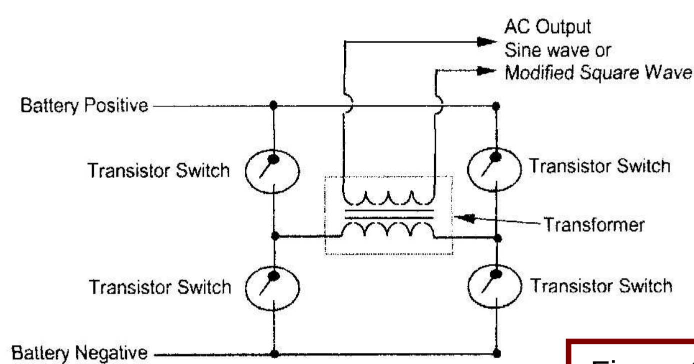


Figure 2

H-Bridge Topology

Figure 3, ***Courtesy of Trace Engineering***

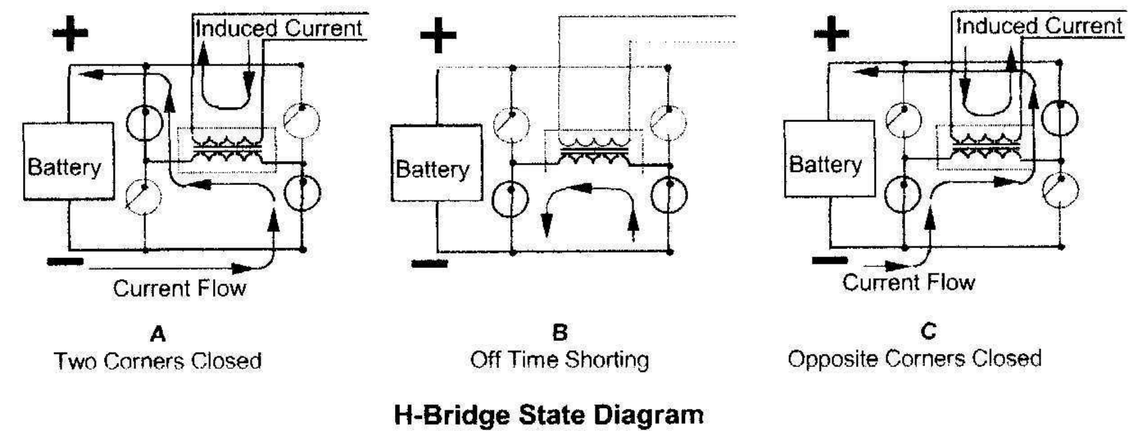
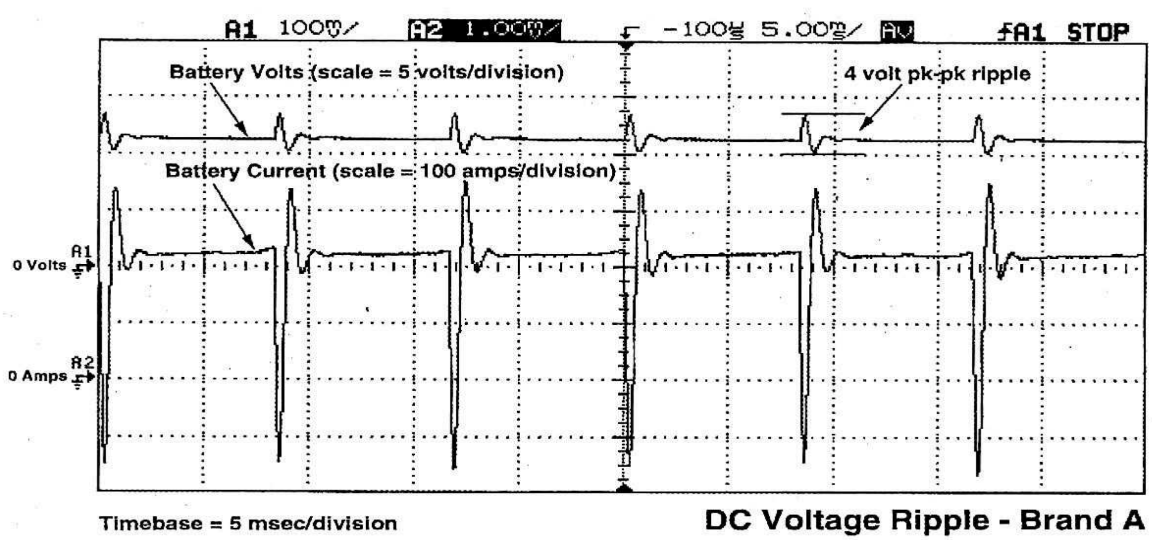
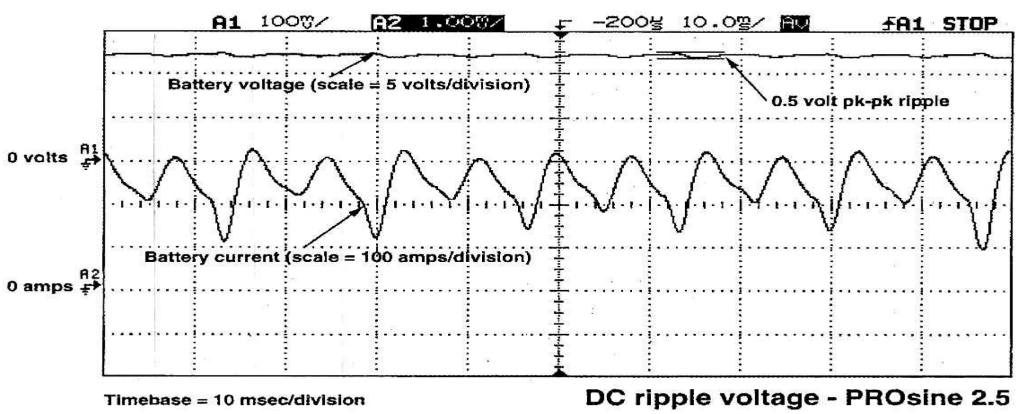


Figure 4, ***Courtesy of Trace Engineering***



DC voltage ripple – 2000 watt quasi-square wave inverter/charger – Brand A

Figure 5, ***Courtesy of Statpower***



DC voltage ripple – PROsine 2.5 inverter/charger

Figure 6, ***Courtesy of Trace Engineering***

Low Frequency Transformer Based Inverters

The following topologies are based on low frequency switching of the low voltage DC side, applying the resulting DC pulses to a step-up transformer. Two common topologies are the **push-pull**, and the **H-Bridge**. The push-pull topology is suitable for production of square and modified square output waveforms, while the H-Bridge is useful for producing modified square wave and sine wave outputs.

The general flow of a low frequency transformer based inverter is shown by the figure below.

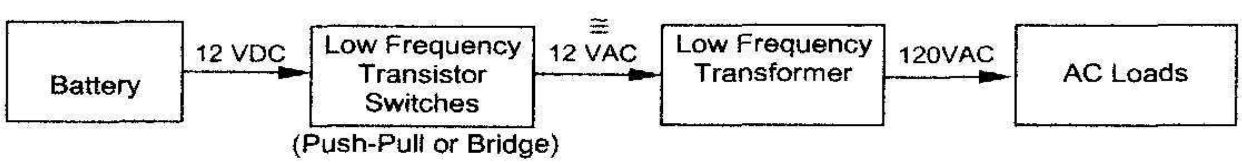


Figure 7, *Courtesy of Trace Engineering*

After a period of approximately 8ms (one-half of a 60hz AC cycle), the switches flip-flop. The top switch opens and then the bottom switch closes allowing current to flow in the opposite direction This cycle continues and higher voltage AC power is the result.

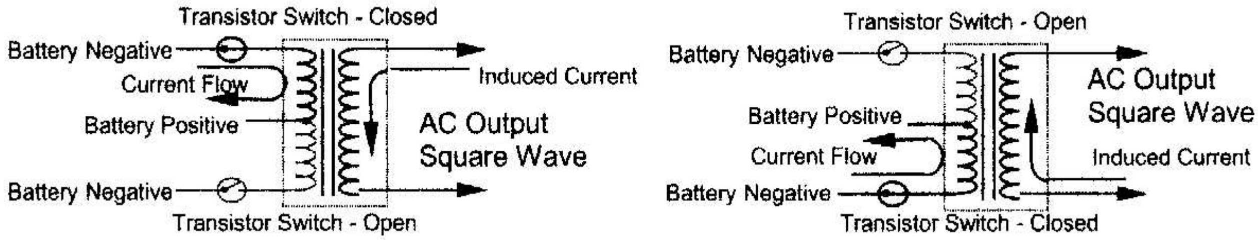
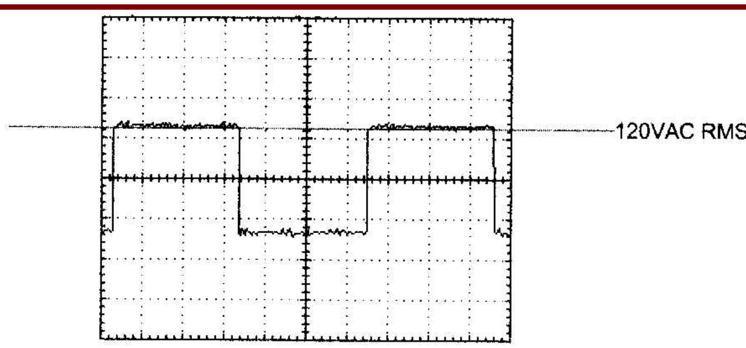


Figure 8, *Courtesy of Trace Engineering*

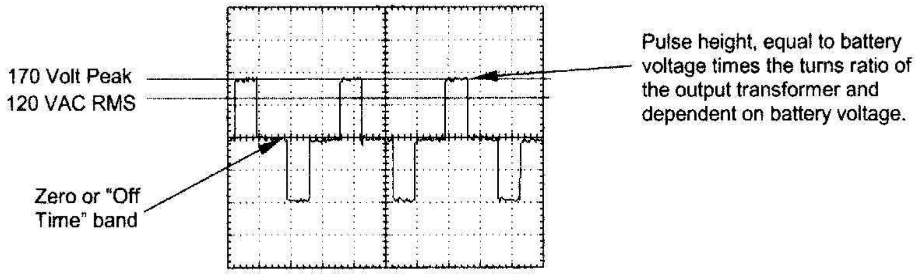


Square Wave Output Wave

Figure 9, ***Courtesy of Trace Engineering***

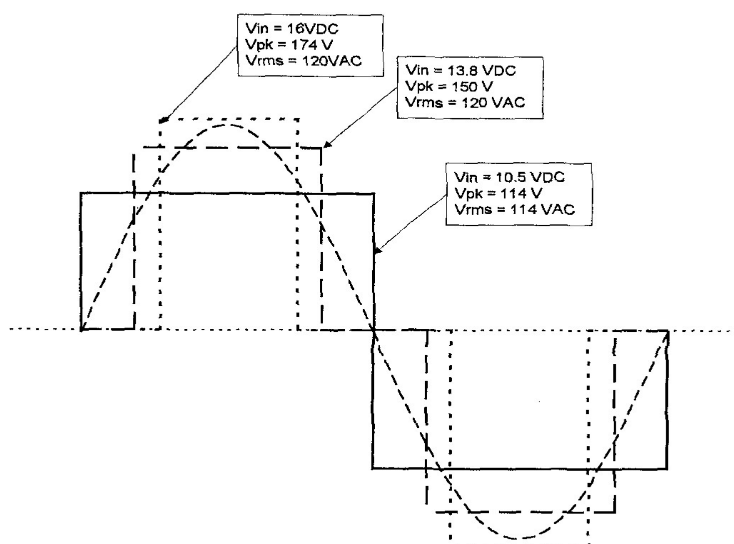
Modified Square Wave Inverters

The addition of an extra winding in the transformer along with a few other parts allows output of a **Modified Square Wave** (often referred to as a modified sine wave by marketing types) while still utilizing a push-pull topology



Modified Square Wave, and Off-Time

Figure 10, ***Courtesy of Statpower***



Regulation of rms output voltage

Figure 11, ***Courtesy of Trace Engineering***

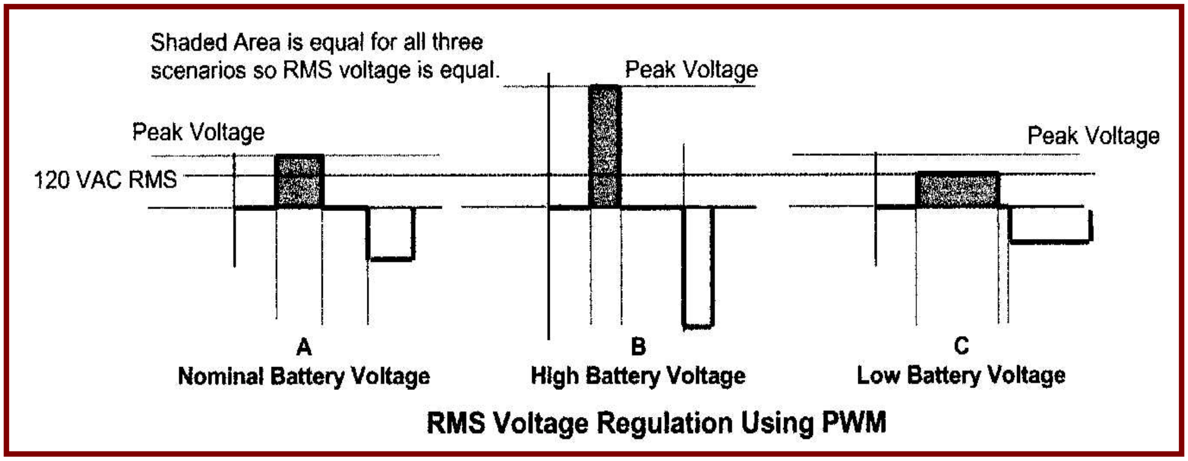


Figure 12, ***Courtesy of Trace Engineering***

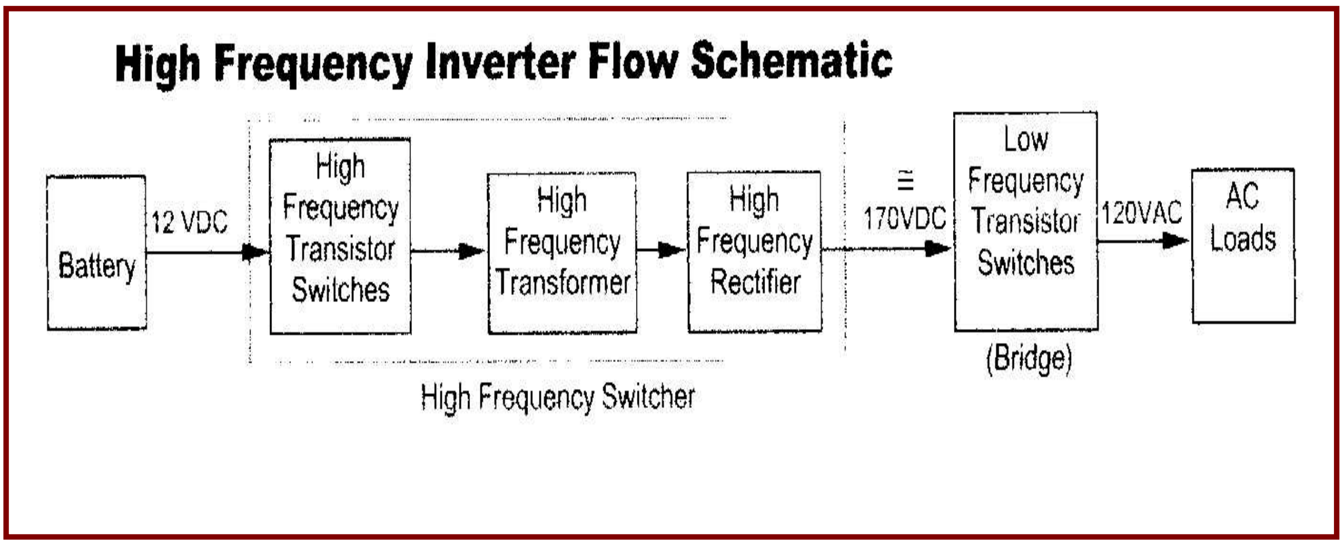
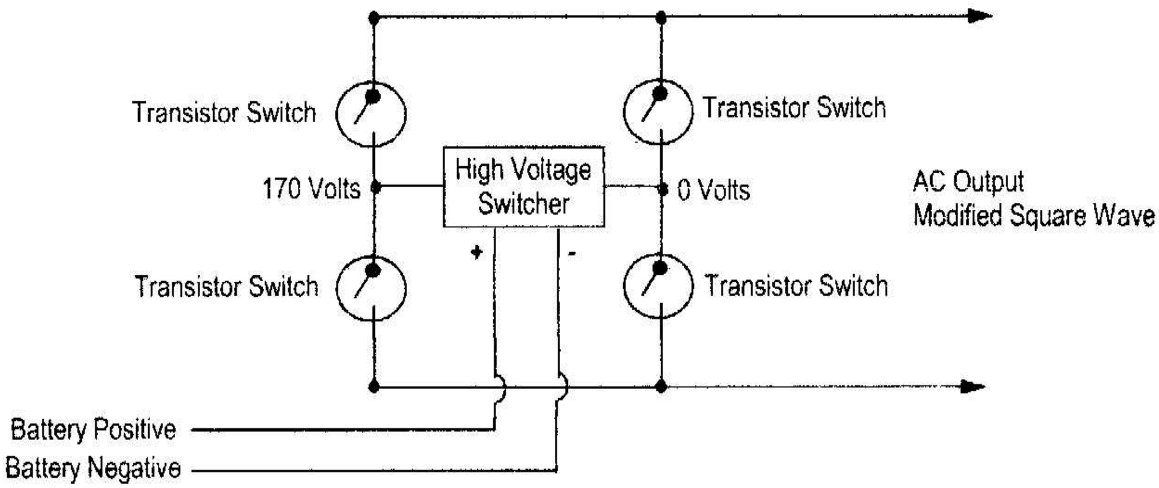
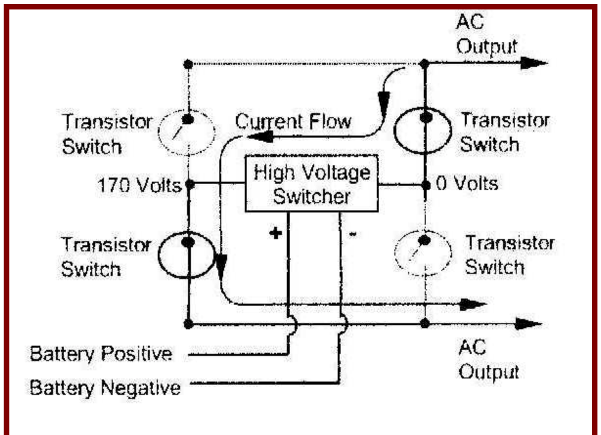


Figure 13, ***Courtesy of Trace Engineering***



High Frequency Inverter with H-Bridge Topology

Figure 14 A, B, & C, ***Courtesy of Trace Engineering***



Two Opposite Corners Closed

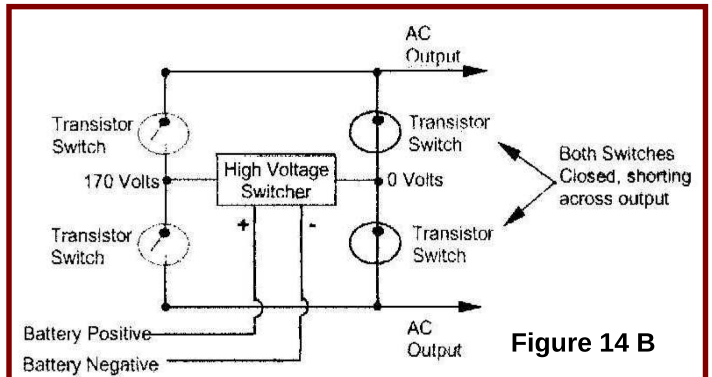
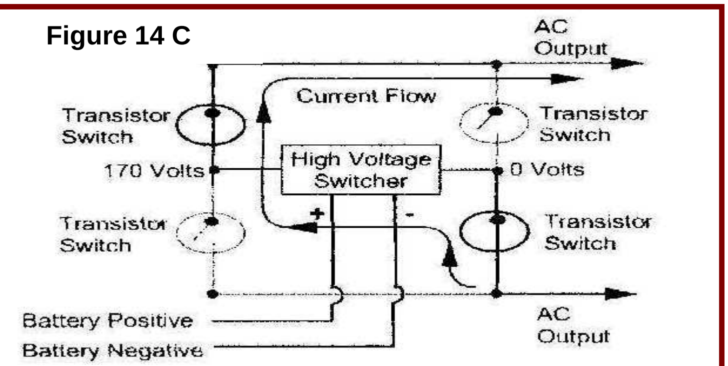


Figure 14 B

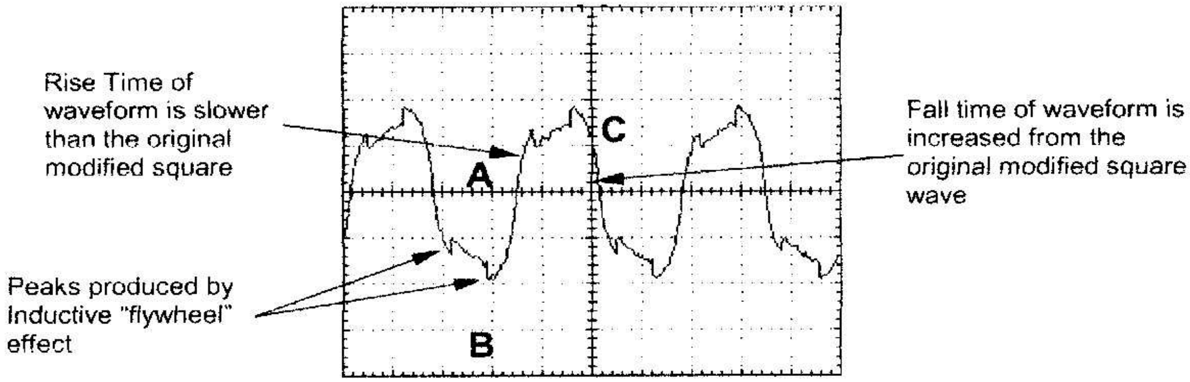
Off-time Shorting

Figure 14 C



Other Two Corners Closed

Figure 15, ***Courtesy of Trace Engineering***



Actual Waveform produced by a Modified Square Wave fed through a Ferro Resonant Transformer, driving a 75W incandescent light bulb

Figure 16, ***Courtesy of Statpower***

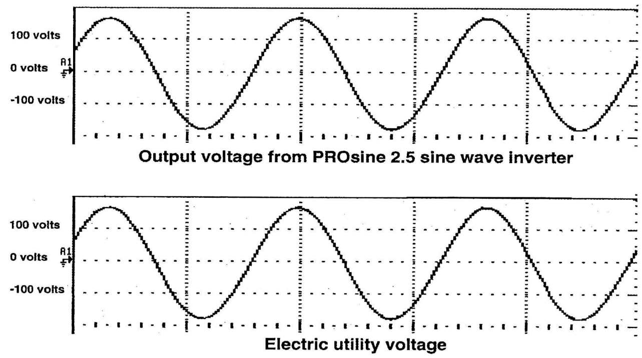


Figure 17, *Courtesy of Statpower*

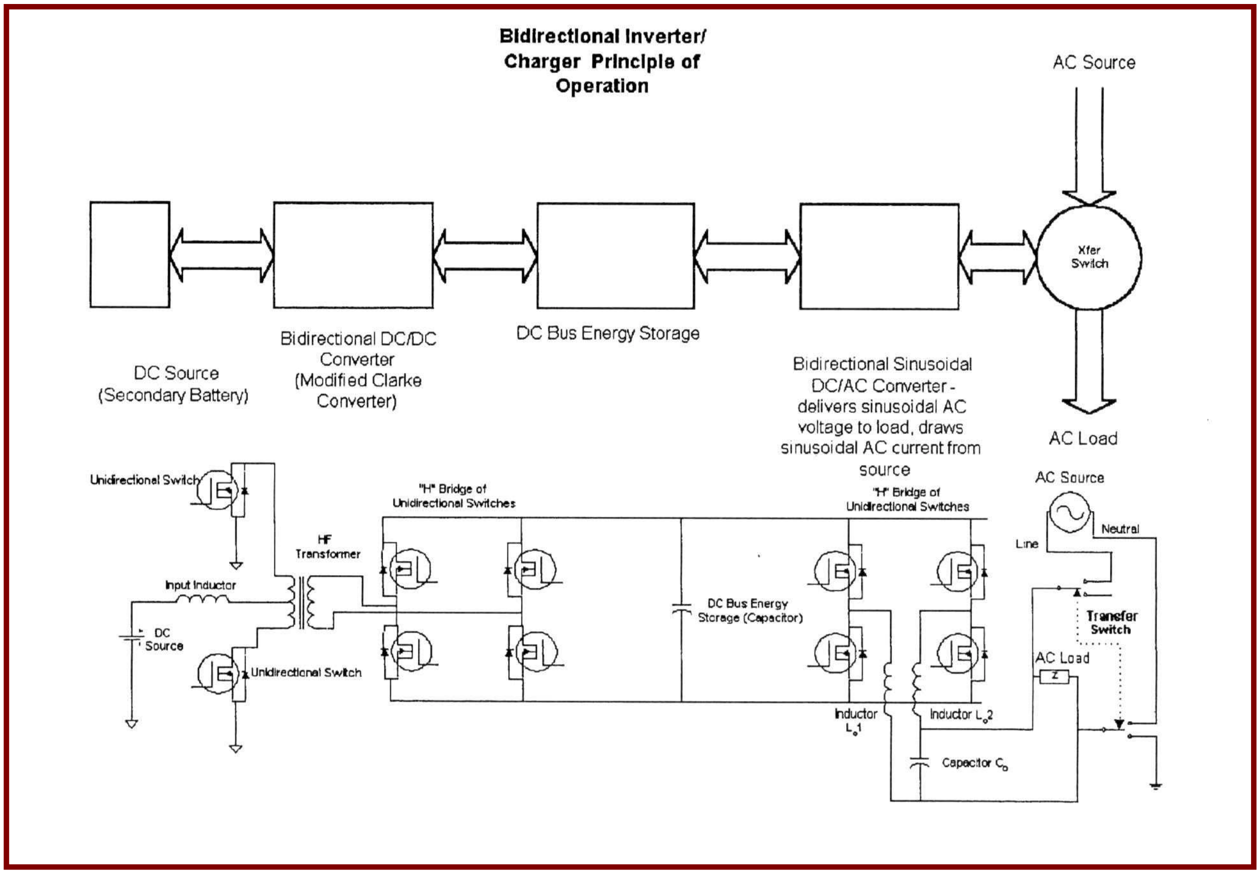
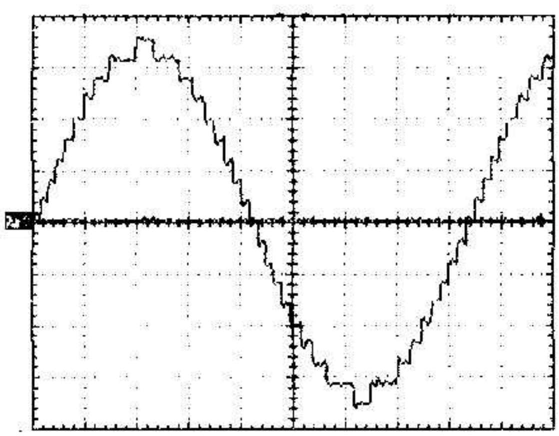


Figure 18, *Courtesy of Trace Engineering*



Trace SW Series Inverter Output

Figure 19, ***Courtesy of Trace Engineering***

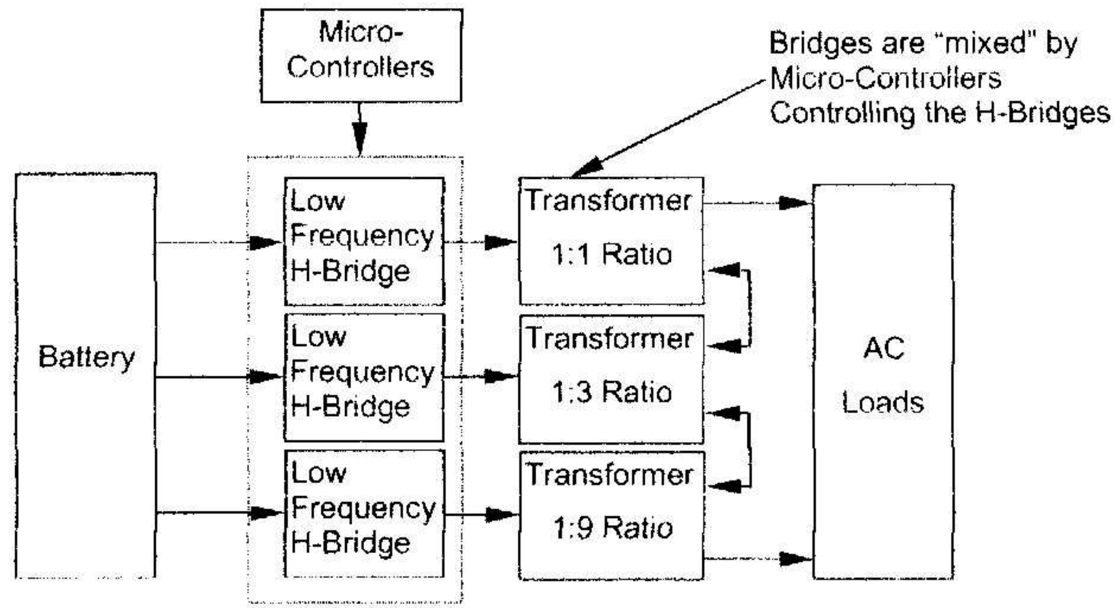


Figure 20, ***Courtesy of Trace Engineering***

Below is a flow schematic for a hybrid inverter.