Control Box for the Honda Inverter:
Electric Power for Larger Boats

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Introduction

A dozen or so years ago, I researched and wrote a book about electric boating called "Electric Propulsion for Boats". The book described the performance that can be expected from a golf cart size, 48 volt DC motor driving a boat in the 20 foot range.

Two years ago, I wrote a sequel, a second edition of the book which described the conversion of a 19 foot O'Day sailboat powered by the popular Etek motor, an efficient "Lynch" design permanent magnet DC motor. The excellent results obtained were described in Chapter 6 of this book. A free copy of Chapter 6 is available by visiting my website www.myelectricboats.com.

With battery power weighing 50 times as much as the equivalent amount of fuel for the same amount of stored energy, it is imperative to use as efficient a motor as possible to obtain the best performance and the longest range. To this end, in the first book, I suggested the use of a 3 phase AC motor rewound for 48 volts. I also proposed the design of a 3 phase inverter using Mosfet switches capable of generating 150 amps of 3 phase AC at 48 volts. Due mainly to the complexity of this idea, the response and the feed back were not overwhelming!

I did receive a number of questions and some requests for ideas to power larger boats in the 30 to 50 foot range with 20 HP or more. Supplying the necessary battery power for boats of this size is easy. By putting enough 12 volt batteries in series, voltages of 120 to 240 volts can be obtained. Efficient 3 phase AC induction motors of any horsepower can also be obtained off-the-shelf. The missing component is a 3 phase inverter capable of controlling the speed and direction of these powerful motors.

To my knowledge, the only off-the-shelf inverters available for the control of large 3 phase motors cost several thousand dollars. They require 230/460 volt 3 phase input which is then rectified into DC and then inverted back to a variable 3 phase AC power to control the speed of the motor. Such a device could probably be modified to accept the DC from the battery instead of the rectified DC, but considering the cost of these devices, I never experimented with them.

With the advent of the Toyota Prius and the Honda Insight hybrid cars, 3 phase inverter/controllers for motors in the 20 HP range are readily available at junk yards, at E-Bay and on the Internet for less than $200. In the case of the Honda inverter, **the device can be turned into a motor controller without any changes whatsoever to the inverter**. A hacker's dream: Plug and Play control of motors.

Toyota Inverter vs. Honda Inverter

Obtaining the necessary documentation or schematics from either Toyota or Honda to make an intelligent decision as to which is better suited for this kind of inverter application is equally difficult. I visited Toyota hybrid expert David Taylor of Re-Involt in Sanford, NC (web: reinvolt.com) to get a first hand look at the Toyota Inverter. I wanted to determine if it could be used as a stand alone component and whether it could be isolated from the other 14 computers that make up the Toyota control units. It turned out that the Toyota motors, transmission and controls are water cooled. This adds a level of difficulty to separating the inverter from the other hybrid components and turning it into a stand alone unit. David provided me with the name of other Toyota experts a well as the name of a Honda hybrid expert, Mike Dabrowski of Grosvernordale in Connecticut. (web: 99MPG.com)

I visited with Mike and after getting a tour of his numerous hi-tech projects, we zeroed-in on the Honda Insight inverter. Being air cooled and interconnected to the rest of the car with connector cables, it is easy to separate it from the rest of the Honda MCM (motor control module). Although Mike does not have detailed schematics of the inverter unit, he does have overall drawings which showed great promise for this project. Mike sold me a Honda inverter unit which I took apart without delay.

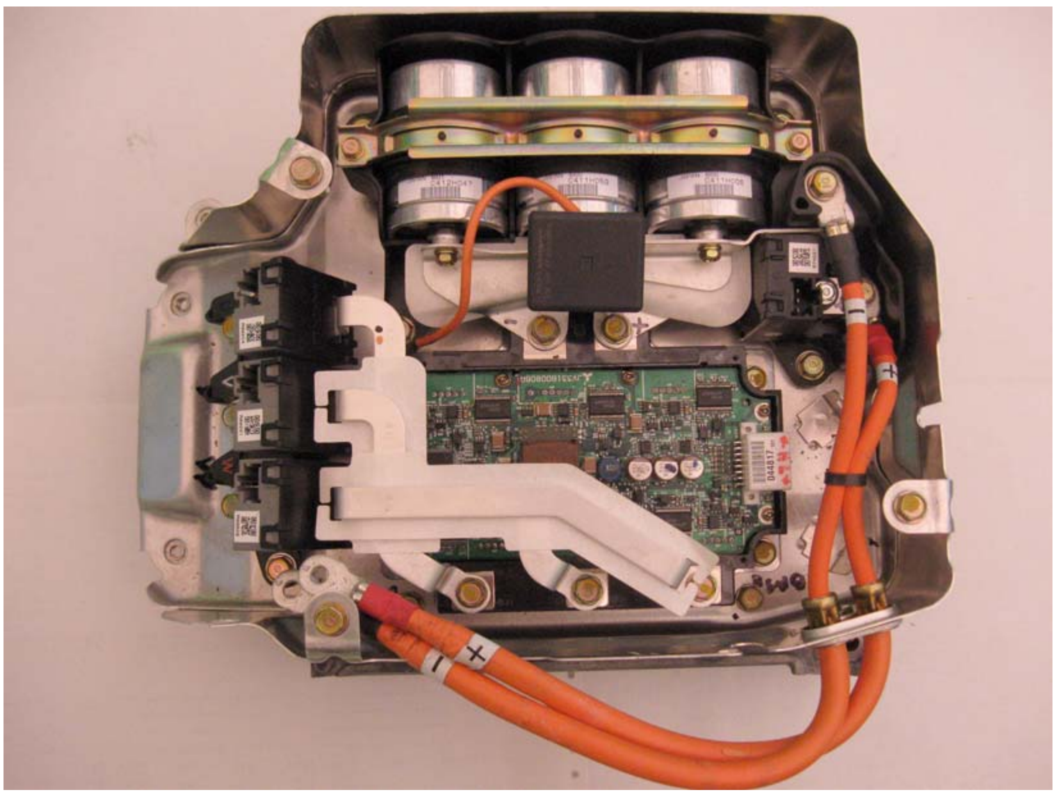
3 Phase AC Motors vs. Brushless DC Motors

The hybrid cars' motors are brushless DC motors. But being 3 phase motors, their inverters are equally capable of driving a 3 phase AC induction motor. The main difference between these two types of motors consists of the 3 commutation sensors in the brushless DC motor. They determine the location of the rotating armature. The output of these sensors is used to sequence the operation of the electronic switches. A 3 phase induction motor does not require sensors because it operates at a speed slightly less than the frequency of the AC source. For example, the most common 4 pole, 3 phase 60 cycle induction motor runs at approximately 1750 rpm.

Disassembly of the Honda Inverter

Curiosity has often been my downfall and it was in this case when I took the Honda inverter apart. As we can see in the picture below, the case holding the inverter measures about 10.5x13 inches, it can be disconnected from the other Honda electronic systems by simply removing the connectors and cables

On the left of the picture, is where the 3 phase outputs (labeled U,V,W corresponding to the 3 phases which we generally call A,B,C) connect to the 3 phase AC motor. The 3 black boxes surrounding the heavy straps are used to sense the amplitude of the current.



At the bottom of the picture, the heavy orange wires marked + and – go to the battery. Just to the left of the + terminal connection, the black device with the 3 connector pins is used to sense the amount of current drawn from the battery.

On top, there are 3 capacitors rated 470 microfarad at 400 volts which are used to stabilize the battery voltage. The black box below the middle capacitor is a high pass filter. The overall quality of the components and of the packaging design is excellent.

The green, 3.5 x 7 inch printed circuit board (PC board) is used for a variety of functions which I have yet to decode fully. It does generate a number of coded serial strings of messages which are used for the operation of the hybrid car. It also contains the 6 switch drivers which in turn operate the 6 high power electronic switches (IGBTs) needed to generate the 3 phase AC. These switches are mounted directly below the green PC board in a flat black plastic container 3/4 inch deep filled with silicone for superior heat transfer. The entire assembly is mounted on a honeycomb heat sink through which air can be circulated for cooling.

This is where my curiosity got the best of me. The electronic switch assembly below the green PC board is a sealed unit made by Mitsubishi, part number: PM 300 CVA 060. It contains 6 IGBTs (Insulated Gate Bipolar Transistor) mounted on a heavy heat absorbing plate. The switch unit is attached to the circuit board with small screws which were easy to remove and led me to believe that the cover could be removed for a peek inside.
Do not attempt it!

When I pried the cover off, the tiny wires to the circuit board broke (mostly at the soldered connecting point). I made a valiant effort to repair the damage but it turned out that the tiny interconnecting wire were aluminum and beyond my soldering ability.

Mike sold me another unit which as the picture shows is still in perfect condition!

The Mitsubishi part number indicates that this unit is rated for 300 amps at 600 volts (180 kw). This is an amazing feat for a box 3.5 x 7 inches. The secret is the excellent heat transfer that takes place between the IGBT's and the cooling plate. The high current capacity is achieved by keeping the tiny wires short and providing dozens of parallel paths.

I've left the description of the most important part of the Honda controller for last. It is the connector socket located at the right side of the PC board and labeled 044817. It has 16 pins of which 11 are used. Pins 1, 2, 9 and 10 carry the power (+15 volts DC at 270 ma.) to the green PC board. 6 signal lines, pins 6 to 8 and 14 to 16 carry the signals to the drivers that activate the 6 IGBT switches.

As previously mentioned, the status line from the Honda PC board to the rest of the electronics in the car is not used. Through this connector, the Control Box described here provides all the signals needed to plug and play the inverter.

How do we "Plug and Play"

Plug and play means that when we attach a cable from a newly designed Control Box to the connector described above, we will provide all the power and the signals needed to operate the Honda inverter. Then, after attaching the battery to the + and- cables and the motor at the U,V,W terminals, we will be able to control a 3 phase AC motor using the following controls: Run/Coast, Reverse and Speed Control. ***No modifications whatsoever are required to the Honda Inverter***.

The Honda Inverter Control Box

A description and pictures of the of the Control Box prototype is provided after the basics of square wave generation are reviewed below. We will also see how a brushless motor can be controlled by this same Control Box a little later.

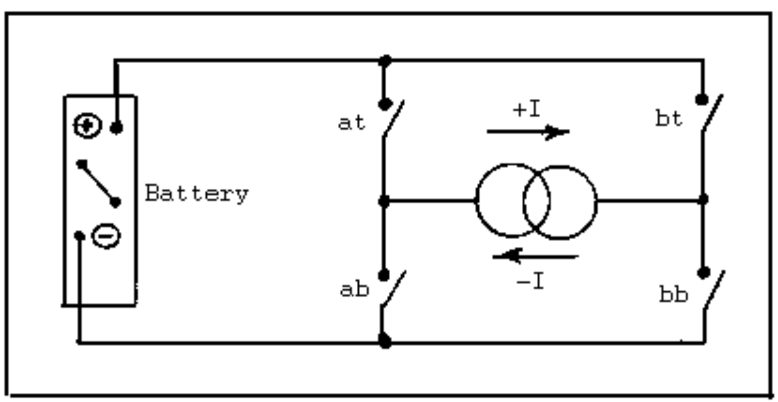
Honda refers to phase A as U, phase B as V and phase C as W. I have reproduced the basics of square wave generation from my book "My Electric Boats". I did not change the phase labels A, B, C to U,V,W. Hopefully, this will not cause too much confusion.

For those interested in such things, here is a quick review of inverter basics using square wave technology.

AC Square Wave Basics

The H Switch

A good way to explain how DC is transformed (inverted) into AC is to consider the operation of an H switch (see diagram below). As the diagram shows, there are four switches: two of them are connected to the plus (+) side of the battery and two of them are connected to the minus (-) side of the battery. (There is a convention of sorts that uses the subscript "t" [for "top"] for the switches connected to the plus side of the battery and the subscript of "b" [for "bottom"] for the switches connected to the minus side of the battery. We will use that convention). Where the bar across the H would normally be is where the load is connected. The two circles shown here represent a motor

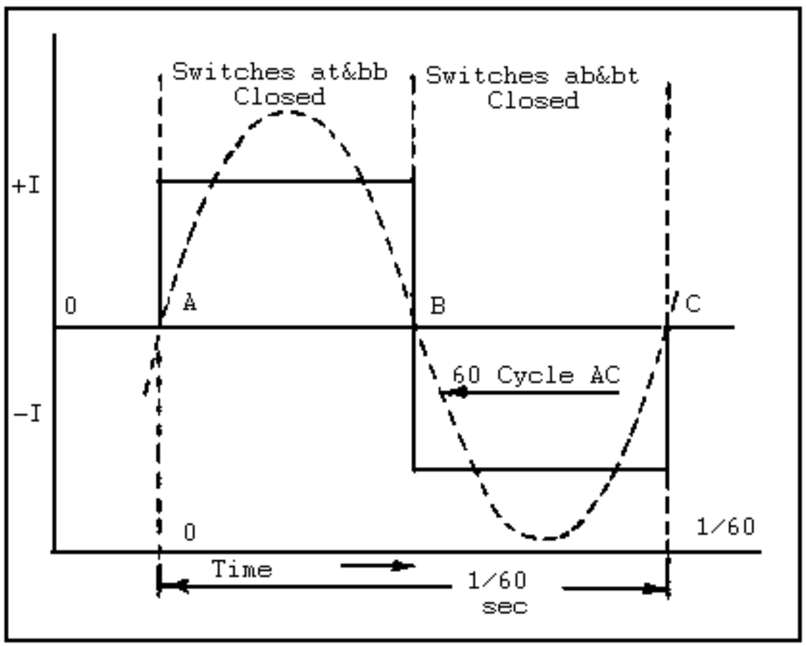


H Switch Diagram

The operation of the H switch is as follows: when switches at and bb are closed, positive current (I+) flows through the motor. On the other hand, when switches ab and bt are closed, negative current (I-) flows through the motor. So, if we were to plot this sequence of events (the current over a certain time period), it would look like the square-wave in the box below (shown as a solid line).

The plot shows “current” on the vertical axis and “time” on the horizontal axis. At point A, the first two switches close, at point B the first two switches open and the next two switches close and at point C the last two switches reopen.

Assuming that the switches shown in the diagram below were controlled electronically, they would operate very fast. The whole sequence of events would take place in 1/60 of a second. The dotted line in the shape of a sine wave represents one cycle of 60 cycle AC power from the power company. As we can see, there is a resemblance between the square wave generated by the inverter switches and the sine wave generated by the power company. A single phase AC inverter works in this manner.

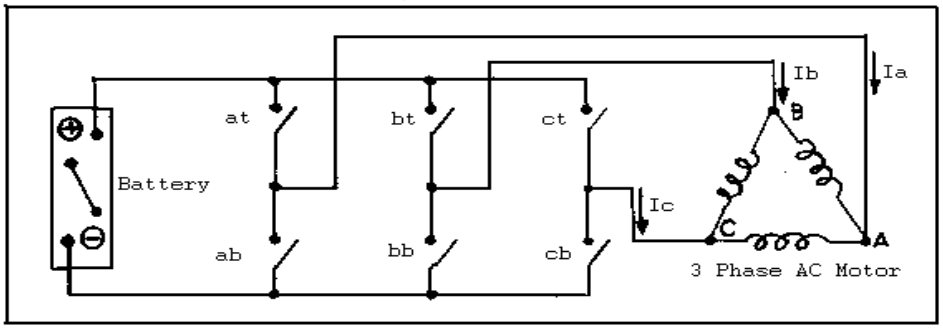


Square Wave (Current vs Time)

3 Phase Switching

At this point, it isn’t hard to guess that by adding more switches, we should be able to simulate a 3 phase power source. A 3 phase switching diagram, using six switches instead of four, is shown in the box below.

Here, we have the battery connected to three pairs of switches (just one more pair than single phase AC). The additional switches are ct and cb. The common connection between each pair of switches is wired to one phase of the 3 phase motor. 3 phase AC devices can be connected in one of two ways: either in “delta” or in “wye.” For now, we observe that the motor is connected in delta.



3 Phase Switching Diagram

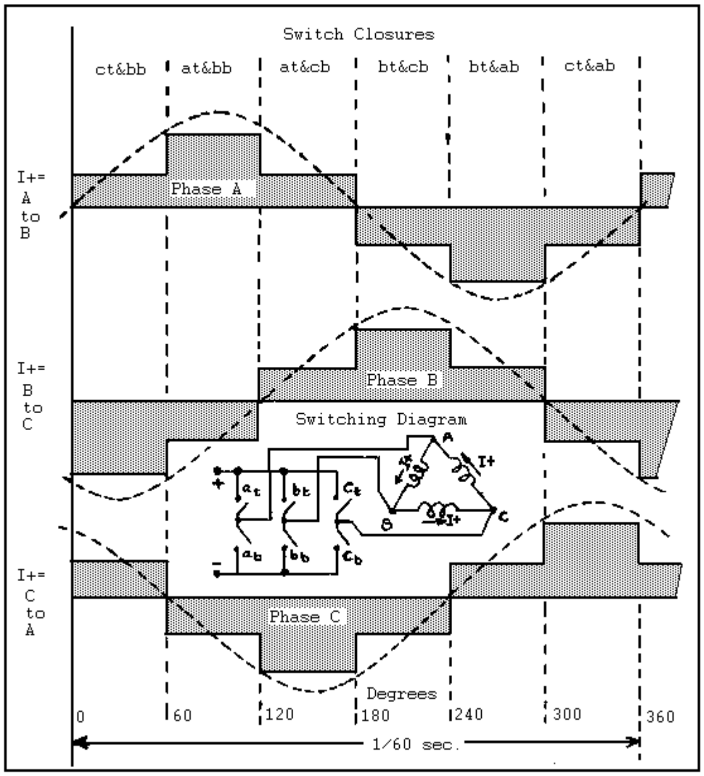
A Note of Caution

This is a good time to make an important observation. **Of all the different combinations of pairs of switches which close simultaneously in both the simple H switch and the 3 phase switch configuration, top and bottom switches of the same phase, such as "at" and "ab", MUST NEVER CLOSE AT THE SAME TIME.** Looking at the switching diagram, we can see that such an action would put a direct short across the battery resulting in the catastrophic destruction of the IGBT switches. I have hundreds of blown out Mosfet switches to prove this point. Some of this destruction was due to my own stupidity, but in most cases it was due to "glitches" in the electronics. Most of the time, the cause was an electrical noise that was generated when high currents were switched on and off.

The so called "anti-ambiguity" circuits which I added, prevent two switches of the same phase from closing at the same time. They should be included in this type of circuitry. I found out the hard way that this precaution is essential.

The Current Trough the Motor Windings

The simplified switching diagram in the middle of the drawing below shows the same six power switches and the common connection of each pair of switches to the input of the motor at points A, B and C discussed above.



Current through the Motor Windings

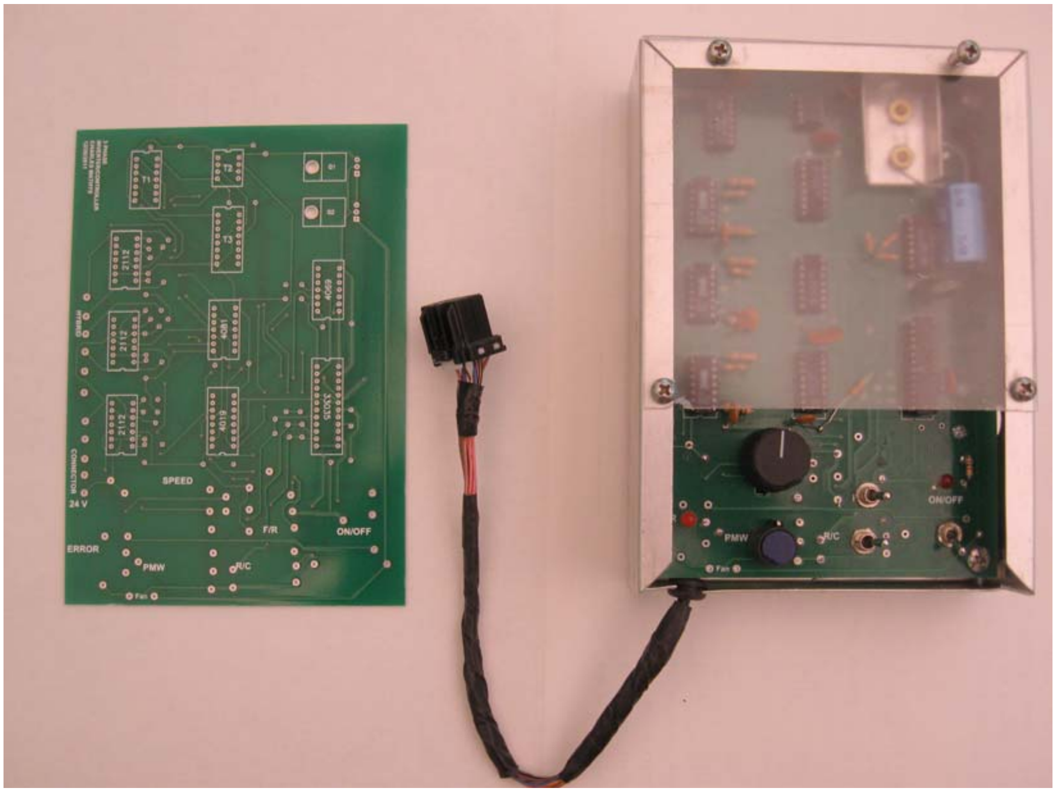
We won't go through the tedious exercise of following the flow of current to the motor windings during the closure of each pair of switches (as I did in the first edition of my book). It should be evident that three square waves can be generated by dividing a 1/60 of a second (of 60 cycle power) into six more 60 degree subdivisions.

The remarkable similarity between the square wave pattern shown here and the 3 phase sine wave pattern from the power company is the reason why the 3 phase inverters work so well.

Control Board for the Honda Inverter

Now that we are familiar with the idea of generating 3 phase AC, we can apply this knowledge to the design of a Control Board capable of plugging into the Honda inverter's 044817 connector and, without modifications to the inverter, generate 3 phase AC which will, in turn, drive a 3 phase induction motor. We will also consider how this same board can drive a brushless DC motor later in the discussion.

A photo of the 5x7 inch Control Board is shown below as well as the populated Control Board mounted in a 5x7 inch box with knobs and switches to control the motor. The cable plugs into the Honda Inverter.

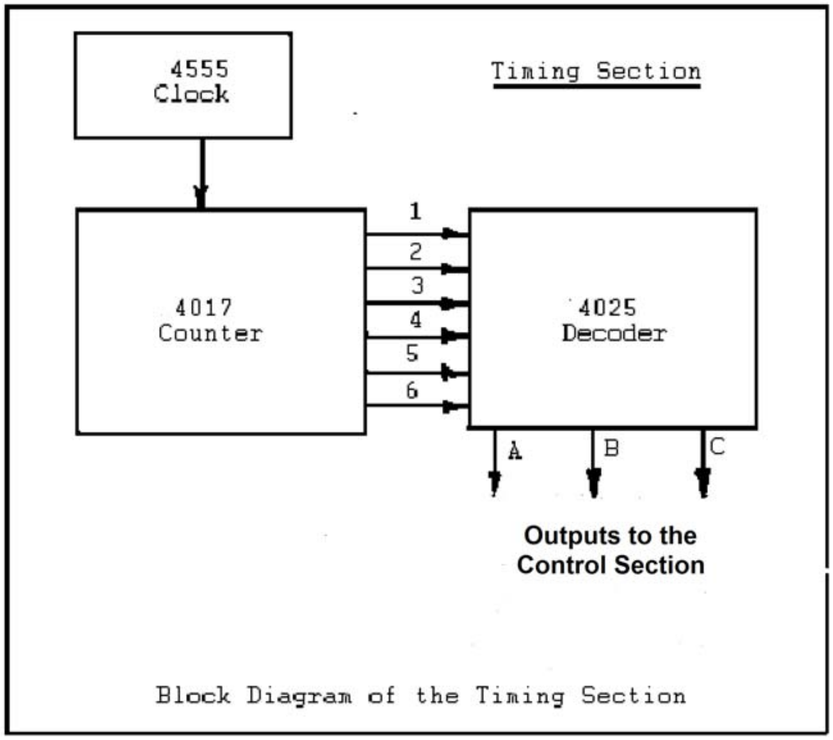


Controller Board Design

The design of the power supply needed by the Honda Inverter could not be simpler. 24 volts of DC power is supplied to the Control Board. Using a 5 volt and a 15 volt regulator, the necessary supply voltage is generated for both the Control Board and also for the Honda inverter's circuit board. The power, 270 ma. at 15 volts, is transmitted to the Honda inverter via the 044817 connector previously described.

The Control Board design consists of 10 Integrated Circuits (IC's). It is divided into 3 logical sections: the Timing Section, the Control Section and the Switching Section. Each section is described below using a functional block diagram. It would be too tedious to describe each pin to pin interconnection and the shape of each signal here (but it is available in Chapter 15 of "Electric Propulsion for Boats". (Web: myelectricboats.com). Each type of semiconductor has a data sheet with much more information for anyone wanting to dig into the details of the operation of these devices. The most useful are the data sheets on the "Brushless DC Motor Controller", MC33035, which can be downloaded from ON Semiconductor. (Web: onsemi.com)

The Timing Section



Using the block diagram shown above, we can see that the timing section is where the pulses which control the entire operation are created. The timing section has 3 IC's: the 4555 clock, the 4017 counter and the 4025 decoder.

The clock is an all purpose chip available at Radio Shack capable of generating pulses at various frequencies. By generating pulses at frequencies varying from 72,000 to 132,000 Hz (hertz or cycles per second), the resulting square waves cause a 3 phase AC, 1750 rpm motor to run at speeds ranging from 1200 to 2200 rpm. A 5000 ohm potentiometer (just like the volume control of a stereo) is used to control the speed of the motor.

It may not seem that this limited rpm range is sufficient to control the speed of a boat but one should remember that the power output of the propeller is a cube function: doubling the speed increases the output power by a factor of eight. A wider frequency range may be needed for other applications, the Pulse Width Modulation (PWM) feature of the 33035 can be used to satisfy this requirement.

Two ICs are used to count up to six and to decode the square waves. These square waves meet the input requirements of the MC33035 motor control IC to which they are connected.

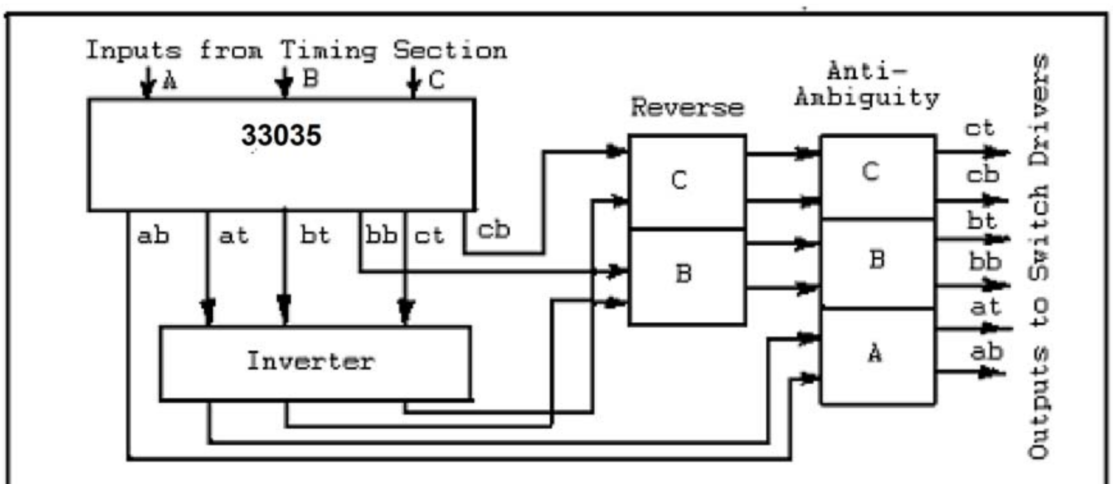
The Control Section

The control section circuits are shown in the block diagram below. The diagram shows that the pulses from the timing logic go to the 33035 motor control IC. The output of the 33035 chip goes to the level inverters, the forward/reverse circuitry, the anti-ambiguity IC and finally to the switch drivers.

The level inverter is simply an inverter IC connected to the output of the 33035. An inverter is used to reverse the polarity of a level. For example, if a level goes from +15 volts to ground (as it does in this case), the level will go from ground (0 volts) to +15 volts after going through the inverter. It is required here because the output levels of the three **top** switch outputs are opposite in polarity from the three **bottom** switch outputs which are designed for P-channel Mosfets.

We've mentioned before that the forward/reverse feature of the 33035 (which is designed for Brushless DC motors), does not work on 3 phase AC motors. The 4019 IC circuit shown here performs the reverse function.

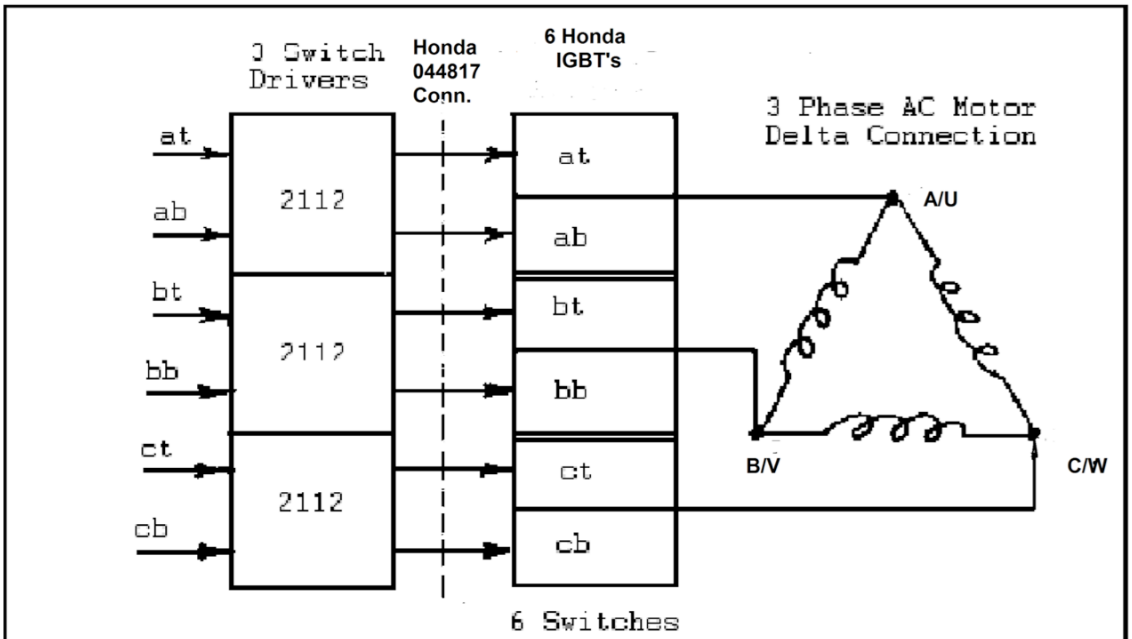
The anti-ambiguity circuits consist of 3 "And" gate circuits in the 4081 IC. They implement the safety feature mentioned before: by activating the SD (shut down) input of the 2112 drivers, they prevent the unintentional operation of the circuit in case 2 switches of the same phase were to close at the same time.



Block Diagram of the Control Section

The Switching Section

Using 3, 2112 switch drivers for this application is probably an overkill seeing that 3 drivers are available in a single IC package. Unfortunately, the single package does not provide an SD (shut down) function which is well worth the added cost. As the diagram shows, the outputs from the anti-ambiguity circuits simply feed the 2112 switch drivers. The switch drivers, in turn, connect to the cable which activates the Honda inverter through cable connector 044817.



Block diagram of the Switching Section

Control Functions of the Control Board

We have already touched on the various control functions implemented in the Control Board but this is a good place to review them as well as to list the safety features implemented in this design.

Power to the Control Board comes from a 24 volt battery or from a 24 volt DC wall transformer: either source plugs into a receptacle on the right side of the Control Board's box. The 24 volt supply is reduced to 15 volts and then to 5 volts to power both the Control Board and the green circuit board in the Honda inverter. The right hand micro-switch turns the power on and lights the On/Off indicator.

The middle 2 micro-switches control the operation of the motor: the top one is the Forward/Reverse control and the bottom one is the Run/Coast control.

Two speed controls are implemented. The top one controls the frequency of the 3 phase AC. It is used with induction motors which do not require a wide range of speed control in applications such as driving pumps or boat propellers.

The bottom speed control is used with Brushless DC motors. It uses the Pulse Width Modulation (PWM) technique which effectively tricks the motor into thinking that the battery voltage has been reduced. 10 to 1 speed control can be achieved with the PWM. The PWM control can also be used in conjunction with the frequency control to improve the efficiency of induction motors at low speed.

The indicator at the left of the Control Board lights up when an error such as over-current has been detected by the 33035 IC.

Safety Features of the Control Board

The main safety feature of the Control Board is the anti-ambiguity circuits which will shut down one phase for one cycle in case two IGBT switches of the same phase attempt to close at the same time. The Microchip development board (which we will discuss later) does not provide this safety feature.

Other safety and protective features are part of the 33035 motor control IC. They include under-voltage lockout which means that if the +5 or +15 volt supply voltage should decrease to the point of causing erratic operation, the circuit will shut down and show an error condition.

The 33035 IC also has a current sensing input which can be wired to slow the motor down in the event that the battery current is excessive and could damage the IGBT switches.

Finally, the 33035 has an internal thermal shut down feature in case the temperature of the IC exceeds its temperature limit.

Using this Board for Brushless DC Motors

As previously mentioned, the 33035 is a brushless DC motor controller IC. Although most of the discussion has been for its application in controlling a 3 phase induction motor, with minor modifications, the Control Board can control a brushless DC motor equally well. Two things have to be done: provide a connection for the brushless motors' sensor inputs and activate of the Forward/Reverse circuit.

Since the frequency control circuitry is not used in this case, the timing circuit IC's can be disabled and the 3 sensor inputs from the brushless motor can be connected in their place. Sensor input, phase A goes to pin 10 of the 4025 IC, phase B goes to pin 9 and phase C goes to pin 6 of the 4025 IC socket.

The 33035 also provides a Forward/Reverse capability. It can be activated simply by grounding pin 3 of the 33035 IC with the Forward/Reverse switch (to obtain reverse).

Other Options for Brushless DC Motors Operation

Microchip Technology (Web: microchip.com) sells a 3.5x5 inch development board (about $140) designed to control the operation of a Brushless DC motor. The name of the board is Picdem MC LV. Light duty switching circuits are included on the board. In order to drive the Honda heavy duty switching circuits, it would be necessary to connect the Honda 044817 connector to the output of the 6 switch drivers which are which are referred to as PWM0 to PWM5.

The PWM speed control and the switches for reverse and coasting are not handy but they could be extended or mounted on a separate circuit board.

The board's power supply can also provide the 270 ma. at +15 volts needed for the Honda circuit board.

An interesting feature of this development board is that it comes with a second microcontroller which can drive a brushless motor without the need of sensor inputs: it makes use of the back EMF from the motor windings.

A small brushless DC motor is also available for experimenting with this board. I did not buy this motor so I cannot report on its capabilities but I have no reason to doubt that it would work very well.

Test Results Using the Honda Inverter

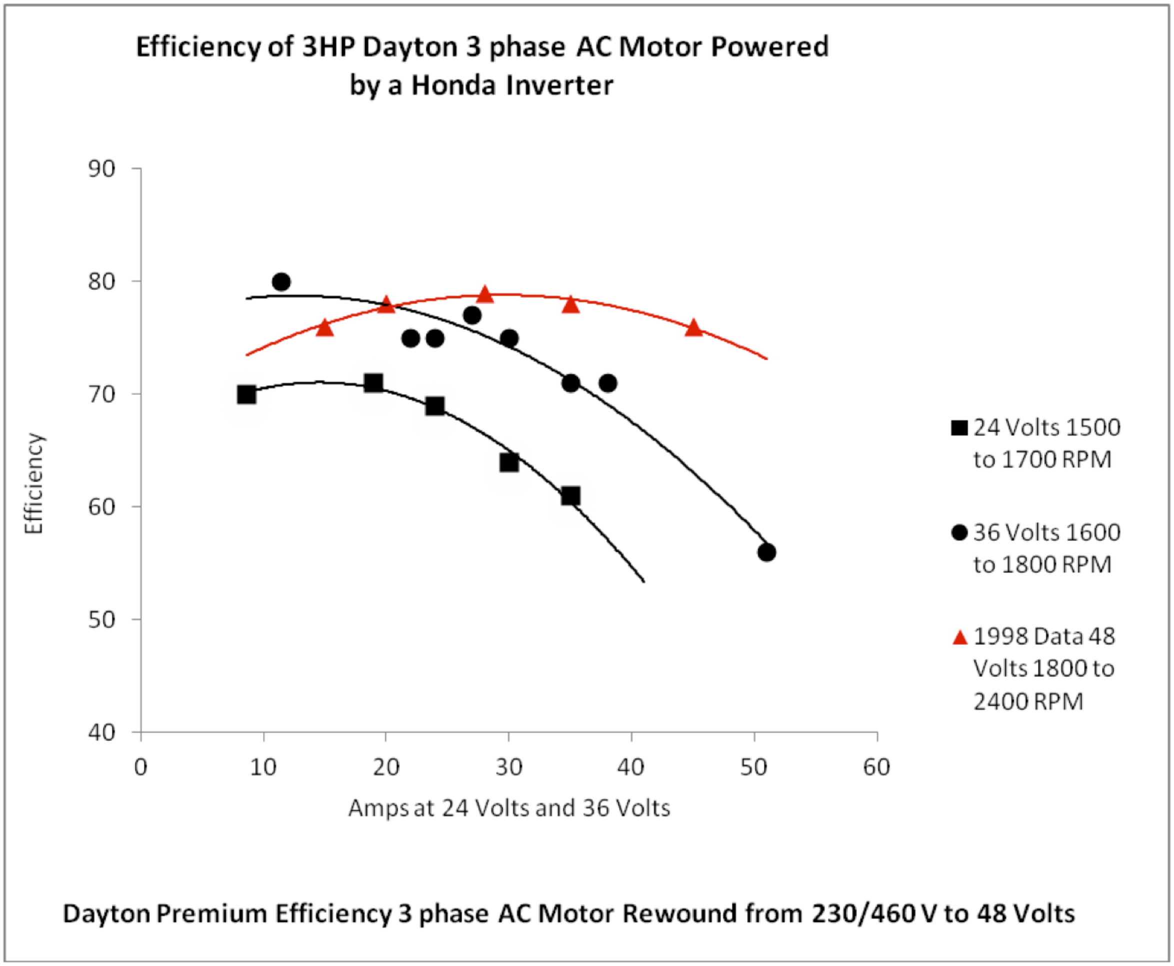
To test the operation of 3 phase AC motors driven by the Honda inverter, I used the same two AC motors that I rewound years ago to operate at 48 Volts DC. To drive these motors, I had used a 48 volt inverter with Mosfet switches which are more efficient than the IGBT's at low voltage, so a decrease in efficiency is expected when we use the Honda inverter in these tests. I also used the same dynamometer which I had built from a B-29 aircraft generator.

The reason for the lower efficiency of the IGBT switches is that, being transistors, the voltage drop across the switch when it is conducting is about 2 volts (Vce on). Since 2 switches are always conducting the total loss is 4 volts. When 4 volts are lost out of a total of 36 volts, a loss is more than 10%.

The loss incurred in a Mosfet switch is less than .5 volt or 1 volt for 2 switches in series. With a 36 volt supply, that's about 3%. So, there is a 7 % difference between the two types of switches when the power source is a low 36 volts.

The goal of this project is to power larger boats with battery power reaching 200 volts. At 200 volts, the 4 volt voltage loss from the IGBT switches is only 2% which is completely acceptable. Mosfet switches are not rated for such high voltages and, therefore, could not be used.

Efficiency Curves



The efficiency curves shown above are for a 3 HP three phase AC induction motor . It is Dayton premium efficiency motor purchased "off-the-shelf" from Grainger for about $250. The original voltage rating was 230/460 but the motor was rewound to operate at 48 volts, 3 phase AC. It was connected in Delta for the dynamometer tests. The starting current with no load was approximately 70 amps at 36 volts. When the motor was connected to the dynamometer at one half full load, starting currents over 120 amps were observed. The Honda IGBT's had no problem switching these heavy currents.

The 3 curves shown in the graph include a curve with 1998 data taken with the same motor and the same dynamometer at 48 volts using the Mosfet inverter as described in Chapter 9 of my book "My Electric boats" The curve is reproduced here in red. Notice that at low battery voltage, the Mosfets are a better choice than the IGBTs.

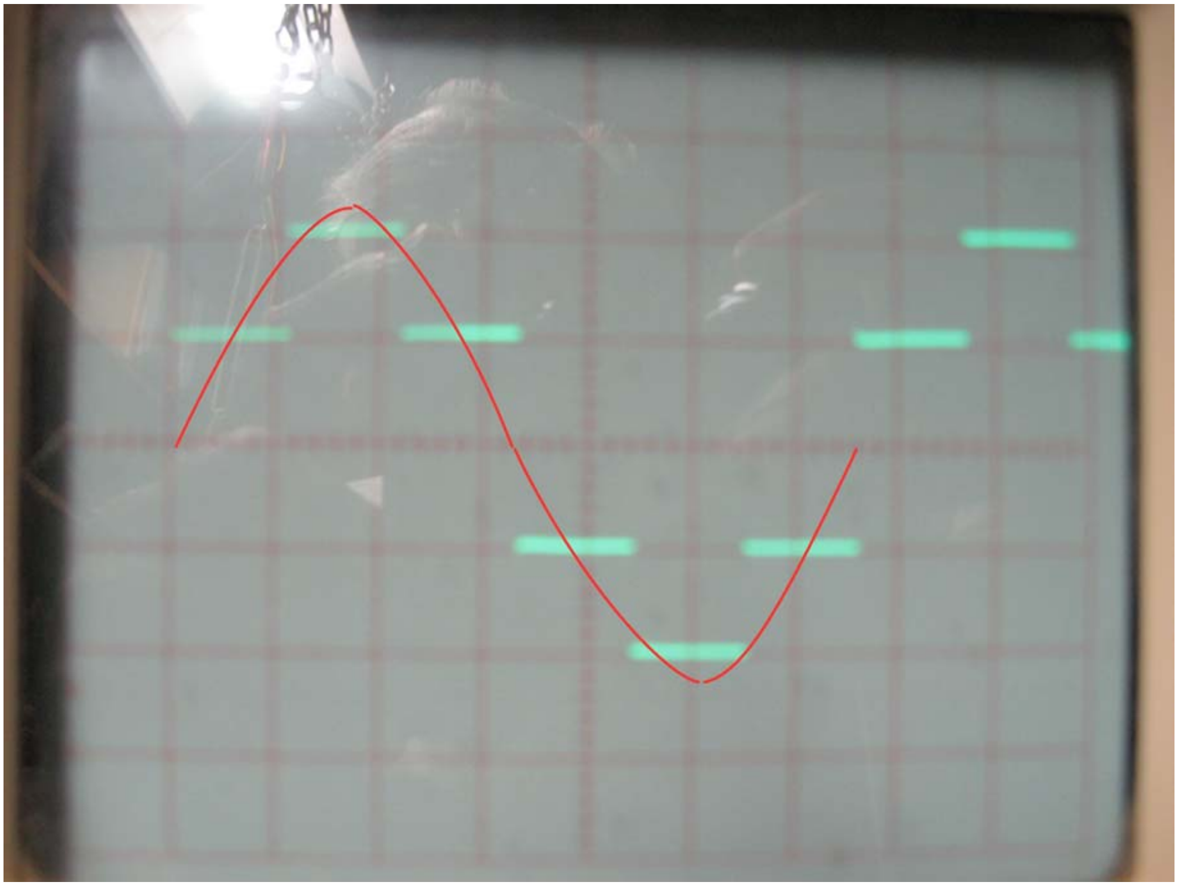
The other 2 curves use the Honda Inverter to power the motor at 24 volts and 36 volts. As explained above, the lower efficiency is due mainly to using IGBT's at low voltage. During the test, at 36 volts, around 20 to 30 amps, there was some motor "hunting" caused by the dynamometer. (The speed would increase then decrease by about 50 rpm on its own). This made reading the speed, current and pounds of force simultaneously difficult and it accounts for the randomness of some of the efficiency points in the 36 volt curve.

Test Results with a Resistive Load

To further check the operation of the Honda IGBTs, 2 resistive loads wired in delta were also tested. The first was built with three 100 watt, 2.2 ohm resistors which drew 15 amps from the battery at 24 volts. The second was a custom made load built with two 15 inch strands of .244 ohm per foot Nickel-Chromium flat heating element. At 21.5 volts, 104 amps were drawn from the battery.

The picture below shows the wave-shape of the current through one phase of the 2.2 ohm load. As we can see, the frequency is approximately 60 cycles and the peak voltage of the square wave is about 20 volts. As explained above, the 4 volt loss (the battery voltage was about 24 volts) is the voltage drop (Vce on) of the IGBTs. This loss, at a battery voltage of 24 volts accounts for most of the low efficiency encountered in the efficiency tests. A preferred supply voltage of 140 volts (as it is in the Honda Hybrid) to 200 volts would reduce this percentage loss to approximately 2%.

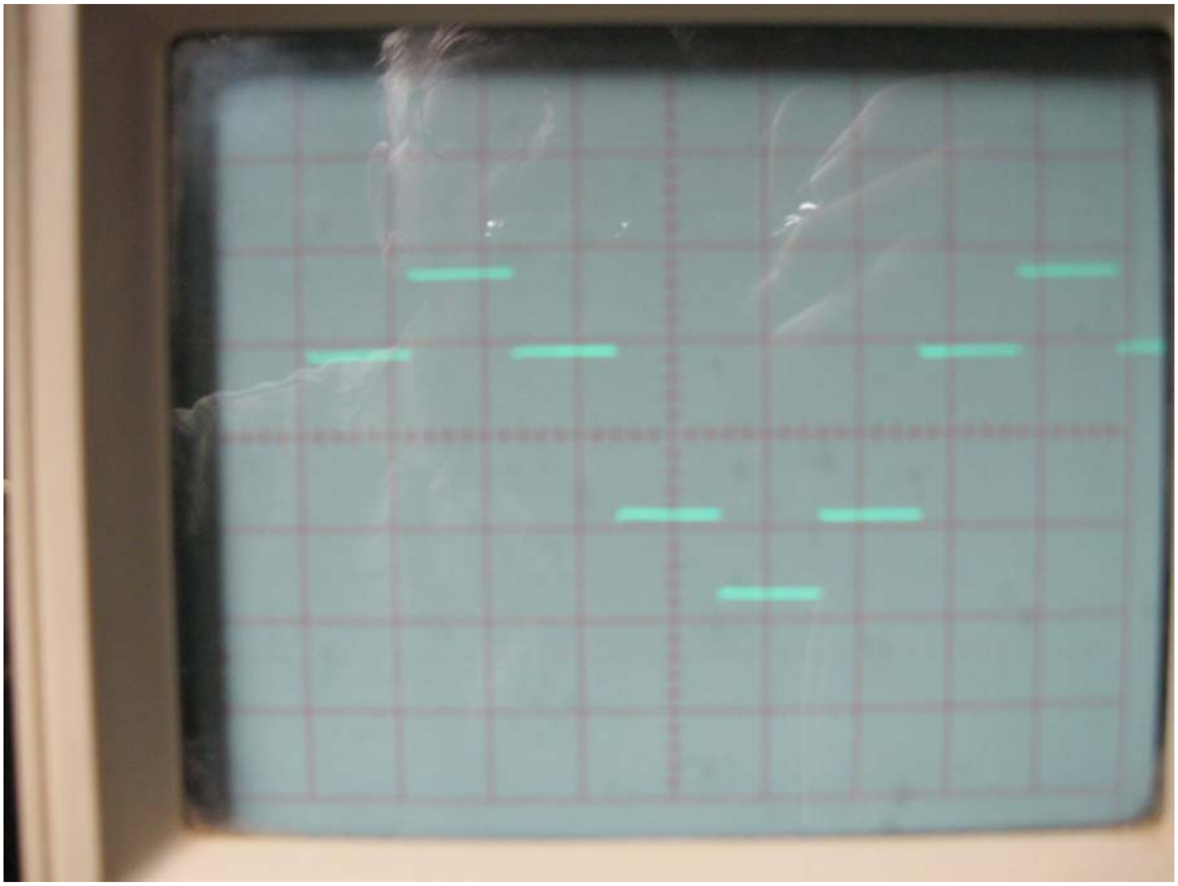
I added the sine wave in red to compare these actual wave-shapes with the theoretical ones derived from the 33035 data sheets as shown on page 8. There can be no question that they are identical. (Sorry about the distracting reflections on the face of the scope)



Resistive load. 15.3 amps at 24.3 volts. Scope settings: 10 volts and 2 ms. per division.

The next picture shows the wave-shape of the 104 amp current through the 3 phase heating element load. Remarkably, the wave-shape at this high current is equally good compared to the low current wave-shapes. It also has fast rise times and constant current values.

An observant reader will no doubt notice that the peak voltage is down from 20 volts (in the previous picture) to about 17.5 volts. This is not due to larger voltage drop in the IGBTs. My lead-acid batteries are 7 years old and they balk at putting out 24 volts at more than 100 amps for an extended period of time. When the picture was taken, the battery voltage with the 104 amp load was 21.5 volts. The voltage drop across the IGBTs was therefore 4 volts, same as it was with the 15 amp load.



Resistive load. 104 amps at 21.5 volts. Scope settings: 10 volts and 2 ms. per division.

There is one more characteristic of the Honda inverter worth mentioning. After the power to the inverter has been turned off for several hours (the 270 milliamp, 15 volt source to the green board via the 16 pin plug) there is a 95 second time delay before the logic operates again (presumably to allow the components to warm up). The “run/coast” switch allows the motor to be turned off for any amount of time while keeping the power “on” to the Honda inverter board. It is used to avoid this delay.

Conclusion

The inverter used in the Honda Hybrid is a powerful, high quality device capable of driving 3 phase brushless DC motors or 3 phase AC induction motors without any modifications with an appropriate control unit. The IGBT switching devices rated at 300 amps at 600 volts, are capable of driving motors similar to the Honda Hybrid's 17 HP motor with ease.

The Control Box described here provides the following motor functions: run/coast, reverse, speed control (frequency control and PWM). The numerous safety features of the 33035 IC are implemented as well as an anti-ambiguity circuit which prevents 2 switches of the same phase from closing simultaneously.

The test results indicate that the efficiency of the control box and the Honda inverter will be excellent with battery voltages in excess of 100 volts at currents in excess of 100 amps.

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