Sine Wave Inverter for 120V 400Hz Three Phase Avionics Instrument Power.

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Background:

This project came about because I acquired some extraordinary monochrome video monitors which were intended for an Avionics application. The power source for these monitors is 400Hz three phase, with a 120V phase voltage (or 208V line voltage) of about 50 to 80 watts requirement.

(These beyond extraordinary video monitors are the subject of a separate article currently under construction. They are undoubtedly the best quality monochrome monitors ever made. Among their many outstanding features, they do not contain a single electrolytic capacitor)

I looked around and discovered that commercial three phase supplies or inverters were available, but very expensive and often massively bigger than the power requirement I had. Presumably, part of the costs relates to regulatory requirements for aviation related equipment. Small inverters that convert 24V DC to three phase 400Hz at around 40W or less are used for some in flight instrument power applications in the Cessna and other small aircraft. However they did not have the power rating that I required and I could not acquire any data as to the quality of the output waveforms or any of the schematics to assess this issue.

I looked at the notion of designing my own inverter and I'm not shy to take on a difficult task. However, it is not a trivial task to design and build a three phase power inverter capable of some hundreds of watts output. Generally, one would start with a DC supply derived from the mains power. Then create three sine wave oscillator outputs, separated by 120 degrees for each phase at the "base" frequency, in this case 400Hz. Those outputs would pass to comparators being fed a high frequency switching or "carrier" signal to generate a PWM (pulse width modulated signal). This would then pass to a three phase bridge output stage, typically with IGBT's.

While the basic design of an inverter like this seems simple enough, there are very important issues in these circuits with isolation required between stages and this often requires an array of separate DC supplies and isolation devices which add to the complexity. There are also the issues of transient snubbing to protect the IGBT's and often a dead-band circuit is also required to prevent simultaneous conduction and catastrophic failure of the IGBT's in the bridge. I also noticed that this sort of project has been presented as a topic for an Electronics Masters thesis by some, giving an indication of the scale of the task, to do it properly that is.

One other option could be simply to use a high power capable analog linear amplifier with a step-up transformer on its output. While free from significant distortion this is not a very efficient method and it would also require a feedback loop to control the amplitude of the output and additional over-voltage protection circuits added in case the output level accidentally ramped up too high.

Yet another option is the VFD (variable frequency drive) used to control AC three phase motors. Though this had been mooted as a solution on internet forums, I was not able to find a finished project as a model. The output of the VFD for each phase is a bi-polarity PWM signal which doesn't resemble a sine wave and this output relies on the load being very inductive. In other words the motor's inductance effectively filters the signal and integrates the PWM signal into a sine wave drive. However, this issue can be solved with a "sine wave filter" added to the output of the VFD.

Building the power supply:

I elected to try a Hitachi WJ200 0.75kW VFD for the application. This is the highest capacity drive in the range that does not have a cooling fan and it is well over-rated for the task. In essence these drives contain all the hardware of a three phase inverter described above, but much more. As time has past VFD’s now contain many useful and diverse software programmable features. For example, these can control the start up and slow down rotation speeds of motors (by varying the frequency of the drive) and the motor torque etc. However, there are some other very useful features built in:

1) An “inverter gain option” which can be set from 20% to 100% so there is excellent control to program a specific output voltage. This is also augmented by a global setting for different motor types in 15V steps.

2) Programmability of the base output frequency, which goes to 400Hz.

3) Programmability of the carrier frequency up to 15kHz.

4) Ability to jump straight to the operating frequency without any delay and also switch it off immediately and bypass the slow start and slow stop frequency build up and slow down protocols used for motors.

The above 4 features on top of the basic hardware allow the VFD to be deployed as an on-off 400Hz three phase PWM power source.

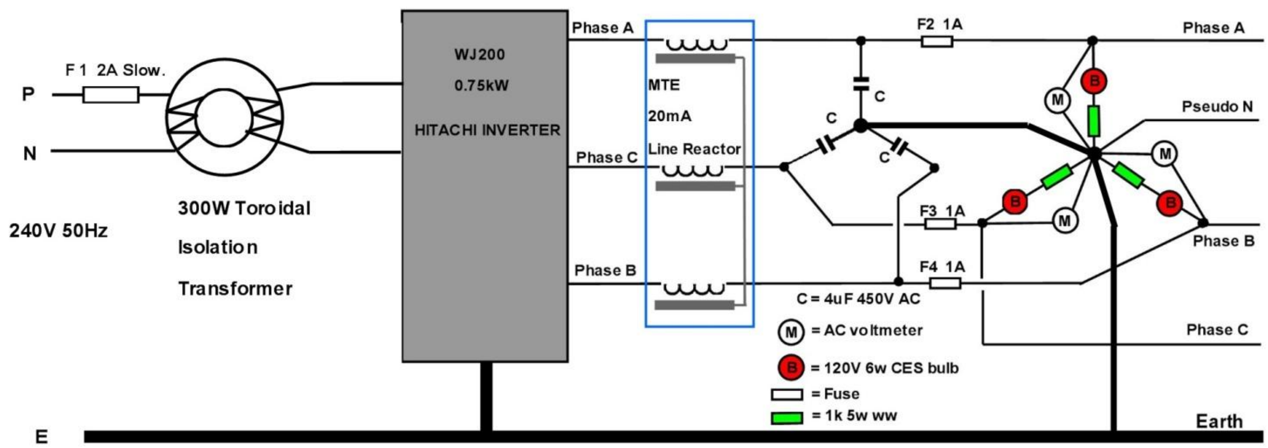
In this case I programmed a base frequency of 400Hz, with an immediate start and stop to and from that frequency.

The inverter was also programmed for a relatively high carrier frequency of 400 x 27 = 10.8kHz. This was for two reasons, firstly is pays to keep the carrier frequency as an odd multiple of the base frequency to help reduce harmonics and waveform distortion. Secondly it is easier to filter the output PWM waveform with a sine wave filter when the base frequency and the carrier frequency have a wide separation. The resonant frequency of the sine wave filter in this case is a little above the base frequency and well below the carrier frequency.

I built the inverter and the sine wave filter into a plastic standard electrical junction box. This type of box has an internal sub panel which is useful for mounting the components on. One disadvantage of the plastic (compared to metal), aside from any EMI issues, is that every metal part exposed on its surface requires a separate earth, including the meter screws, lamp bezels, handle, connector shells and metal vents etc. However the plastic is easier to cut, but on this particular housing it was pretty tough & thick.

The basic diagram of the inverter is shown below. An off the shelf MTE brand 20mH 3 phase line reactor was combined with some 4uF motor capacitors (in a *wye* configuration) to create the sine wave filter.

VFD with added sine wave filter and psudo neutral:



The *Wye* configuration of the filter capacitors is such that they have 1/3 the effect as they would if wired in the Delta connection. So the 4uF capacitors are electrically equivalent to to three 1.33uF capacitors wired between the phases in the Delta configuration. However in *wye* the voltages across the capacitors are lower than in the Delta arrangement. The capacitors, along with the loads provided by the large indicator lamps, help to create the psuedo neutral connection, which in this case is a useful return for the meter connections. I wanted the meters to display the *phase* voltage of 120V, not the line voltage of 208V. Also the video monitor this device powers makes use of the neutral wire as there is one winding on its wye connected power transformer that takes a small load from just one of the phases, causing a very slight assymetry.

Isolation issues:

The monitor that this unit powers has an elaborate 3 phase harmonic filter unit, consisting of capacitors of over 1uF between the phases, neutral and earth and resistors between those points too. When powered in an actual aricraft, the system neutral is normally connected to the airframe and therefore the monitor's metal body body as well. It can't really be called "ground" but for practical purposes it is the same thing inside the aircraft.

Therefore if one attempts to power this monitor (with a pseudo neutral or not) from a VFD, since the output of the VFD is ultimately derived from the mains phase input, then enough of an unbalanced current flows to ground in the harmonic filter assembly, tripping the dwelling's RCD. Therefore isolation is required. Perhaps the ideal way to do it would be with a Delta to Star 3 phase 400Hz 1:1 isolation transformer. On the output side the neutral from the star output winding could be connected to the system ground, in this case mains earth. I couldn't find an "off the shelf" transformer to do this and a custom wound one is very expensive. So instead I isolated the mains input feed to the VFD with a 300 watt rated toroidal 1:1 single phase mains isolation transformer. This made it possible then to connect the pseudo neutral connection to the system ground (mains earth).

It should be noted that any power supply which isolates the mains power with a power transformer, which is the case in many appliances, or a switchmode power supply too for that matter, that this isolation defeats the dwelling's RCD (safety switch) from the perspective of the safety of any voltage sources derived from the transformer or power supply's *secondary*.

If the power supply output, is of a "high voltage" nature, typically more than 70V and aggravated by the fact that one terminal of this supply, typically negative, is connected to ground or the chassis, then it poses a "non-RCD protected lethal shock hazard" where a current can flow from a single point in the circuitry, via a human being, to ground. So a shock can be acquired by touching one terminal of the circuitry only and this will not trip the break box RCD.

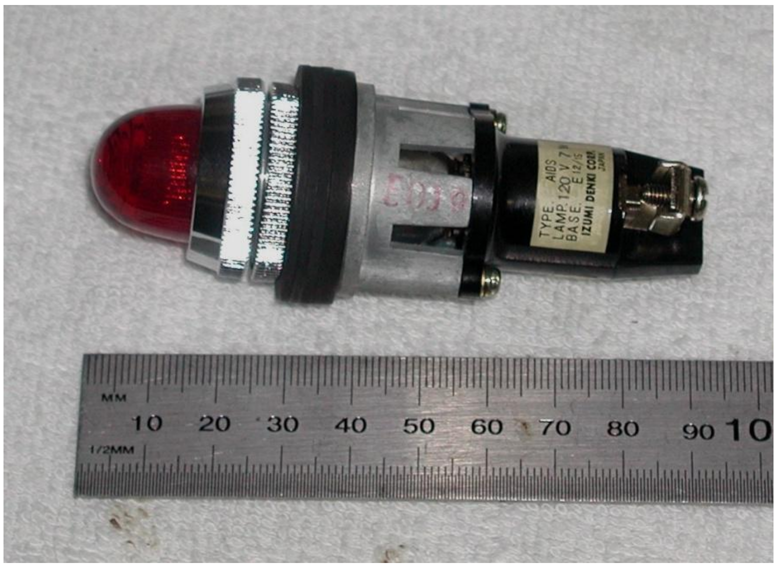
It pays to remember this, that is; not to rely on the mains power circuit RCD when working on appliances such as vintage TV sets, that use power transformers or any other appliance that uses these or an isolated high voltage supply, especially where one output of the high voltage supply has one terminal grounded. The high voltages inside those appliances becomes non-RCD protected by the nature of the isolation afforded by the power transformer or isolated supply they possess. So just because there is a "safety switch" or RCD on the breaker box, doesn't mean its safe.

Although "transformer-less" TV sets and tube radios are thought to be "unsafe" in general because of the "Hot Chassis" issue, at least they do not defeat the dwelling's breaker box RCD in terms of detecting a current that can flow between some single point in the circuitry, via a human being's body, to ground. So this is about the only advantage (aside from cost savings on a transformer) that a transformer-less set has.

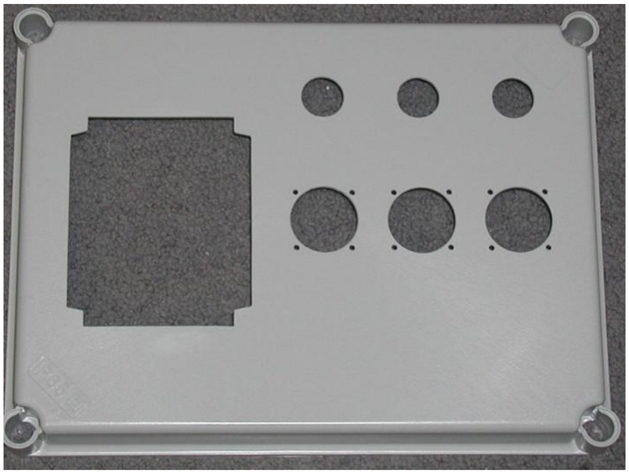
Therefore, like any mains operated isolated power supply with more than 70V output, it pays to be aware that the three output phases of this unit are not RCD protected and the breaker box RCD provides no useful protection to the isolated output side of the supply.

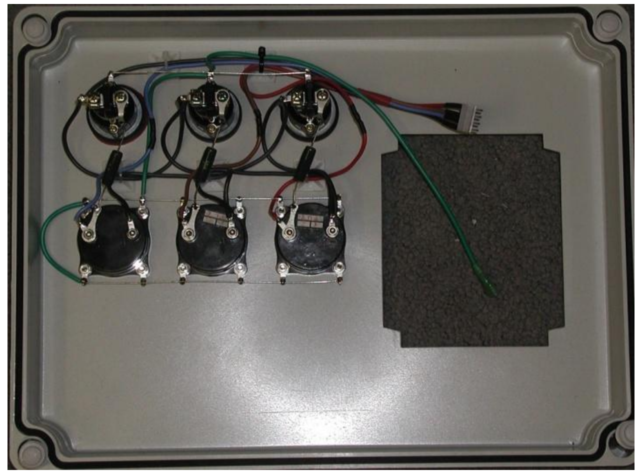
The 120V indicator lamps are not just for display, they provide a small initial load to the inverter. Each lamp is dimmed (by the series 1k resistor) so that the voltage applied to the lamp is 88V. Running a lamp at lower than its rated voltage means it will run many years longer before needing to be replaced, if at all. The total power dissipated by the three lamps and their resistors is about 12W.

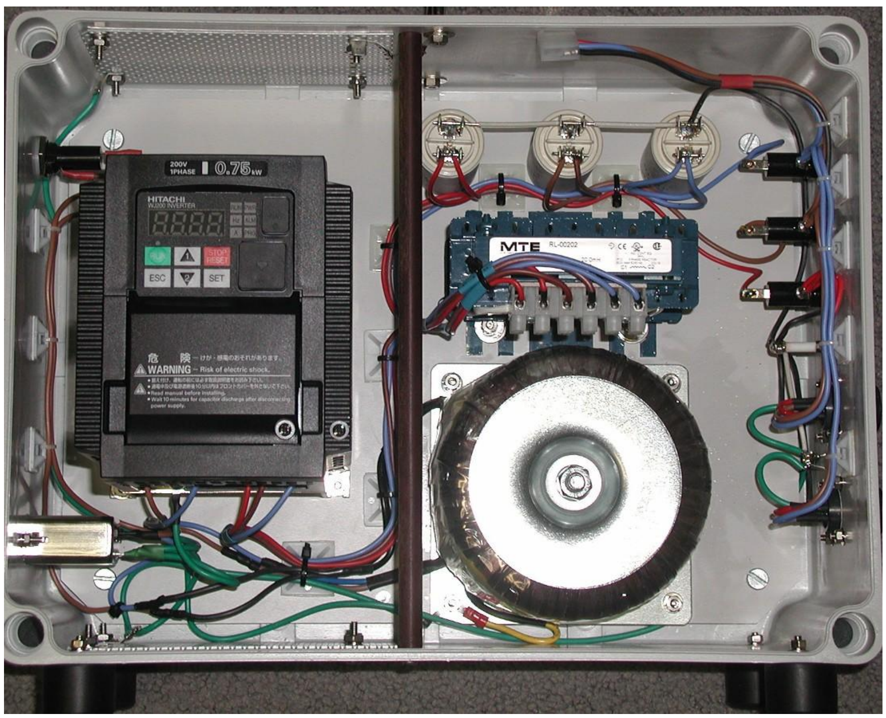
The indicator lamps were actually quite difficult to find. The ones I settled on are very high quality Japanese made industrial engineering parts with large glass (not plastic) lenses and a ventillated machined socket assembly. They came with 120V 7W lamps, and I reduced these to 6W lamps as well as adding the series 1k resistors so the overall heat dissipation from them is not an issue and they acts as an indicator lamp and load.



The inverter, line reactor and the capacitors were bolted directly to the enclosure’s internal sub panel.The front panel cover had holes cut for the meters and the inverter body and the wiring for these components was placed on a plug-socket to allow easy removal. A Tufnol rod was added to strengthen the case:







A large rectangular ventillation hole was cut above and below the inverter and fitted with a perforated aluminium panel. The entire case is on large rubber feet so there is a good convection current through the unit and past the VFD’s heat sink. The VFD is rated to 750W, so this unit can easily supply two 60 watt monitors at once and it only gets a little warm, most of the heat being from the indicator lamp/loads, not the VFD itself.

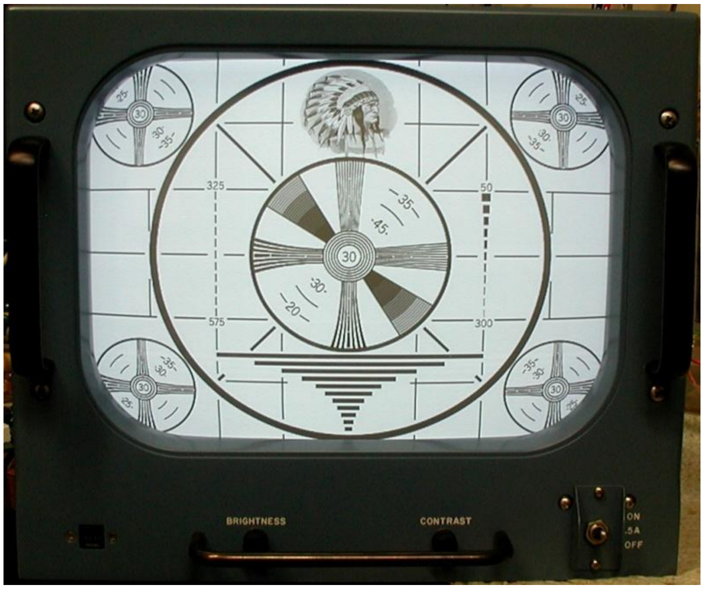
(When working on this unit I used the Tektronix 222ps Powescout scope. This is a very special scope with high voltage isolated probe inputs so the probe earth can be connected anywhere without risk. Otherwise it can be a hazardous business even with isolating transformers and trying to avoid currents a standard scopes' earth connections).

The recording below shows what the PWM output signal looks like across two of the phases directly out of the VFD prior to the line reactor. It was difficult to get a stable sync lock on the scope display because of the high frequency components in the waveform. This is the waveform, that in a motor application, would often be sent directly to the motor windings. Although, many people in the VFD-motor drive industry have realised the benefits of sine wave filtering, before sending it to a motor and a photo of the filtered output:

As shown in the photo, the sine wave filter does a very good job of re-assembling the PWM signal into a respectable sine wave. I was surprised how good filtered waveform looked, with the nature of the PWM signal, I was expecting more distortion. Under heavier loads than just the 3 lamps some small irregularities appear, but generally the waveforms are good.

Once the power supply was made I was able to power the 14 inch Avionics video monitor (fitted with a 14BAP4 CRT) and obtain an image from a Testcard generator.

(This is Richard Russell's generator programmed with the famous American Indian Head test pattern) I had to defocus all the photos a little to avoid the moire effects from the sharp focussed scanning lines of the 14BAP4 crt. The other images are still frames from Voyage to the Bottom of the Sea: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