THE POLYPHASE LOW VOLTAGE POWER SINE WAVE GENERATOR.

Dr. H. Holden. Dec. 2024.

INTRODUCTION:

The rotating Magnetic Field was conceived as early as 1824 by Francois Argo, but according to Nikola Tesla, he conceived of its use for an AC Electric Motor while walking through a park in Budapest in 1882 (Silicon Chip Oct. 2024 pg. 14)

Three phase power systems are a critical part of modern society. And three phase systems are not only useful for creating a rotating magnetic fields and powerful motors, but are more efficient than a single phase system in transmitting power over the World's Domestic and Commercial Power Grids. Much of the important high power motor driven machinery, which we have now come to take for granted in modern life, relies on and uses three phase motors.

Historically at least, various "Generators" were kept in Teaching Institutions to demonstrate electrical phenomena. The common ones were DC power supplies, and various single phase AC power supplies, sometimes Dynamos & Alternators too. Two others that come to mind are the Wimshurst Machine and the Van de Graaff Generator, both for generating high voltage electrostatic fields. Yet there seems to have been a paucity of compact apparatus to demonstrate the principles of Polyphase AC power systems and their rotating magnetic and electric fields.

Ideally, Teaching Institutions, Universities, High School Physics Departments and Students of Electrical Engineering and Hobbyists too, would have access to a compact low voltage and safe Polyphase Generator with which to conduct experiments.

The Polyphase Generator design here is aimed to suit the Student of Electrical Engineering and for use in Physics Departments in Schools and Universities. Also for Electronics Laboratories and Workshops and Hobbyists interested in working with and learning about Three Phase systems. This Generator allows students to safely explore the principles of polyphase power and directly visualise rotating electric and magnetic fields with motors or test setups that they can make themselves. This Generator certainly served its purpose in my case, because I wanted to learn more about Three Phase Systems.

A WIDE FREQUENCY RANGE POLYPHASE POWER SOURCE:

A suitable Polyphase Generator should cover a very wide frequency range, to be able slow down the rotating fields for observations and have enough power to drive simple kinetic laboratory models of three phase and two phase machinery. It should also be safe with a low range output voltage.

(On the other hand, three phase high voltage Line Power is hazardous to experiment with and although it can be stepped down to safe voltages, the frequency is fixed at 50Hz or 60Hz depending on the country).

There are multiple ways to generate three phase Sine wave signals and voltages electronically. Three phase signals are relatively easy to generate with oscillators and phase shift networks and Analog Op Amp circuitry, at any one particular single frequency. However they don't operate over a wide frequency range with accurate phase relations. R-C phase shift networks are frequency dependent. PWM signals can also efficiently generate Sine waves , but the harmonic filtering is awkward over a very wide frequency range especially below a few Hz.

Digital circuits do better at synthesizing three phase signals, especially over a wide frequency range with a constant amplitude. However, in many cases, the circuit's outputs are usually "signal levels" and have too low an output power to run small experimental three phase kinetic machines, unless additional output amplifiers are added. I have seen cases on internet projects where audio power amplifiers are added, but in many cases, these do not go down to very low frequencies below 10Hz unless modified for DC coupling.

Ideally the Generator's frequency output would be from DC level (stopped) to its upper limit. 1000Hz is a satisfactory upper limit.

The Polyphase Generator described here has a suitably low peak output voltage, yet still enough practical power (10 watts) for the demonstration of rotating fields, even with low efficiency demonstration motors or other moving machinery where frictional forces have to be overcome.

After studying the three phase system, it became apparent that it could be very instructive to have a Generator with a wide frequency range of 0.1Hz to 1000Hz and also have a function to stop its clock at any point of the three phase cycle. The low frequency, of a few Hz, or less, is particularly useful in making the rotation of both the the Electric & Magnetic fields very easy to physically observe.

Also it would be ideal if the Generator had a stable and controllable output voltage amplitude across its full frequency range and have accurate phase relations at all times between its three Sine wave outputs. The Generator should also be capable of producing both two phase and three phase power signals, because a two phase system also creates rotating Electric and Magnetic Fields. If such a Generator was at hand, what could be the very first practical and simple experiment to demonstrate the effect of a rotating magnetic field? Clearly Tesla's Columbus Egg is on the list. The initial choice of two simple experiments and a demonstration is explained at the end of this article with two videos. The first experiment is called "The Bermuda Triangle"

POLYPHASE GENERATOR DESIGN:

The Generator described in this article has an internal clock based on the MAX-038 frequency synthesizer IC, which runs at 768 times the Generator's output frequency.

The output frequency is 0.1Hz to 1000Hz selected in 4 ranges by a panel switch. The frequency control is both coarse and fine on two front panel controls. This covers common frequencies of three phase systems at 50Hz or 60Hz and the 400Hz commonly used in Avionics applications.

A number of the effects of two and three phase fields are better demonstrated *slowly* at low speeds where the Human visual system can better observe them. Which is why an adjustable Timebase was arranged which would result in a very low output frequency. Also the generator's clock can be stopped so that the voltage of the three phase Sine waves at any moment can be frozen in time.

The frequency of the three phase output is monitored by a special type of panel mounted digital frequency counter which is capable of measuring down to very low frequencies. The counter was specified to work down to 0.15Hz, however on testing it still can actually read a 0.1Hz signal, but it reports every second sample as zero. This is not of concern as mostly the generator is run at 0.15Hz or above and the counter is still able to measure the 0.1Hz rate.

The power output of the generator is 3.3333 Watts per phase, making a 10W total output power. This is a practical value to make small moving three phase electromagnetic demonstration models. The models can have very low efficiency and still have physical movement to overcome frictional forces.

The *peak* sine wave output voltage is adjustable from zero to +/-10 Volts per phase (7.071V rms) with one level control affecting all phases equally. When the output is 10 Volts peak per phase with a Star load, it is 17.32V peak between the three conductor Lines. (See 3 phase theory below for the explanation of why this is the case).

For most practical experiments, the DC resistance of the load for this Generator should be no lower than 15 Ohms per Phase with three loads in a Star configuration, or 45 Ohms between each Line connection, in a Delta configuration.

For experimental small electromagnetic devices and motors, if the DC Resistance of the experimental coils is less than these values, then simply a series resistor should be added to bring the resistance up to the 15 or 45 Ohm value, or greater, so as to limit the maximum output current and power.

The Generator can also be clocked by an External Clock. It also has a Stop button. If the generator is funning at a low frequency it is easily stopped at any point in the cycle/s and stays stopped with the button held down. Switching to external clock, before the stop button is released, will freeze it in that condition if there is no external clock signal provided. The DC voltages of each wave, at that time of their stopped cycle remain on the output terminals. This has some interesting implications with the "DC analysis of three phase systems" (see below).

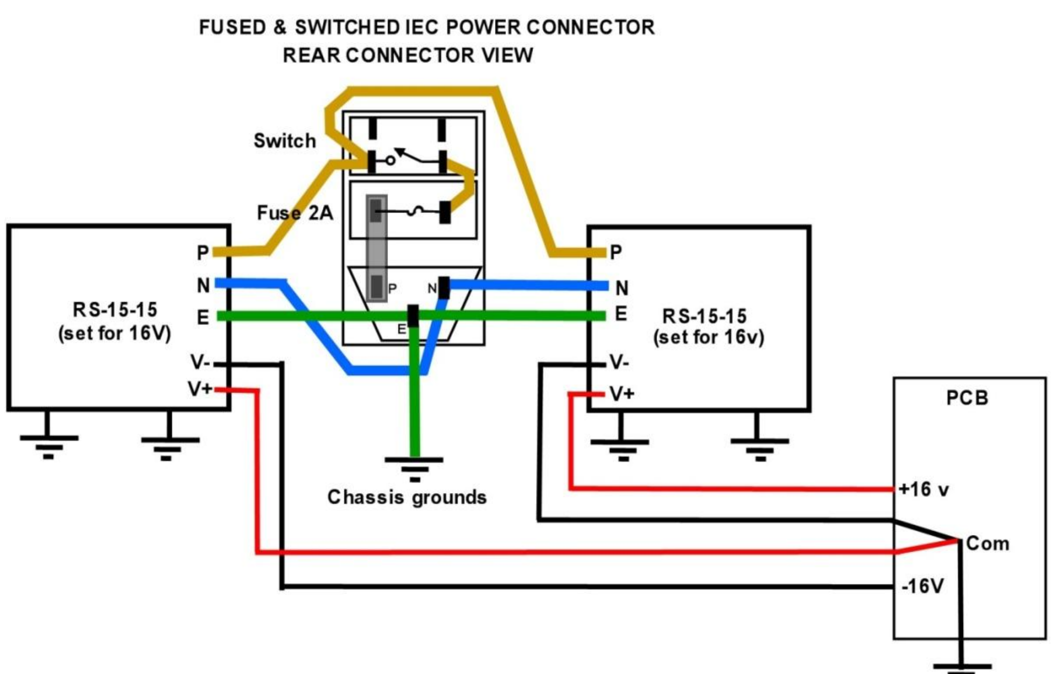
Three Class B output stages drive the three loads. These are comprised of medium power Darlington transistors on a heat-sink on the rear of the instrument.

CIRCUIT DESIGN:

Power supplies:

The unit is powered by two 15 Watt rated Mean Well 15V switch-mode PSU's, that are set to 16V on their preset potentiometers so as to create a +/- 16V supply. These are universal line voltage input types, so that this generator can run in any Country.

The basic input wiring is shown below. Each of the Mean Well supplies contains its own internal 2A pcb Line fuse, still it is better to also use a fused IEC connector. A 2A fuse was chosen to help prevent nuisance fuse blows from power up surge currents when the capacitors in the two supplies initially charge up.



The voltages are further down regulated with Analog regulators and voltage reference IC's required for the task. The main +5V source rail for the logic IC's is provided by a 7805 voltage regulator on a small heat sink, Jaycar part HH8516.

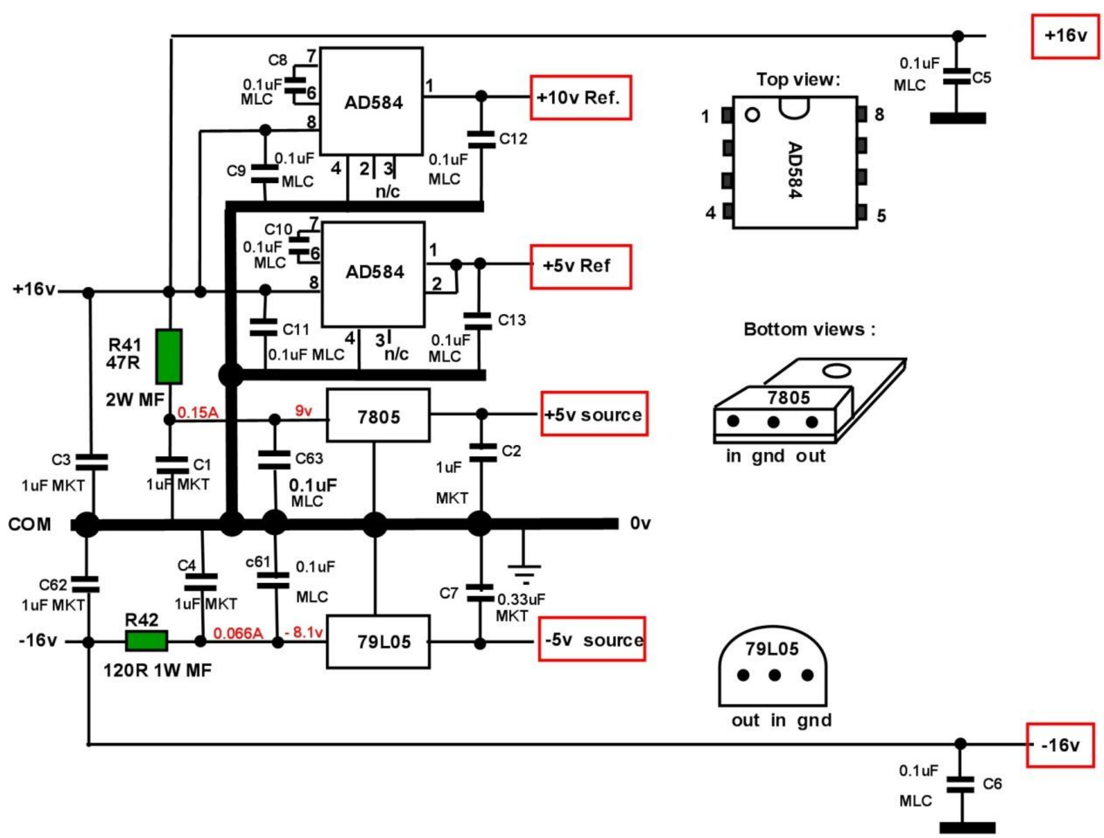
The +10V reference from one AD584 is used for the AD7226 Quad DAC and to provide the analog control voltage for the three AD633's (voltage multipliers) via the output voltage amplitude control potentiometer on the front panel.

The smaller 79L05 regulator provides the -5V source. This is used by the AD7226 for improved current sinking in its output amplifier. And it is also used to help power the MAX-038 Timebase.

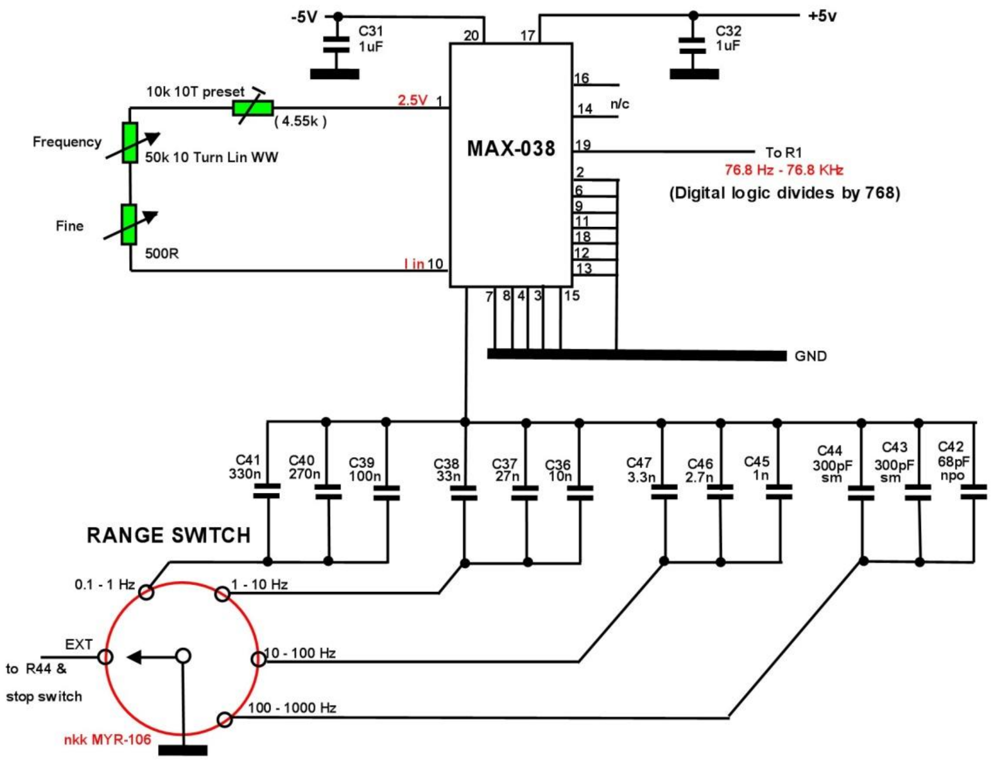
A +5V reference is derived from another AD584 to use as the offset reference for the AD633's to correct for the fact that the DAC's outputs are a Sine wave voltage centred around 5V but the output of the generator's phases is required to be centred around zero volts.

The MLC capacitors are multi-layer 0.1uF 100V rated AVX parts. The other capacitors are Wima Film types.

ANALOG SUPPLY SECTION:



THE TIMEBASE:



Pin 1 of the MAX-038 IC is a 2.5V source. The ratio of the maximum and minimum resistances between pin 1 and pin 10, set the range over which pin 10's current alters. This has to be greater than a factor of 10, to allow for overlap of the frequency ranges selected by the front panel's coarse and fine frequency controls.

Either a 500R or a 1k Fine Adjustment potentiometer may be used. In the case of a 500R potentiometer, the total series resistance with the 50k main tuning control at zero Ohms (with the fine control in the mechanical centre) is 4550 + 250 = 4800 Ohms. If a 1K fine control potentiometer is used, the 4.55k preset should be set at 4.3k.

The 10k preset could be replaced with two 9.1k 1% resistors in parallel in one case or a 4.3k 1% resistor in the other case. However the advantage of the 10T preset it that is can be used for allow for variations in the film capacitors to help make sure the Timebase tunes over a frequency range that just overlaps each range on the panel.

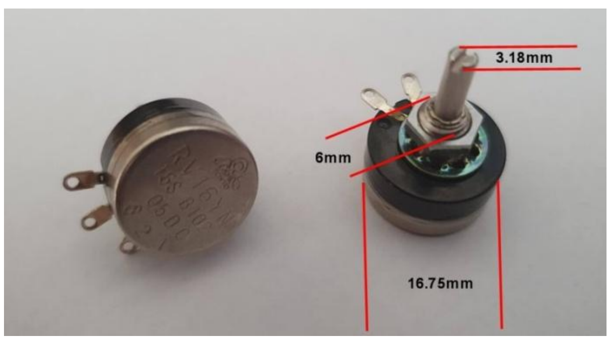
The total capacitance in the 10Hz to 1000Hz range is lower than the other ranges (allowing for the factor of 10 difference) This high range corresponds to the MAX-038 running at 7.68kHz to

768kHz and stray capacitance effects added require a lower total value of 668pF rather than the calculated or expected 700pF.

To acquire the 668pF capacitance, other combinations of capacitors could be used such as capacitors of 330pF + 330pF + 8.2pF would be satisfactory. They should be NPO types.

The 50k 10T main frequency control is a Mouser part 229-M-22E1050k, however there are also Pots made by Vishay/Spectrol that suit. The Vishay pots tend to have a 9mm diameter metal bush, the Mouser part cited has a 9.3mm Plastic bush.

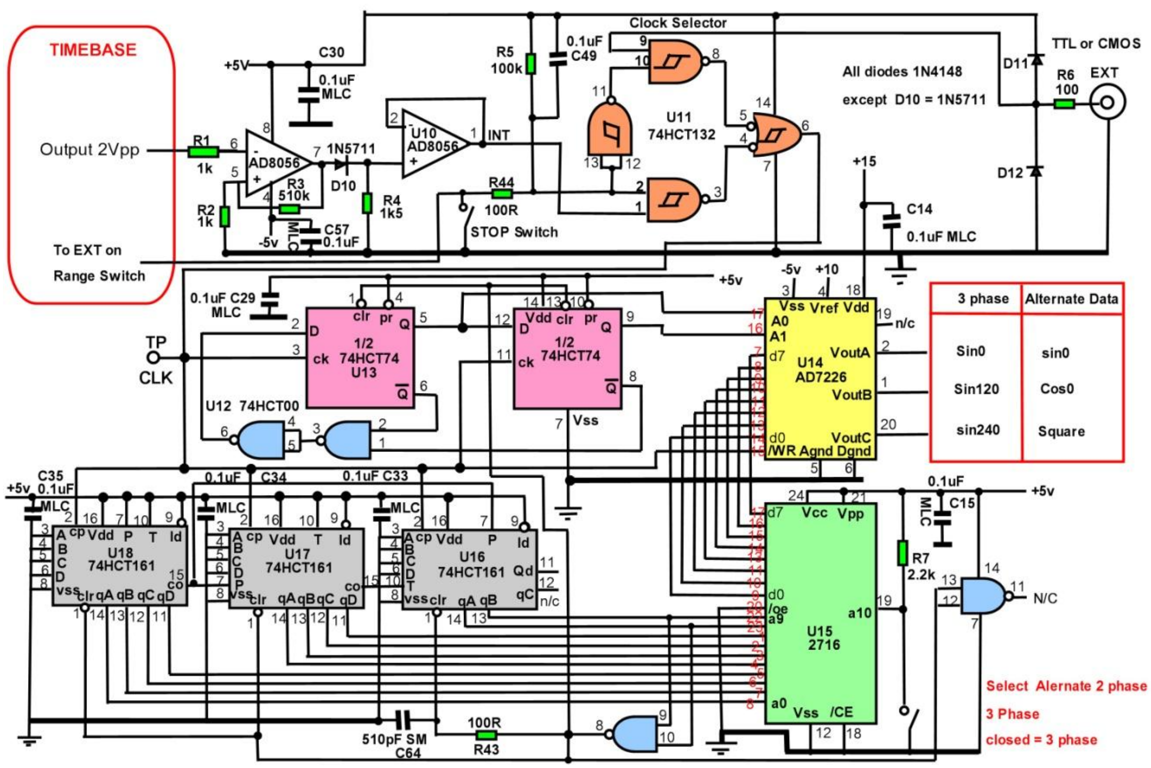
Suitable potentiometers for the fine frequency control or the Level control (see circuit below) with 6mm mounting holes are the Japanese COSMOS RV16YN B501 (500R) or RV16YN B102 (1k) and the RV16YN B103 (10k). It pays to get the Japanese parts which can be identified by carrying the COSMOS logo. These are on Aliexpress. There are inferior copies out there.



POLYPHASE SIGNAL GENERATION:

The three phase signals are derived from stored ROM data in a 2716 (2k UVEPROM). Three sets of 256 bytes of data are stored, one set for each Phase staggered one address or one byte location apart. This uses up 3 x 256 = 768 ROM locations. The data for the ROM was generated by a simple BASIC program. However there was an interesting error with the Phasing of the waves in the Analog devices application note AN-321 which describes the use of the AD7226 Quad DAC to generate three phase waves (see below)

Note: Since there is extra space in the 2k ROM, an alternate Data Set was placed in there to generate instead a Sine, Cosine and Square wave. This was done by controlling the ROM's upper address line. The Sine & Cosine waves are also also useful to generate rotating fields.



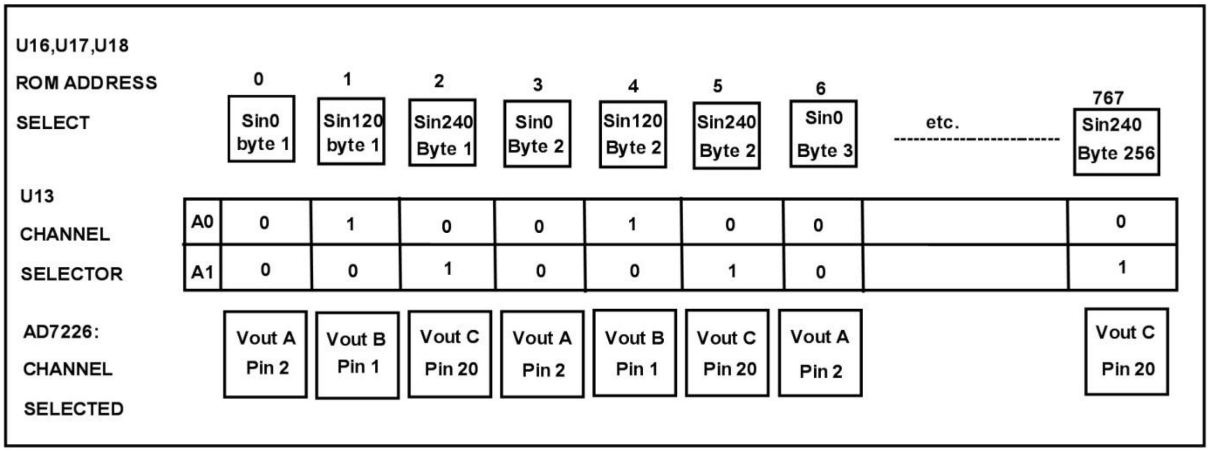
The MAX-038 is configured for a square wave output. An AD8056 high speed RF capable OP amp was used to initially process the signal from the MAX-038 because the maximum output frequency is 768kHz and to have a very good square wave at that fundamental frequency requires the 9th odd order harmonic or a response to around 7MHz. The AD8056 essentially level converts the output signal from the MAX-038's 1V peak bipolar square wave, into one ground referenced signal of just on 3v peak, suited to driving a TTL threshold gate input on the 74HCT132 (U11) pin 1.

The 74HCT132 Schmitt Trigger gates serve as a clock selector and further squares up the clock pulses and improve noise immunity in an external clock signal.

The 8 bit Data from the ROM is fed directly into an Analog Devices AD7226 U14 Quad DAC.

Only three of the four sections of the DAC are used. The DAC's "0ne of four" channel select control is by A0 and A1 on pins 17 & 16. These two bits are controlled by a counter, based on a 74HCT74, U13, which counts respectively for input bits A1 and A0: 00, 01,10 and then returns to 00 with the aid of Nand gates U12. This allows control over the AD7226 to select Output A, output B and output C in a regular sequence over the full counting range of zero to 768.

The data in ROM is organised as shown below:



Each of the three DAC's used inside the AD7226, receives 256 bytes of data over the course of one of the phases of the Sine wave cycle. The circuit divides the clock pulse by 768.

One quirk not alluded to in the Analog Device's Application Note AN-321 for this method of Sine wave generation using the AD7226 is, if their particular circuit example in their application note is exactly followed, a big problem develops:

The initial counting state of the 74HCT74 (or any 7474 IC) is random at power up unless resets are provided. But ideally the 1 of 3 count selector circuit (the 7474) is reset to zero with each reset pulse of the address counter chain. If there is no reset and the channel select system is not synchronized with the initial byte read from the ROM. This randomises the select sequence for the AD7226 to one of three possible starting states. The effect is to exchange which phase, or which one of the 256 data array values gets selected to the AD7226 specific outputs A,B & C. Perhaps one reason they didn't do it was the CD4029 Cmos counters they use require a positive going preset pulse. But a negative pulse is required for the 7474's /CLR input, and there was not one available without adding extra gates to their circuit. I changed the counters to the 74161 type which, also require a low clear pulsed and moved away from the AND gates to NAND gates instead.

To prevent this anomaly, a reset pulse must be applied to clear the 74HCT74 counter circuit to state 00, prior to the start of the first count of zero from the address counter chain, so that the sequence remains fixed. If not, and a three phase motor was being run, it would and could reverse directions, as the Sine wave phases selected from the ROM file get switched around at power up.

One other issue, the design document shows the 2716 ROM Enable line (/OE) connected to the system clock. I found though that a cleaner output waveform results with the ROM permanently selected. In this case the transitions of one step to the next are clean. I incorporated a jumper on the pcb to test this issue. The fourth channel of the DAC, output D on pin 19 is not used.

The address counters are three cascaded 74HCT161 synchronous types U18,U17 and U16. These count from zero to 767. However immediately as count 768 is reached, it is a non persistent state, it is detected by pin 9 and 10 of the Nand gate U11 and the three counter IC's, with a very short delay are asynchronously reset to a condition of zero. Therefore the actual count, in practice, is 0 to 767.

Of note, the small R-C delay (510pF and 100R) added to the CLR pin of the counter IC U16, is to slightly delay its reset pulse. The reason is that as soon as U16 is cleared, the reset pulse is terminated because the inputs to the NAND gate U12 pin 9 & 10 fall low. This produces a short reset pulse of around 30nS width. The reset pulse then has "probably" also reset counters U17 and 18. By delaying the reset pulse a little, for U16, this widens the reset pulse to around 100nS and helps to ensure that U17 and U18 are definitely properly reset along with U16 at the end of the count.

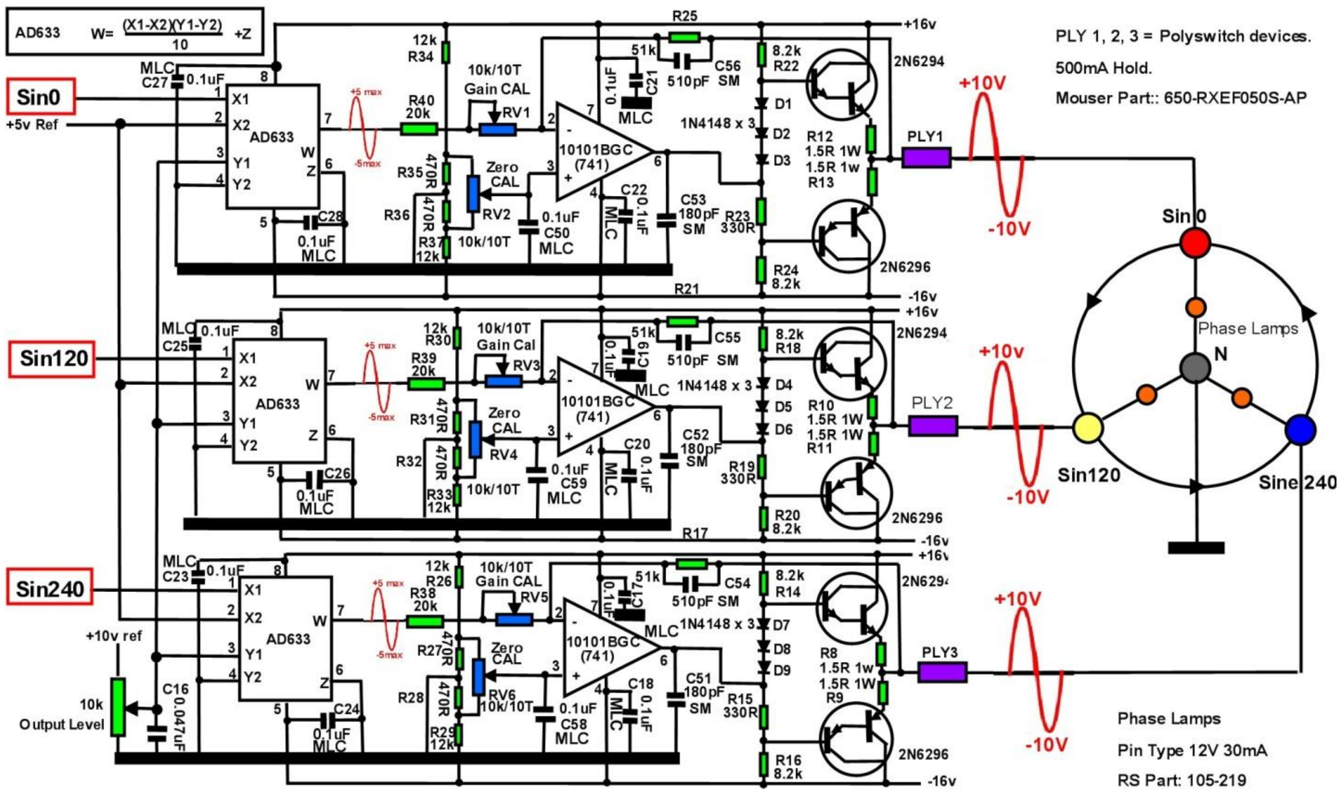
It is not critical that U17 and U18 are reset at all, because at the point in the count where address lines A9 is already high and the count from A0 to A7 is 255 (all bits high) the next clock pulse sets A8 high and A0 to A7 are then all low anyway. Still, it is better to 100% ensure that the counter chain stays in the range of 0 to 767 by providing a good reset pulse to the three counter IC's at the end of the count and so that the counter chain can never get into the condition where it can count higher than 767.

The largest harmonic of the Sine wave, quoted in AN-321, is -55dB below the fundamental and the THD typically -48dB. TI's Application note AN-263 cites an eight bit derived wave distortion at 0.5% unfiltered and as low as 0.1% filtered.

The circuit of the gain control system and output amplifier is shown below:

Gain Control:

The output of the AD7226 DAC for each of the three channels is fed to an AD633 Analog multiplier IC into its X1 input. These IC's are powered by the +/- 16V supply and used for two functions.



The AD7226 is a single power supply DAC, its output varies from 0 to 10V (with a 10V reference voltage on pin 4) over the range of the 256 bytes it is fed. Essentially its output waveform, in the Sine wave case, is centred around +5V. Therefore a +5V Reference voltage is introduced at the minus (X2) input of the AD633 to subtract five volts from the DAC's signal output so as to create a +/- 5V peak sine wave centred around zero volts at the output of the AD633.

The Multiplier function of the AD633 is used to make a voltage controlled attenuator. Zero to 10V is supplied by the front panel Level control to the three AD633's Y1 inputs, with the Y2 inputs at zero volts. The Summing Z input is not used. The equation for the AD633 is:

$$\text{Output} = \frac{(X1-X2)(Y1-Y2)}{10} + z$$

The Output Amplifier:

The +/- 5V peak Sine waves from the AD633's are then fed to the 741 OP amps. These are configured as inverting amplifiers to drive two complimentary medium power Darlington transistors in a Class B configuration, with feedback, to acquire a voltage gain of 2. It is designed to deliver 3.333 Watts of power per phase into the load. Signal inversion of all three phases here has no effect on the relative signal phases.

In the usual manner, a small initial bias is used to overcome cross over distortion. In this design TO-66 package devices were used, the 2N6294 and 2N6296, however the pcb has been configured so that modern flat pack TO-220 epoxy cased parts such as the TIP110 and TIP115 could be mounted to the pcb directly and have their tabs screwed to a real panel/heat sink arrangement.

The 10101BGC OP amps are the merely the mil spec quality equivalent of the 741. As often noted though, by critics of the 741, the 741 is significantly out-spec'd by modern day OP amps, especially with their features such as input and output near rail to rail swing and a much high gain-bandwidth products.

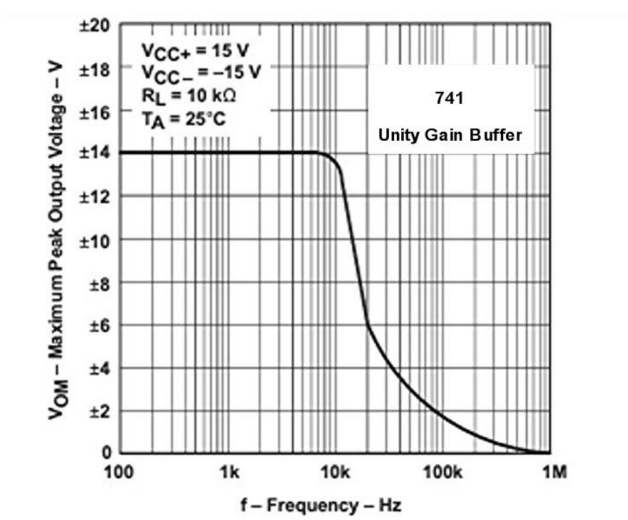
However one has to consider the performance of an OP amp with large signal output voltage swings and the maximum frequency of operation in the circuit along with the effect of the Slew Rate. The 741 being powered by +/-16V is capable of a +/- 10V peak output voltage. The Slew Rate is a modest 0.5V/uS for the 741 or 500,000 Volts per second. In this application a lower range slew rate OP amp is helpful.

The maximum slew rate of a Sine wave output signal as it crosses zero is 2π(Vk)f where the peak voltage Vk is 10V in this case. Making this equal to the slew rate of the 741 at 500,000 where the 741 itself would then start to limit the waveform reproduction, and solving for f:

$$f = 500{,}000/2\pi Vk$$

$$f = 7957 \text{ Hz.}$$

This is essentially why the graph from the 741's data sheet below, shows the output voltage of the 741, for large signal output swings, rolling off, starting at around the relatively low value of 8kHz.



This is highly suited to low frequency applications and immunity to HF difficulties or interference. The maximum Sine wave frequency presented to the 741 in this application is only 1kHz.

However there is another reason why this specific topology with a 741 and the Darlington pair was chosen for the task for this Generator. The basic arrangement as a medium power amplifier was already known to be stable driving a combination of a mixed resistive and inductive load. A version of this topology was once used in the early 1980's as the Vertical Deflection yoke driver raster scan VDU's. Practical loads with this Generator will mostly be combinations of resistive and inductive elements, which is why this arrangement was chosen.

At full output voltage of 7.071V rms and minimum load resistances per phase of 15 Ohms and using the generator, the rms current is in the load for each phase is 471mA. Given that the output could be connected to a load resistance that was too low, or perhaps accidentally shorted out, 500mA hold current Polyswitch self reset-able fuses are placed in series to provide some protection for the power amplifiers. If the Polyswitch goes to a tripped high resistance condition, it is obvious from the phase lamps on the front panel. The unit is then de-powered and allowed to cool down so the Polyswitch resets, to its usual value in the order of 0.5 Ohms.

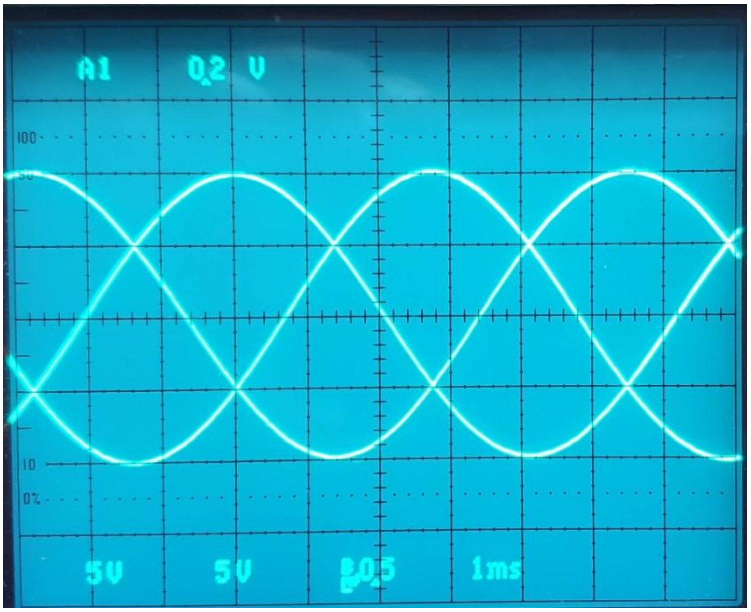
Testing at full load and 10 watts delivered to it, power consumption from the Mean Well supply outputs is 13.28W from the positive supply unit and 11.52W from the negative supply unit, making a total of close to 25w.

Arrangements are made with two multi-turn calibration presets per channel to ensure the zero is correctly set at the amplifier outputs and the exact voltage gain is set so that each channel on the maximum output setting, under full load has a 10V peak Sine wave (7.071V rms).The feedback loop stabilizes the voltage, regardless of the load, but the resistance of the Polyswitch devices are not enclosed in that loop, so there is a small voltage drop at full load due to the Polyswitch devices of around 0.25V.

Due to the behaviour of the AD7226, the output signal is glitch free on the digital step transitions and a smooth output waveform could be attained with a single value of filter capacitance for all of the frequencies. The feedback capacitors C54, C55 and C56 value at 510pF roll off the output amplifier's high frequency response, were simply chosen so that it was the largest capacitance value possible before any significant amplitude attenuation was seen with the output wave at 10Vp running at 1000Hz.

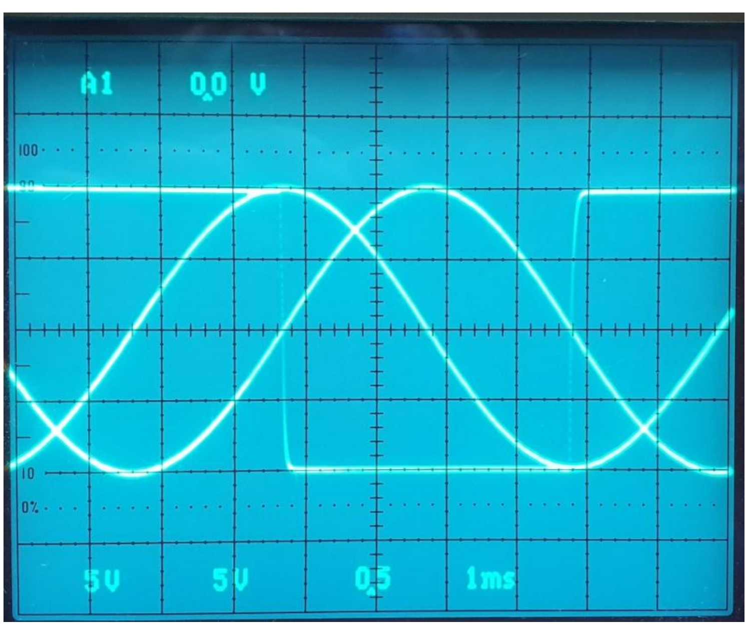
Switching in filter capacitors of higher values could have been an option for the lower frequency ranges, however it would have required a multi-gang frequency switch or another switching method, and examination of the output waveform quality indicated this was not required.

The photographs below show the Generator's output waves displayed on a 2465B scope:



The scope grab above shows the three phases of 10V peak each. The quality of the sine wave is very good. The widest spaced steps in the wave, from its digital makeup of 256 sample points per cycle, occur around zero crossing and they are at that point in the order of only 200mV apart, so they are not easily seen on a recording of a 10V peak wave.

The recording below shos the instrument switched into Sine/Cosine/square wave mode:



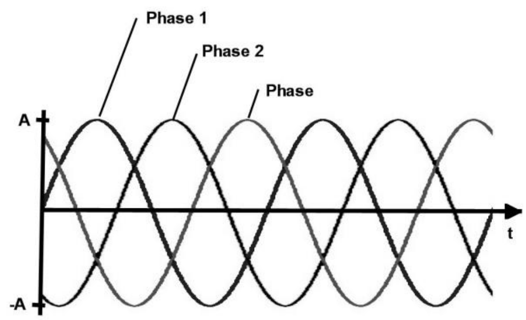
THREE PHASE THEORY AND VECTOR DIAGRAMS:

In most electrical engineering documents the vectors representing the current, voltage or magnetic flux, with a magnitude and an angle, are regarded as rotating *anticlockwise* as per international convention. Therefore the angle increases in a positive direction with anticlockwise rotation. The three phase wave equations where A is the peak amplitude, f the frequency, t the time and $\omega = 2\pi f$ are shown below. Of note the values enclosed in brackets are in Radians, 2π Radians = 360 Degrees. For example the value $2\pi/3$ is equivalent to 120 Degrees and $4\pi/3$ to 240 degrees.

Phase 1 = $A\sin(\omega t - 0)$

Phase 2 = $A\sin(\omega t - 2\pi/3)$

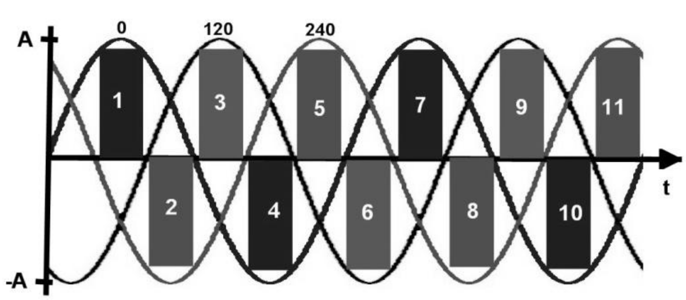
Phase 3 = $A\sin(\omega t - 4\pi/3)$



The format of the equations in Analog Device's AN-321 application note for calculating the 256 Byte values per phase placed the values of 120 and 240 in as *positive numbers*, rather than subtracted from the Phase 1 wave angle. This has the net effect of phase advancing (rather than retarding) the the phase 2 and phase 3 waves with respect to Phase 1. In a train of Sine waves this effect reverses the position of the phase 2 and phase 3 waves with respect to Phase 1. The very first ROM I programmed had this issue which was corrected for the final ROM file by entering the 120 and 240 degree values as negative numbers.

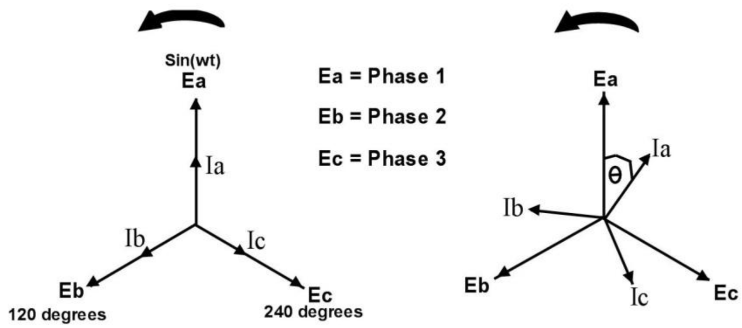
Also, intuitively, I had initially expected when the phase lamps were examined at a low speed, the effect would appear to be anticlockwise rotation. It would in fact be that way if LED's were used, half wave rectifying the waves because of the sequence of them. It turns out that the ***power delivery*** to the lamps (which obviously conduct on both half cycles) is essentially a ***clockwise*** rotation (now there is a counter-intuitive surprise) How this occurs is shown in the diagram below where the rectangles represent pulses of energy fed to the phase lamps:

Energy delivery sequence to Phase Lamps results in apparent clockwise rotation



If the Generator's load is purely resistive, the voltages and currents remain in phase then θ in the diagram below is zero and the currents do not lag the voltage, which they do with inductive loads**.** Also a Sine wave has its peak amplitude at 90 degrees so it is customary to draw Sin(ωt) pointing straight upwards.

And the vector diagrams where Ea, Eb, Ec are the phase voltages and Ia, Ib, Ic the respective currents are simply:

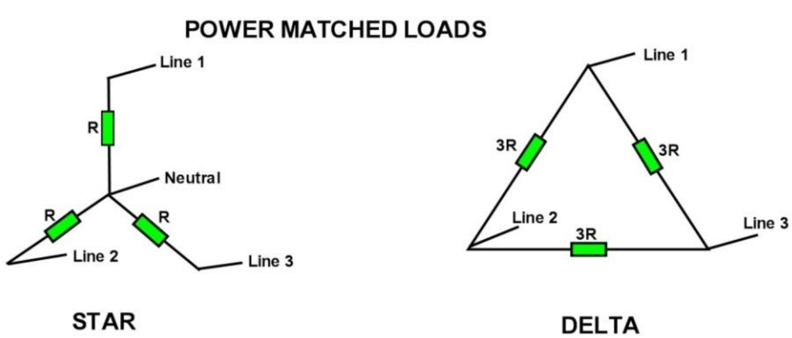


The discussion from here largely confines itself to resistive loads, without taking lagging currents and Power Factor (Cos θ) into account.

In a low power system such as this, for experimental models, the loads will be primarily resistive in nature. The lower the test frequencies, the smaller any reactance of test coils, which result in a lagging of the current vector.

Three Phase loads can be configured as Star (Wye) or Delta(Mesh) connected.

For any given fixed Power value delivered to a three phase load, in some system of fixed Line voltages, the **Line Current** is the same, regardless if it is a Delta or Star connected Load. However the **Phase Voltages** and **Phase Currents** are not the same comparing Star and Delta for the same power load.



The voltages applied to the load elements are different because the Line voltage of the Delta connected system, which is also the Phase Voltage of the Delta system, is higher than the Phase Voltage of the Star connected system.

For experimental work, with rotating fields, the Star system is preferable, with a Neutral connection included, because the load resistance values are lower for the same power and there does not have to be a balanced load.

Clarifying Terminology:

"Phase Voltage" Vph, is the voltage seen across a load element in a three Phase system.

"Phase Current" is the current via any of the load elements.

"Line Voltage" VL is the voltage between any pair of the three Line conductors.

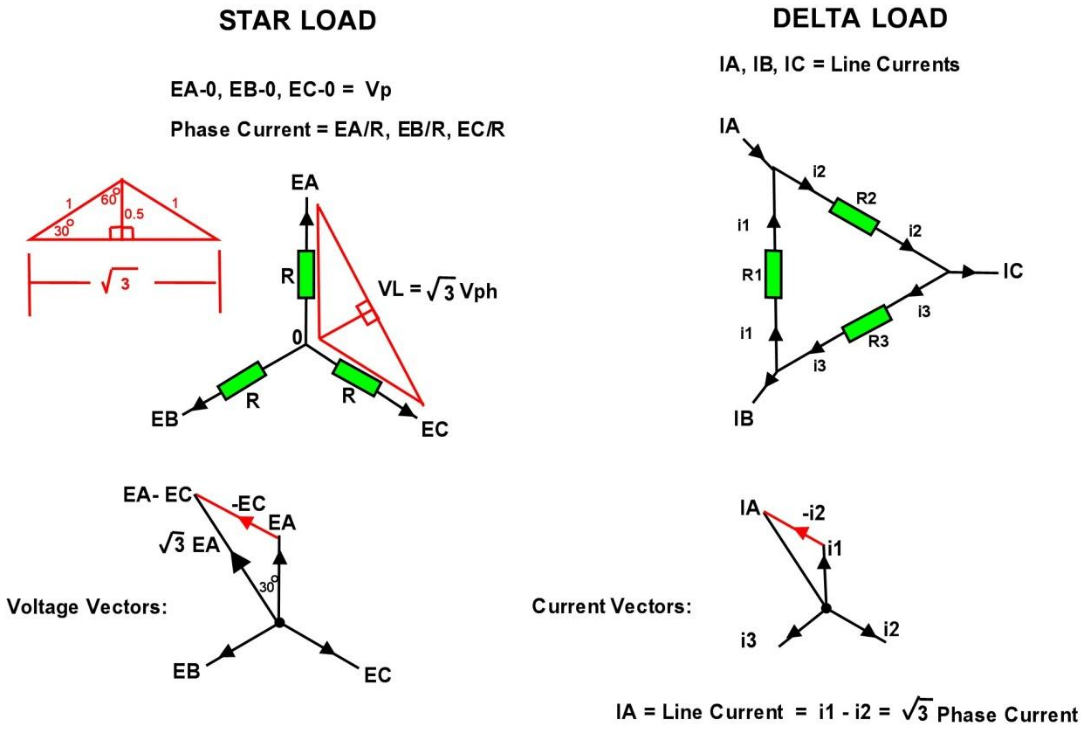
"Line Current" is the current in any one of the three Line conductors.

To clarify further, the term "Phase Voltage" does not imply that there is a Neutral present:

(Unfortunately one of the definitions of Phase Voltage seen on the internet says it is the voltage between Phase and Neutral. In the Delta connection there is no Neutral and the Phase Voltage is the Line Voltage. Therefore Phase Voltage is better defined as the voltage across a load element in a three Phase system rather than the voltage between a Phase and Neutral connection).

To find the voltage relation between the Lines VL, and the vector magnitude of a Line to Neutral or the Phase Voltage Vph, of the Star system, the Phase voltage vector in the diagram below EC, must be subtracted from the Phase voltage vector EA to find the Line voltage vector between EA and EC. The diagram below shows how the $\sqrt{3}$ factor is derived, by simple geometry, just for one phase to avoid cluttering the vector diagram.

In the same manner, the Line current for the Delta connection in conductor IA is found by vector subtraction of two currents i2 and i1:



STAR AND DELTA LOADS ON THE GENERATOR:

For purposes of explanation the Generator's outputs are used here, with the recommended minimum load resistances.

Star Load:

In the Star connected load, the Phase Voltage Vph, is related to the Line Voltage VL in that

$$Vph = VL/\sqrt{3}$$

Vph is in this case, is the voltage across a resistor between one of the three Line connections and the Neutral (centre connection).

The Phase Current in in the Star connection is the current via one of the three load resistors which is the Phase Voltage divided by the Resistance. The Line Current In the case of the Star connected load, in each Line conductor, is simply equal to the Phase Current.

With this Generator and a Star load of three 15 Ohm resistors, the Phase Current via each resistor is 7.071 rms Volts/15 Ohms = 0.4714 Amps and this is equal to the Line Current. The power dissipated in each 15 Ohm resistor is therefore 3.333W.

One important point to note is that in the Star system as a load, the current in the Neutral leg sums to zero. That is if all the loads were equal (balanced) and therefore the Neutral wire could in fact be disconnected from the generator feeding the load.

Delta Load:

In a Delta load the Phase Voltage is again the voltage across any of the three load resistances. In this case though, it is equal to the Line Voltage VL, defined as the voltage between any pair of the three active conductors.

The magnitude of the Line Voltage, VL, is $\sqrt{3}$ times the Phase Voltage Vph seen in the Star connected load:

$$VL = \sqrt{3}\ Vph$$

Since power in a resistor is equal to V^2/R and the voltage applied to the resistor is $\sqrt{3}$ times higher ,this means that for the the same power dissipated in each resistor, the resistor value has to be three times larger at 3 x 15 = 45 Ohms, for the same 3.3333W dissipation per resistor for a Delta connection all else equal.

This makes the resistor's current (or the Phase Current) in the Delta load (for the same power as the Star case) $\sqrt{3.3333/45}$ = 0.2722A.

However, with a Delta load, the Lines each supply current ***to two load resistors*** and the Line current is the vector difference of the current supplied to the two loads.

The Line Current in Delta load case is $\sqrt{3}$ times *the Phase Current of the elements in the Delta connected load.*

$\sqrt{3}$ x 0.2722A = 0.4714A, exactly the same as the line current in the Star connected system.

Inside the Delta connection, there no circulating currents because at any one instant, the voltages across the three loads and therefore the current inside the mesh sums to zero.

Summary Delta & Star Loads:

As noted before, in a system with the same Line voltage, for the same transferred power to a Load, the Line current is the same in the Delta and Star load arrangement.

The formal equation which applies to power in the load of a *balanced* Three Phase system, either Delta or Star connected, where VL is the line voltage and IL the line current is:

$$\text{Power} = \sqrt{3}(VL)(IL)\cos\theta$$

Where cosθ is the power factor required when the loads have a reactive component. For a resistive load only, $\cos\theta = 1$.

In three phase systems, in general, each Phase can be regarded as carrying the current return for the other two phases:

$$i1 + i2 + i3 = 0$$

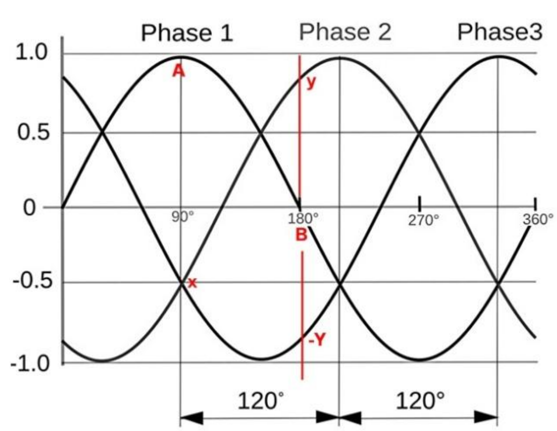
$$i1 = -i2 - i3$$

Owing to the fact that the voltages and currents are Vector quantities they must be added or subtracted as vectors.

STOPPING THE CLOCK:

DC Analysis of Three Phase AC ? DC analysis of an AC system might be controversial as it appears to be a contradiction in terms, however it provides some insights into 3 phase fields. This is why a Clock Stop button has been incorporated in this Generator for demonstration purposes.

Examining the three phase cycle of the voltages, certain things are self evident from looking at various points in the cycle (stoping the clock):



Of interest are two places in the timing, one is where one phase voltage is at zero volts, and the other where one phase voltage has peaked.

Looking at the Phase 1 voltage at point A on the graph above, where it has peaked, at that moment the other two phases, at point X on the diagram, have an opposite polarity and half the peak value of Phase 1.

Since the resistors as a load do not have a time domain property, or put another way are not frequency dependent, if the total power in the three resistors is calculated, the total power remains unchanged regardless of the operating frequency. However, if the clock stops, it is another story with respect to the power dissipated in each individual resistor.

In the case of 15 Ohm load resistances and a 10V peak Sine wave per phase, the power in the resistor with 10V DC now applied, with a stopped clock is $10^2/15$ = 6.666W and in the other two resistors 5^2**/15** **=** 1.666W each making up the total of 10 Watts. And the current in the line feeding the resistor with 10V would be 0.6666 Amps. As pointed out previously with a 10V peak Sine wave from the Generator (7.071V rms) the current per phase, and the line current for a Star load with 15 Ohm resistors was 0.4714 Amps.

The implication is, that if it is planned to stop the clock, for a time where one of the line voltages has peaked at 10v across one of the load resistors, the minimum value load resistance should be kept at 22 Ohms, not 15 Ohms, so as to keep the Line current below 500mA. The outputs of the class B power amplifiers have been protected from overload by 0.5 Amps hold current Polyswitch device and while it could support 0.666 Amps for a time, it could possibly go to its high resistance state.

Now looking at point B on the graph above, when the Phase 1 voltage is zero, the value of each of the other two phases have values of Y and –Y indicated. Their voltage value could easily be found on the calculator or Sine Table. However, using the principle of the Conservation of Energy instead, we know that those two voltages each must produce 5 Watts dissipation each in the respective two 15 Ohm load resistors, which are the only two being powered.

Solving for V in the equation V^2**/15 = 5 Watts,** yields a voltage of $\sqrt{75}$ or 8.66 Volts. Checking on the calculator for the value of Sin(180-120), or Sin60, indeed yields a value 0.866 agreeing that the voltage at point Y and –Y has a magnitude of 8.66V when the peak output voltage of the generator is 10v (max setting). The value of 0.866 is also $\sqrt{3}/2$.

What happens to the magnitude of the magnetic flux vector inside a set of six motor coils as the vector rotates?

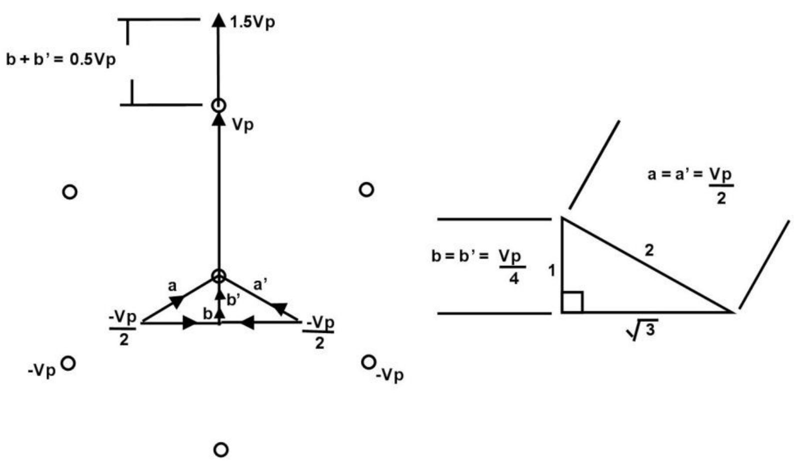
With the six coils contributing, the overall magnitude of the magnetic flux vector is stable regardless of the angle of rotation. The same applies to the electric field vector magnitude, if one had a special CRT with an arrangement of 3 pairs of plates spaced at 0, 120 and 240 degrees too would demonstrate this. (Though I have never seen a 6 deflection plate CRT myself).

This is shown in the two diagrams below, where for instructive purposes, the clock has been stopped.

Considering the case where rotation has stopped at 90 degrees. We know at this point that Sin(ωt) is at its peak value of 1 and positive ,so the voltage is at its peak, Vp. The other two phases of 120 and 240 are at 50% of their peak value and negative each –Vp/2 volts. But we could just as easily be referring to the currents in the coils or the magnetic flux produced by them.

If we add these together on a vector diagram we can readily see that the net magnitude of the magnetic (or electric field) vector is 1.5 times its peak value:

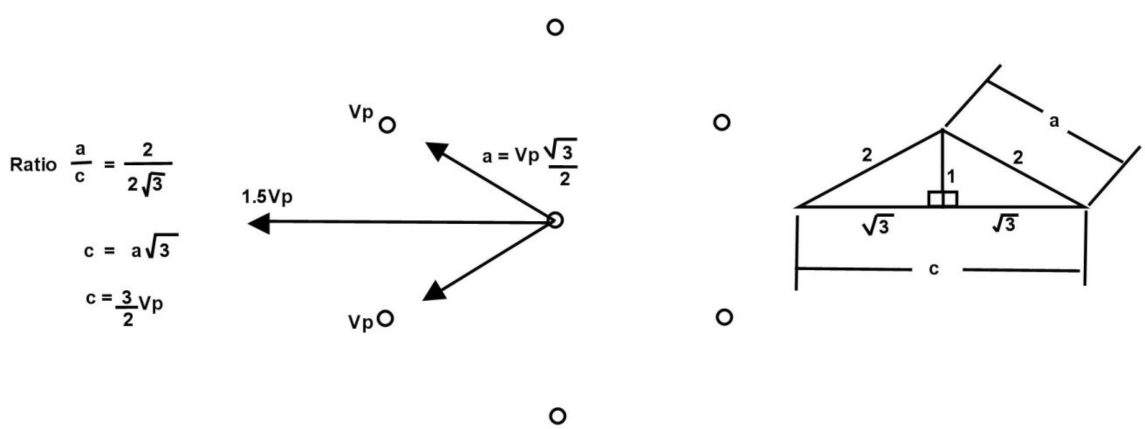
Net Vector magnitude = 1.5 x Vp



Stopped Clock 90 Degrees

Likewise if we stop the clock at 180 degrees when the net vector is between two of the phases, the result is the same, the vector still has a magnitude of 1.5 times the peak value.

Net Vector magnitude = 1.5 x Vp



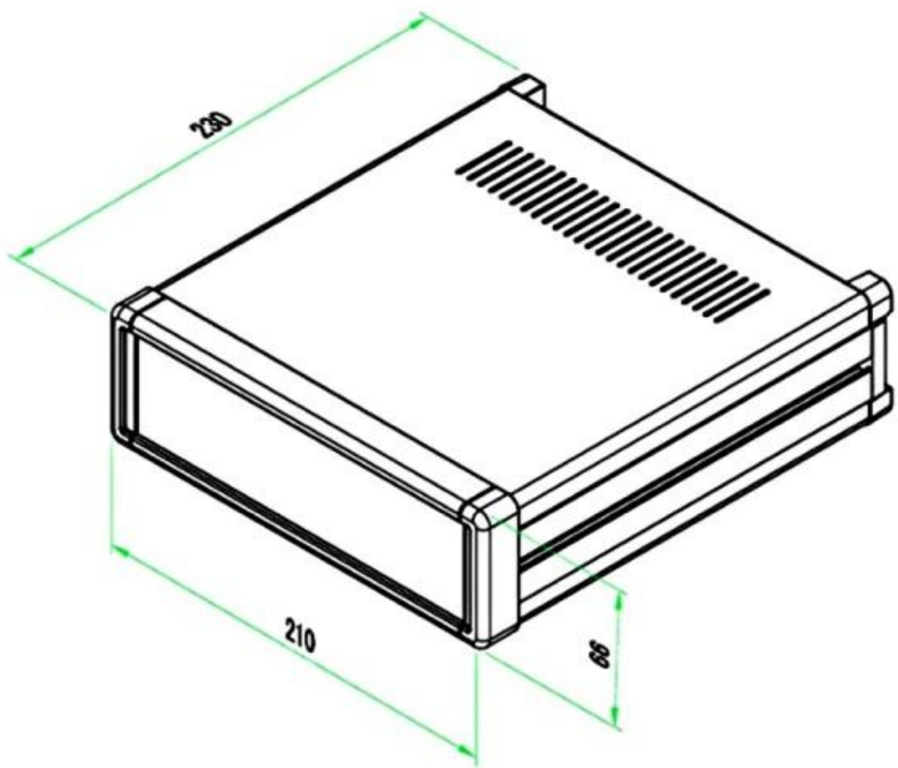
Stopped Clock 180 Degrees

We can conclude from the above that the three Phase arrangement of coil pairs with three phase voltages applied, results in a rotating electric or magnetic field vector, or flux vector, **of a constant magnitude of 1. 5 times the peak flux for the individual coil pairs.**

On the other hand, it is much easier to show on a diagram that the result of a Sine and Cosine wave applied as an electric or magnetic field on the X and Y axis results in a rotating Vector of a constant amplitude tracing out a circle. And it is easy to display the circle, of a uniform diameter on a simple Oscilloscope in X-Y mode.

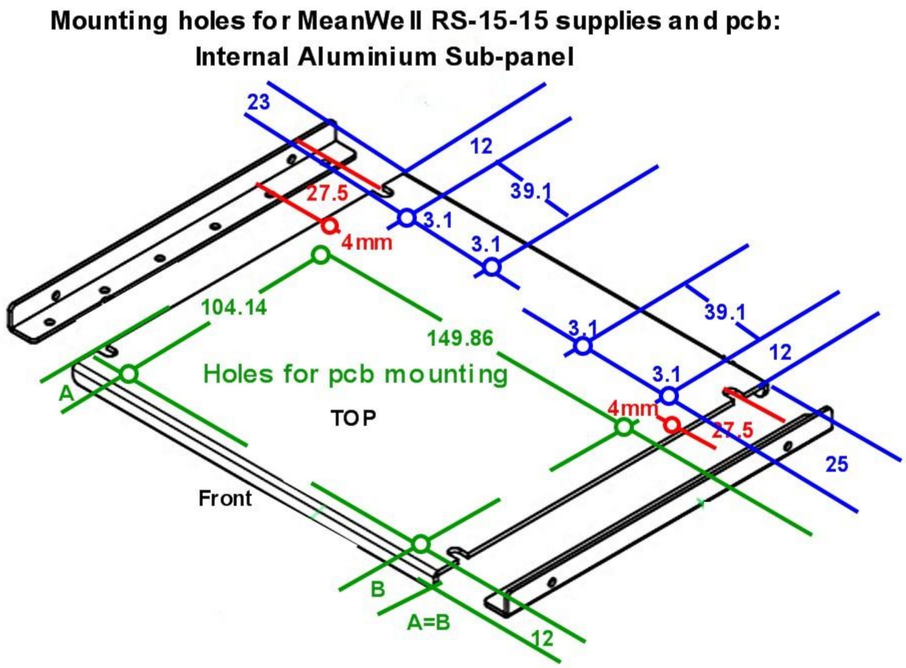
CONSTRUCTION OF THE GENERATOR:

The instrument case is the compact Takachi MS-66-21-23 G with the Tilt feet option TL-45SG and the aluminium internal sub-panel option part MSC21-23, it comes with the required screws and mounting flanges. These cases have extruded aluminium sides and cross struts, with painted steel bottom & top with a ventilated top. The basic external geometry is 210mm x 230mm x 66mm. They are an excellent housing and also have a carry handle which is available on request. These are available by the mail order section of Takachi Japan on their Website.

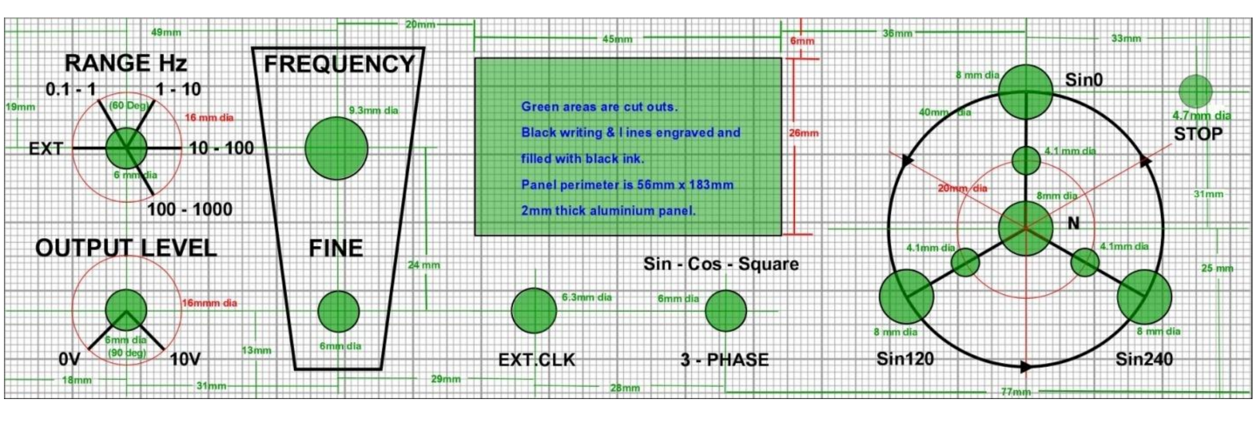


The internal sub-panel is particular helpful. Due to the position of the two Mean Well RS-15-15 power supplies, an alternate location for two of the panel's mounting screws is shown in Red. There are threaded holes already present in the steel side flanges to receive the screws. The holes for the Mean Well supplies in blue and for the pcb in green.

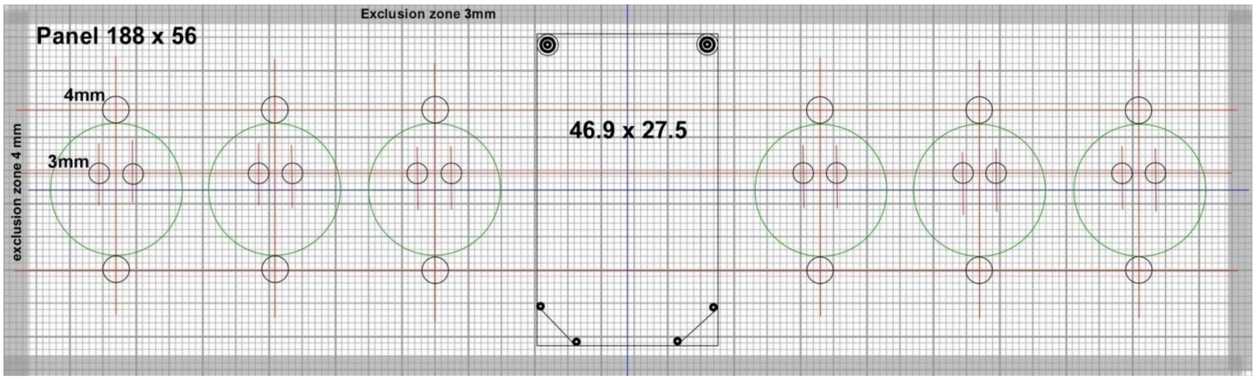
To mount the pcb in my unit I used some ¼" tall 4-40 UNC stand-offs and threaded those into the plate, but 3mm standoffs with screws are fine. The corner holes in the pcb itself will clear 3.3mm.



The front panel was laid out on a 1mm grid. The panel is 2mm thick aluminium with a Satin Anodised surface finish. The artwork shown below, the holes cut and and the engraving was done by Sunquest Industries Warana 4575 QLD. They fill the engraving with black paint and it gives a beautiful and long lasting wear resistant finish, superior to any form of sticker or label method.



On the other hand, the rear panel was a simple affair, requiring the hole for the IEC Line power connector and for the 6 transistors. Obviously if the output Darlington transistors were changed to TO-220 types the arrangement would be different. To hand manufacture the panel, I simply printed out the diagram on paper as its exact size and used it as a stencil to mark the holes.



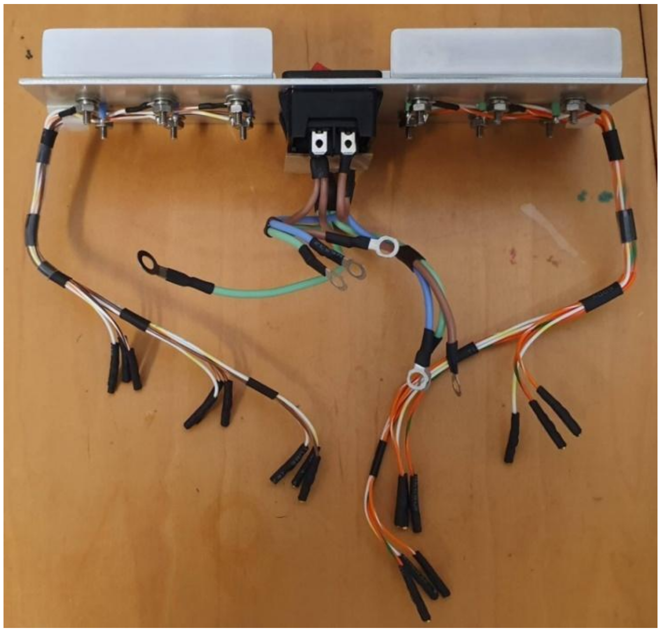
The photo below shows the rear panel under construction with the IEC connector fitted and the holes for the six TO-66 cased transistors. It is important that the holes are fee from burrs. The transistors are mounted on Mica insulators and have the usual plastic the usual mounting washers. I use clear silicone grease on these washers as it is less messy than white compound. However, I used the white thermal compound between the heat fins and the rear panel

The same stencil was used to mark out the holes for the transistors on the heat fins. The heat fins were fabricated from 1.2mm thick aluminium plate, are 70mm wide and 50mm outer dimension (taking the fold into account) and the flange projects 16 mm from the rear panel surface. Due to the height of the grey plastic fittings, retained by the black screws, the edges of the heat fins clear a table surface by a couple of mm if the instrument in placed up on its end on a table.

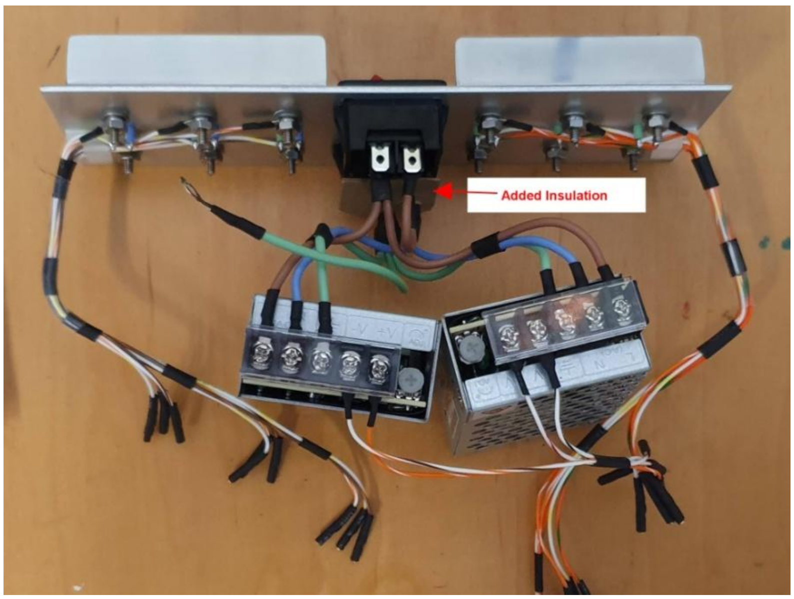
The transistors are grouped on the rear panel as viewed below as PNP's on the right side and NPN's on the left as viewed from the rear.

The rear panel is then completed with its wiring.

Note that individual Jaycar 0.9mm Gold plated connector pins and sockets have been used. This is because they are more reliable and can carry a higher current than the single wipe plug connectors with rectangular pins as seen on many pcb's. In practice using them it pays to "condition them" by lubricating the socket with some Inox MX-3 and fit a spare pin held firmly in pliers, in and out least twice, so it does not take excessive forces to connect and disconnect them. Also if two layers of heat shrink sleeve are added over the sockets, then they are easier to finger grip for removal without pulling on the wires. The wires are better soldered to these sockets rather than crimped.



The line power wires and Earth wires from the IEC connector use high voltage Silicone rubber coated appliance wire, with soldered termination lugs. (Never be tempted to put stranded wire under the screws on a power supply's terminal block. It requires lugs). Also, note that there are three earth wires from the Earth pin on the IEC connector, one each for the two power supply units and one for the main earth to the instrument's body. The earth on the power supply units is connected to their case too, so that when they are screwed down by their two mounting screws each, the chassis is earthed by three conductors to the IEC earth pin.

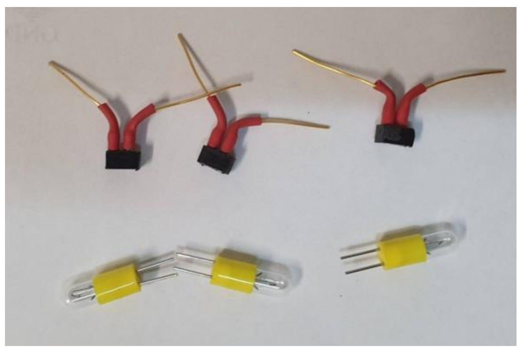


The rear panel assembly along with the the two PSU units can then be fitted to the case awaiting the front panel assembly and the PCB:

Of note the two PSU's should be powered first to adjust both of their output voltages to 16.0V (The preset pot on these PSU's allows the voltage to be set as high as to 16.5V). It also pays to add some insulation on the rear of the IEC connector.

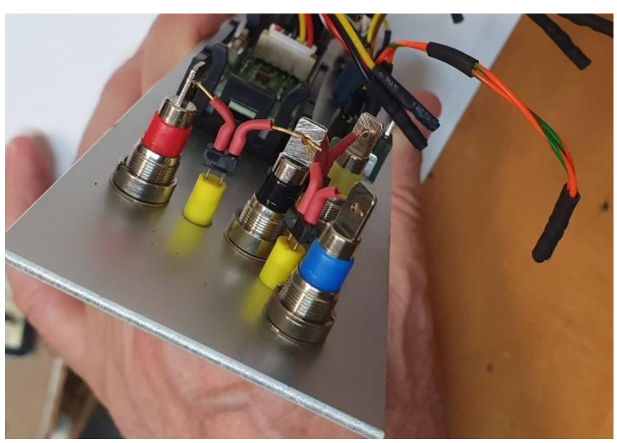
The front panel assembly is completed in a similar manner as a unit which can be detached from the pcb with the aid of the individual 0.9mm sockets & pins. Before assembling the panel though, three sockets are made for the 12V 30mA Phase lamps. They are simply made by cutting up a Machine pin DIL IC socket.

The pins on the lamps are 0.5mm diameter and fit well into the machine pin sockets. However, it is unlikely these lamps would have to be replaced very often if at all, because the peak voltage they receive, running on a low or stopped 3 Phase wave is only 10V and they are 12V rated lamps. Mostly with a higher frequency three phase wave they receive around 7V rms.



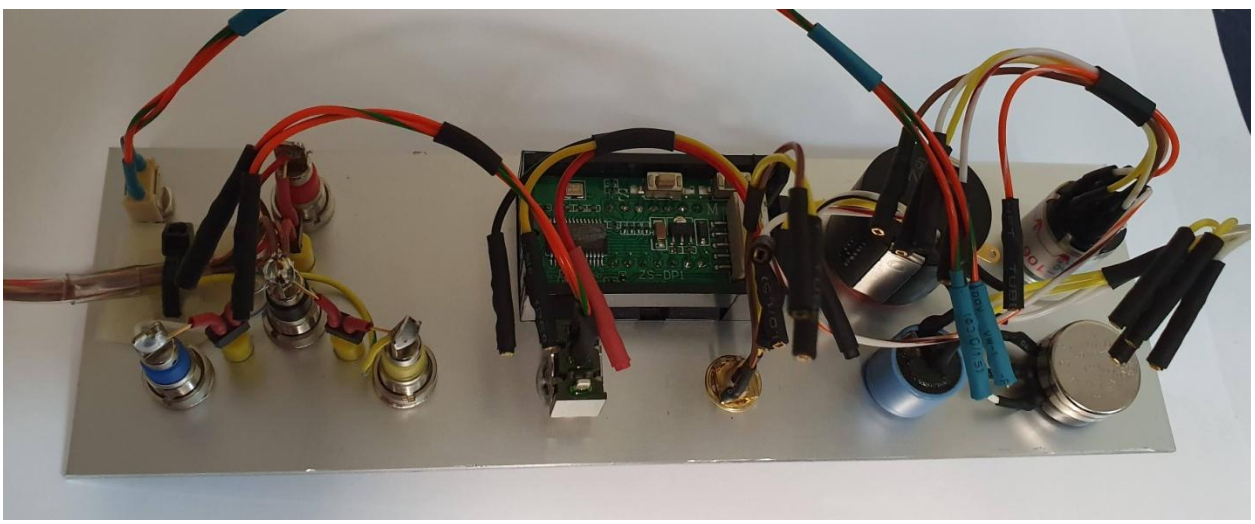
The 4mm Banana sockets for this Generator are made by Adafruit. They are available from Mouser and are a superior quality connector. Mouser P/N 485-3691. They come in a packet of 5 different colors and in this case the Green is not used.

The photo below shows the lamps and their sockets wired between the Adafruit Banana connectors:



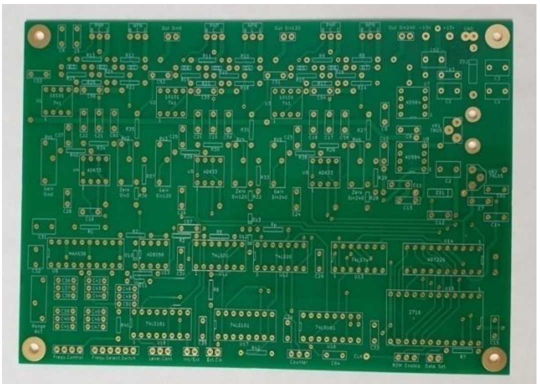
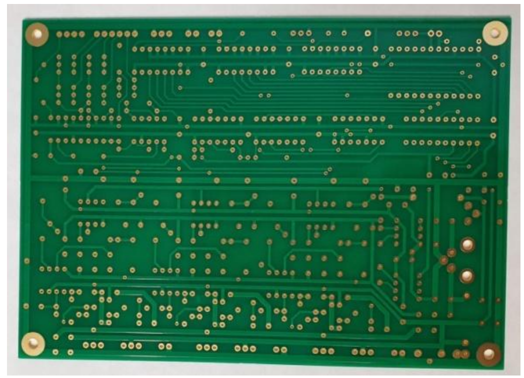
Front Panel assembly:

At the time of the initial engraving a Stop switch was not decided upon and added later with a label. The Red Dome over the SMA connector for the external clock input is a dust cover.



The PCB:

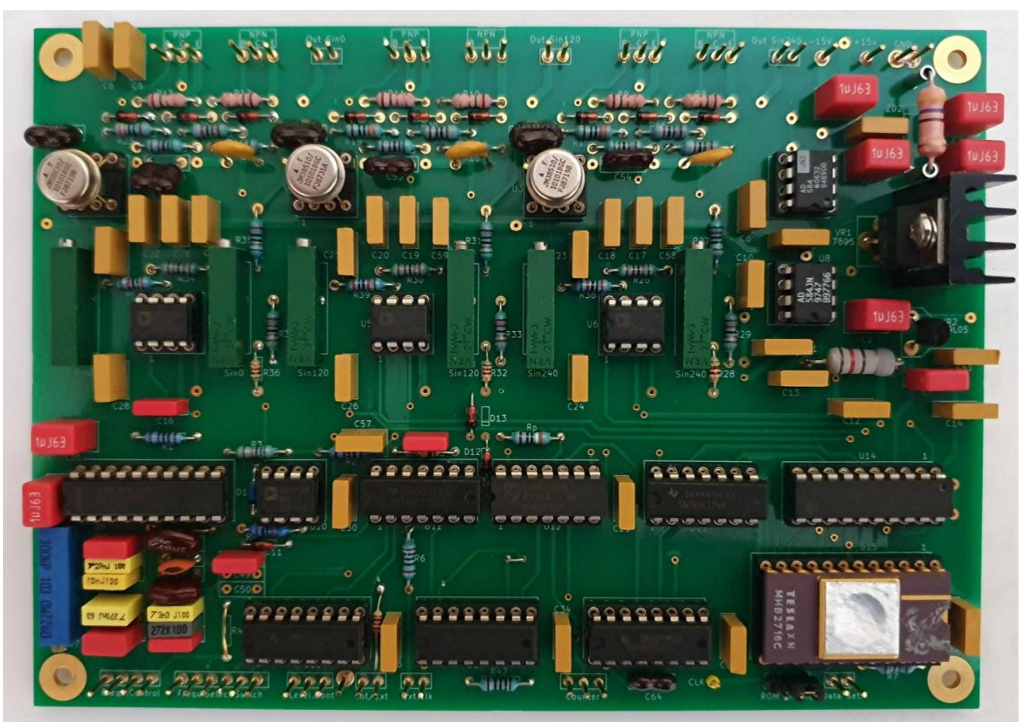
An excellent quality PCB was made for this unit by Mr Kim Chan at Storm Circuit Technology Ltd, in Shenzhen China. He makes particularly high quality pcb's at good prices.

Subsequently, some ,modifications were made to improve the pcb layout, for example rotating six of the 10 turn pots by 180 degrees for better access for adjustments and moving the occasional pcb pad to a better position. The resulted in a final Kicad file, which is readily converted into Gerbers.

The pcb below shows the assembled prototype unit ready for use. A few notes about it:

There are no electrolytic capacitors on the pcb. This helps promote long term reliability. The mustard coloured capacitors are AVX 0.1uF 100V MLCC types made by Kyocera. Any 0.1uF Ceramic capacitors will work, it is just that the AVX ones are very good quality. The red capacitors are Wima film types. The dark Brown capacitors are Silver Mica types, but can also be ceramic types. Generally I used the parts that I had on hand.



THREE PHASE EXPERIMENT 1:

"The Bermuda Triangle"

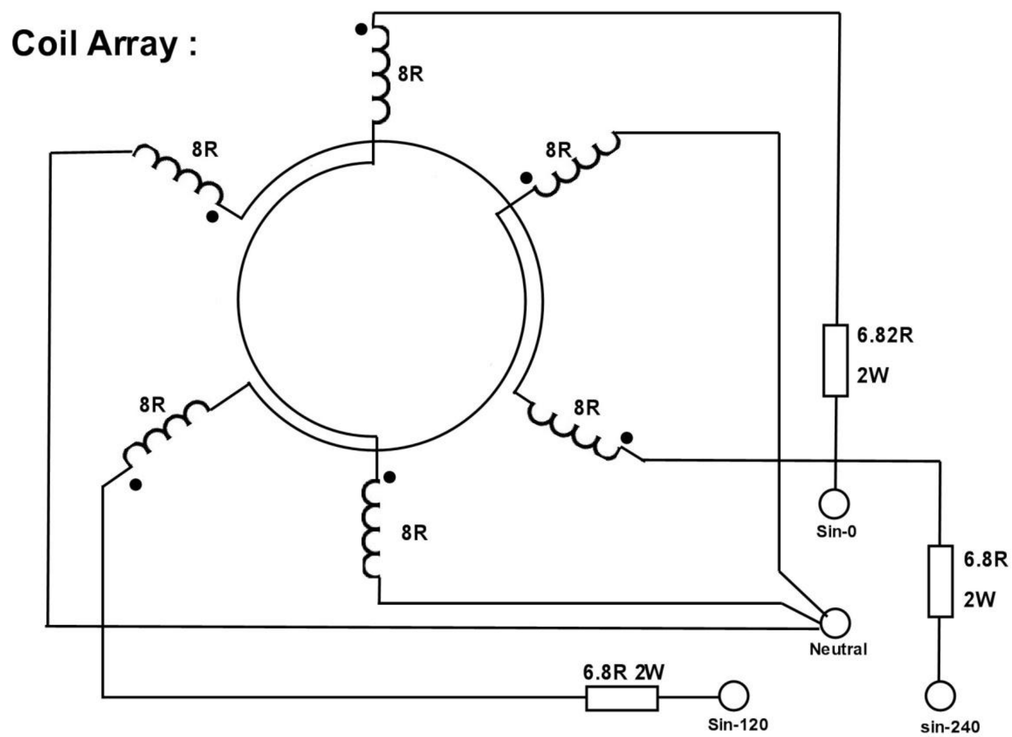
In popular culture at least and with conspiracy theories about Shipwrecks and Plane crashes, there were stories about a Pilot's or a Ship Captain's Compass spinning around and around in the "Bermuda Triangle" possibly aptly named, if the triangle somehow formed a three phase rotating magnetic field. Mostly though, it was a case that a Compass in that locality tends to point to true North rather than Magnetic North. Still, it is fun to have an interesting name for any experiment. I arranged six coils on a plastic board. The board is handy guitar scratch plate material.

The purpose is to demonstrate the rotation magnetic field of the three phase system. Each coil was wound on a Jaycar Bobbin (part number LF-1060) with 375 turns of 0.224 mm enamelled copper wire, which measures 0.25 mm diameter including the enamel insulation. This yields a coil with close to 8 Ohms DC Resistance. And the two coils for each phase gives a total 16 Ohms. Due to the fact that the frequency for this experiment may be slowed to a stop I added 6.8 Ohm resistors in series with each coil pair to keep the resistance above the recommended 22 Ohms for a stopped condition.

The coils are air cored. No magnetic cores were required for this demonstration, because of the sensitivity of the Compass. The Demonstration Board is 200mm x 200mm in size.

The polarity of the coils was chosen so that when Sin0 is at its peak positive value, the Red North seeking compass needle is pointing directly upwards.

The wiring of the coils is shown below:



Each of the coil pairs has an inductance of close to 3.3mH. At the frequencies involved in this experiment, less than 10Hz to observe compass rotation, the inductive reactance is only about 0.2 Ohms. So for practical purposes the coils can be regarded, from the load perspective on the generator, as being DC resistances composed from copper wire. At around 400Hz though, the coil pair's inductive reactance is around 8 Ohms. However to make a compass rotate at that speed, would require a special compass in an evacuated chamber where there was no wind resistance on the metal vane.

Video of the compass Rotating:

https://youtu.be/5buQ_RbL3EU

TWO PHASE EXPERIMENT 1:

In this demonstration the generator is switched to Sine & Cosine mode. These signals are then applied respectively to the X & Y inputs of an Oscilloscope. The Timebase in the Generator again is running slow, so that the CRT's beam can be seen moving in a circular motion. This is the simplest form of a Lissajous Figure, named after Professor Lissajous of Toulouse, who first formed these by the reflection of a beam of Light from two mirrors vibrating at right angles.

The video:

https://youtu.be/6nQc-ME_6ic

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