AC Power supplies and motor drive systems

Introduction. Inverters: Creating AC from DC

Inverters take a DC supply and use it to create a variable frequency and variable voltage AC supply. The DC supply may be obtained from batteries, a rectifier or some other source. The inverter creates an **Alternating** supply from the DC one by swapping the connections between it and the load repeatedly. The connections are swapped using a set of power electronic switches arranged in a bridge fashion.

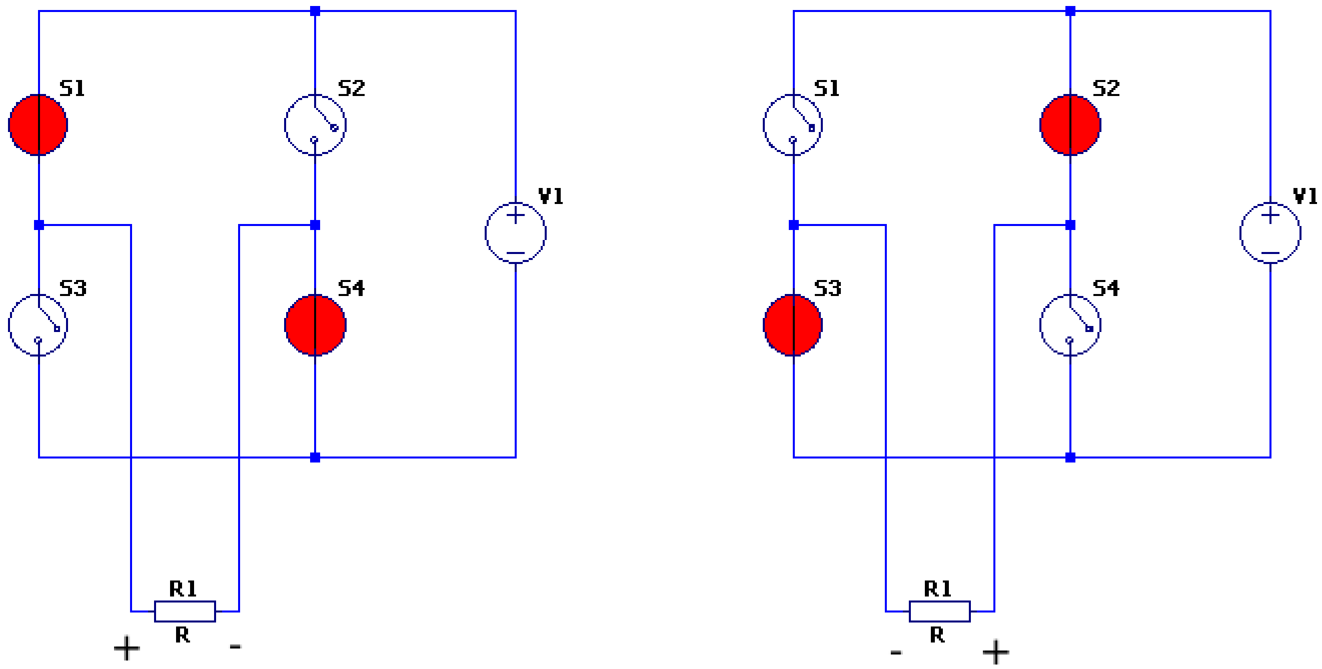


Figure 1. Principle of inversion

Outline circuits of single and three phase inverters.

The figures below show IGBT based single and three phase inverter bridges. Gate drives and connections to the controlling microprocessor are shown for only one branch of each circuit. Note the use of flyback diodes across each transistor.

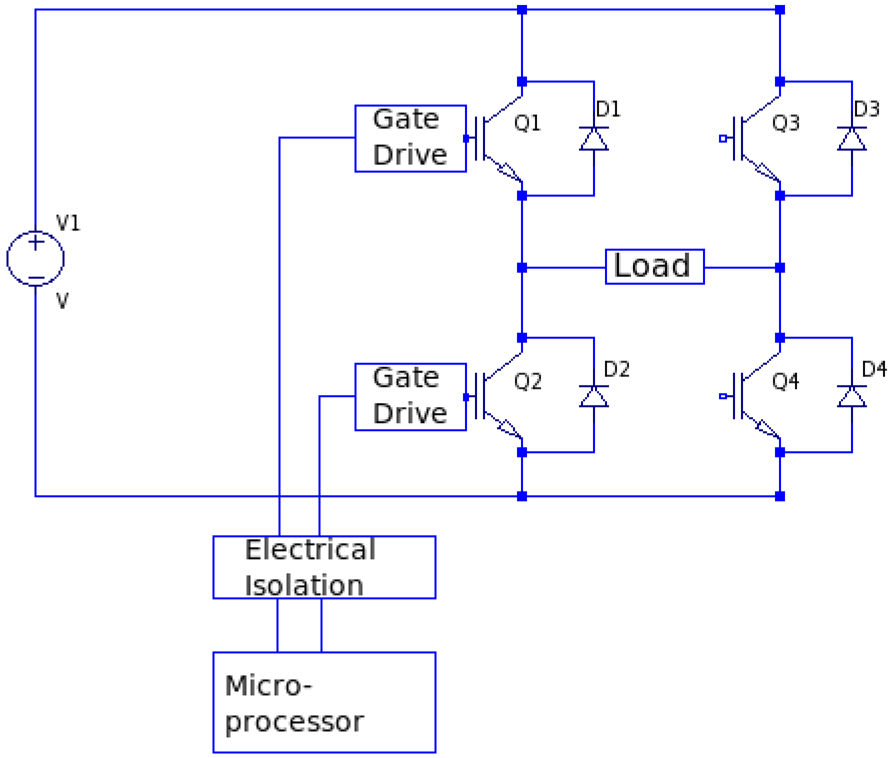


Figure 2. Single phase inverter

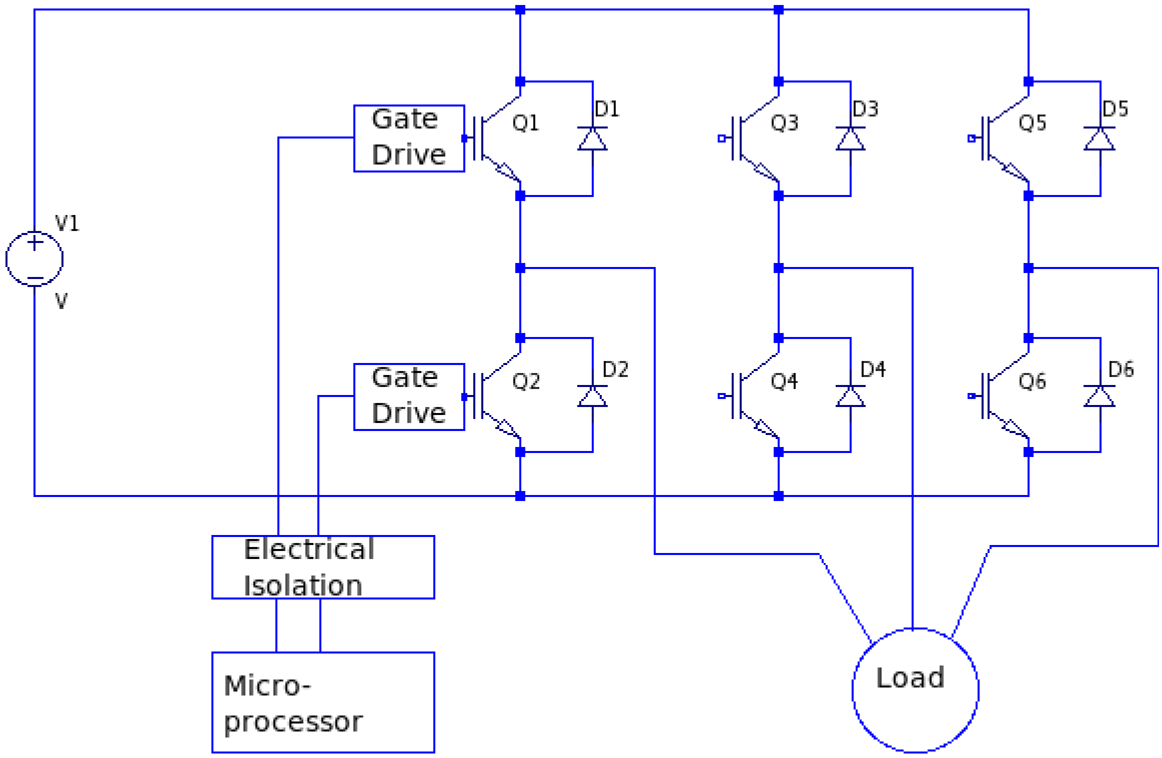


Figure 3. Three phase inverter

Interfacing inverters to microprocessors

The return paths from the transistors in the inverter are mostly at different potentials. This prevents a common frame of reference from being used for gate drive signals. As a result of this, gate drives typically include some kind of optical isolation between the controlling microprocessor and the power electronic bridge.
This can be achieved relatively easily using transformers however this can cause problems at low frequencies. Optical isolation is quite widely used these days as there is a good set of devices out there to support it. An opto isolator circuit is shown below in Figure 4. A pulse from a microcontroller (Vg1) drives current into an LED which turns on an opto-transistor. Both the LED and the transistor are built on one chip and are packaged together (U1). The transistor output is quite weak and must be amplified using additional external transistors. These additional transistors require an additional isolated DC power supply. The output (Vout) is then applied to the gate of a MOSFET or IGBT.

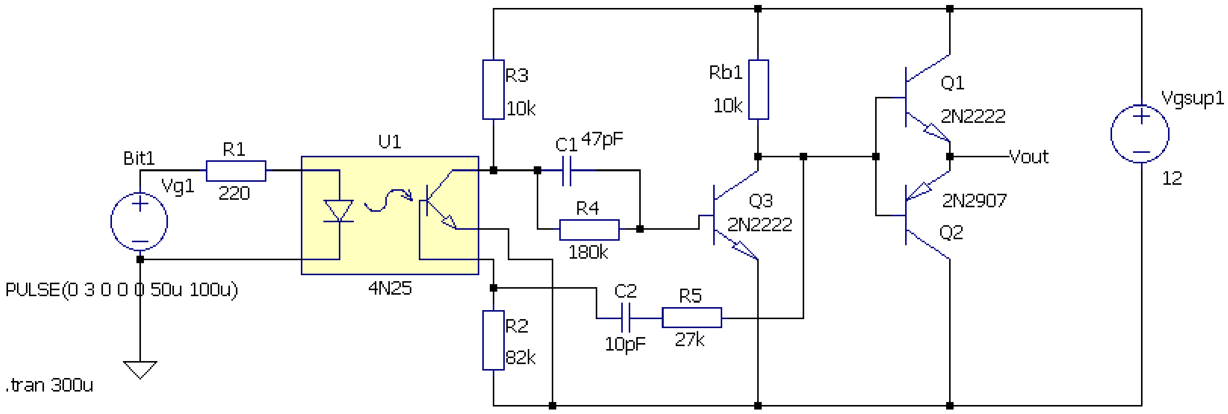


Figure 4. Opto-isolator circuit based on the 4N25 optocoupler/optoisolar.

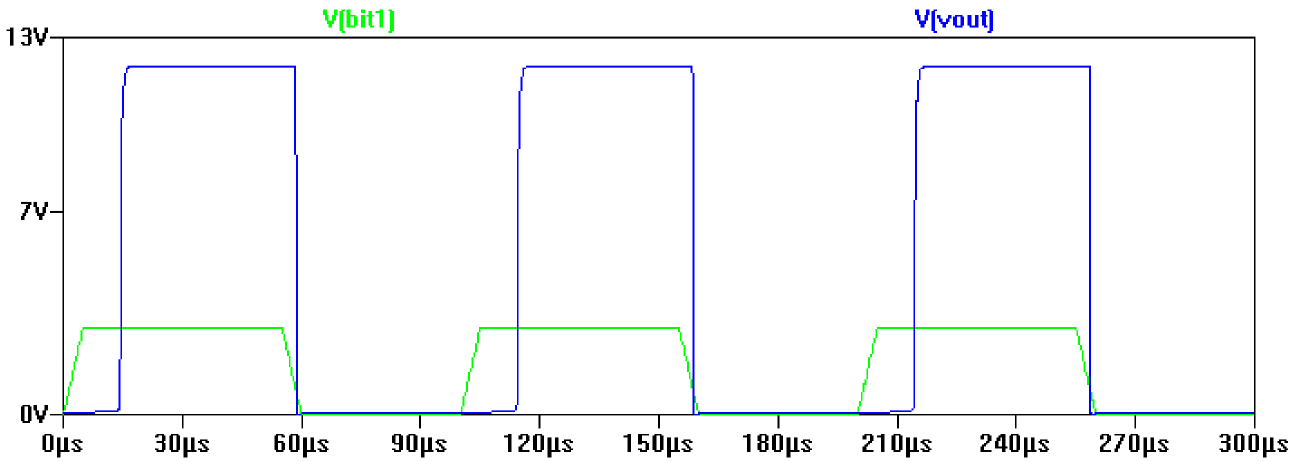


Figure 5. Input and output voltage signals for the opto-isolator in Figure 1.

The circuit in Figure 4 is reasonably complex to tune and get right. Gate drive integrated circuits are available that greatly simplify all of this. One such is the HCPL-3140 – the datasheet for which is available in your webcourses module. Another such device – the IR2106 (whose datasheet is also on webcourses) – incorporates two MOSFET drivers. One drives the upper transistor in a bridge circuit, the other drives the lower. This high-side/low-side arrangement is quite common and easy to use. It also eliminates the need for many of the additional gate drive power supplies that would otherwise be required. Consider the three-phase bridge circuit shown in Figure 6 below. The gate drives for each of the top MOSFETS require an independent isolated DC power supply. Additional power supplies are also required to supply all of the lower transistors (they could actually share one supply).

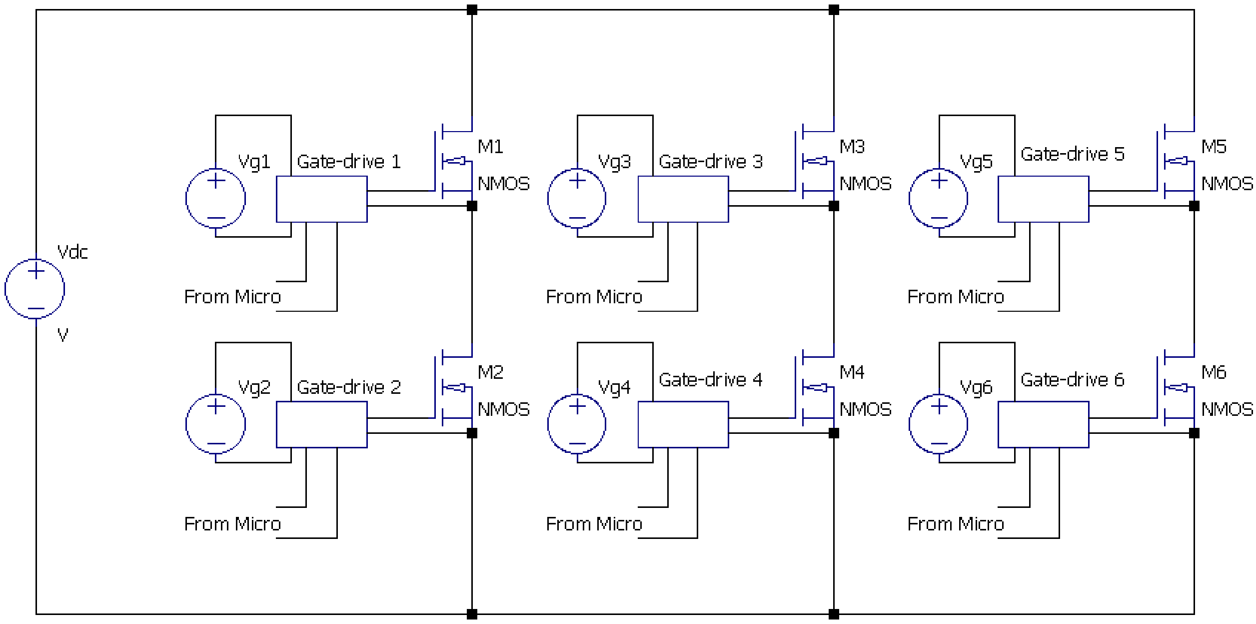


Figure 6: Powering IGBT gate drives in a three-phase inverter. Up to 6 independent DC supplies may be needed.

In order to see how all but one of these external supplies can be eliminated we need only consider one branch of the circuit. Figure 7a shows such a branch and a single gate drive power supply that could supply all gate drives. The capacitor C1 acts as the power supply for gate-drive 1. It is charged up when M2 turns on as shown in Figure 7b. When M2 turns off C1 retains its charge which can be used to turn on M1 later when the need arises.

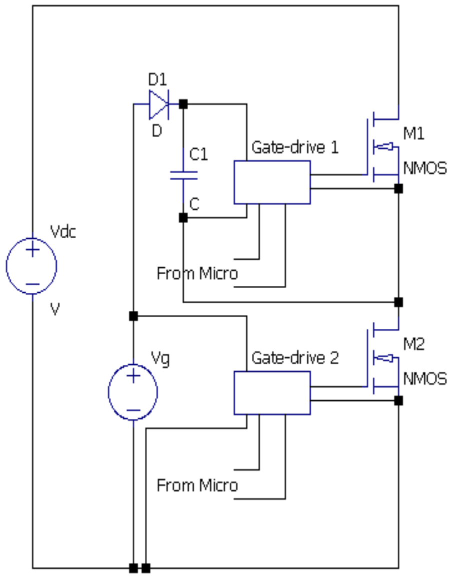


Figure 7a

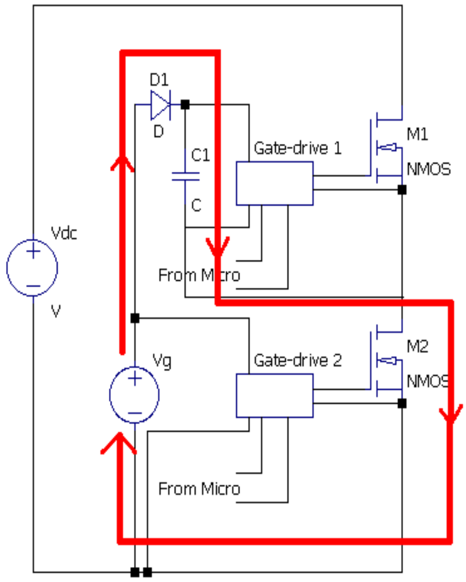


Figure 7b

Figures 7a and 7b. High-side and low side drivers in action. Figure 7b shows how C1 is charged via D1 when M2 is on.

Control strategies for inverters.

Quasi Square Wave

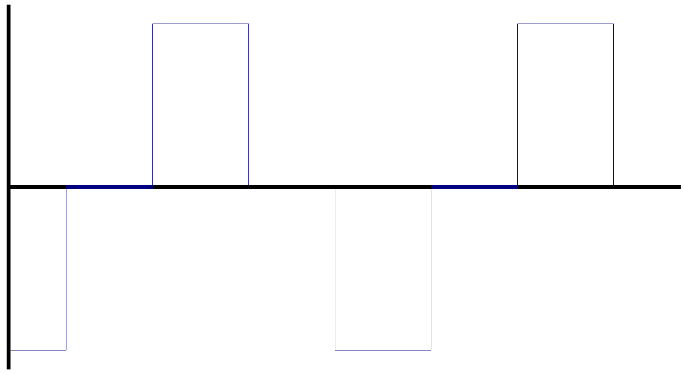


Figure 8. Single phase quasi-square wave

The voltage waveform for a single quasi square wave inverter output is shown in Figure 8 above. Each half cycle consists of a single pulse, the width of which is adjusted to vary the RMS value of the AC output. This output has the advantage that it is easy to produce however it does suffer from poor harmonic content as shown in Figure 9.

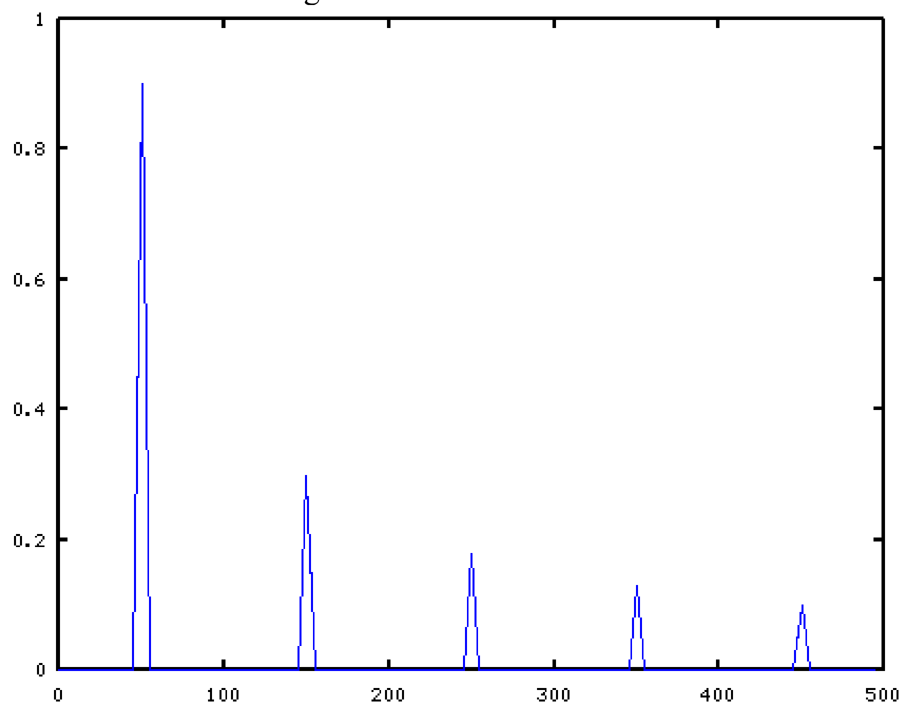


Figure 9. Harmonic content of quasi-square wave

The output from a 3 phase inverter using quasi-square wave modulation is shown in Figure 11 below. The top trace represents a phase-phase voltage while the lower traces are phase-neutral voltages (no neutral is available from a three phase inverter typically as the DC supply used is not split as in this case). The output voltage can be varied (crudely) by varying the width of the high pulse. The frequency can be varied by switching more quickly or slowly.

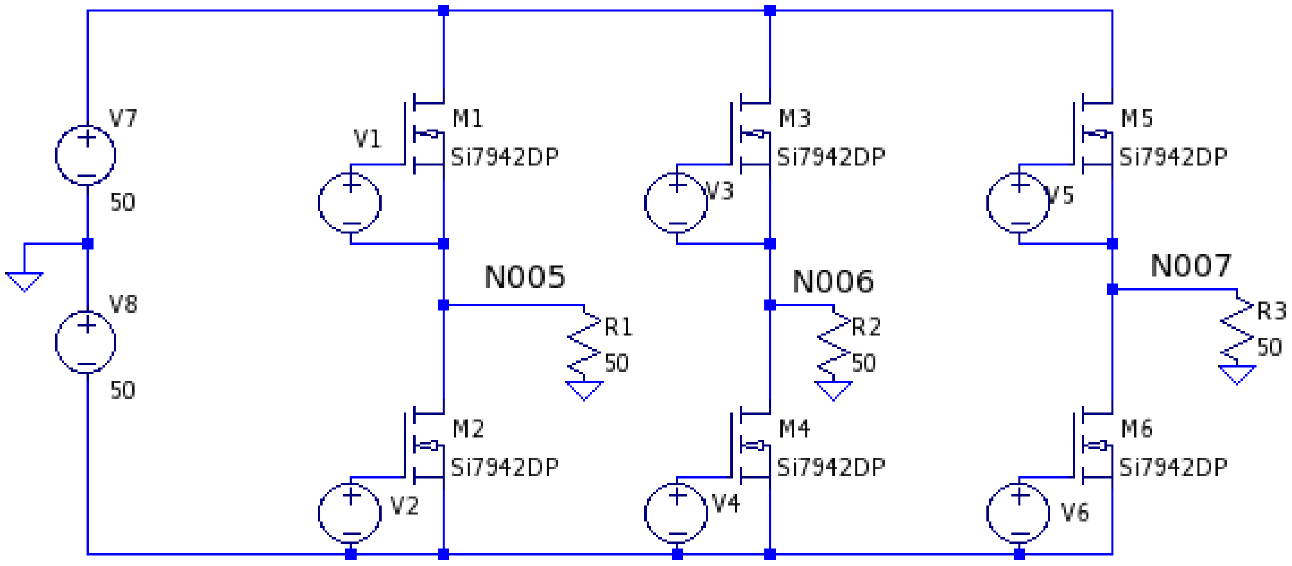


Figure 10. Inverter for waveforms in Figure 11

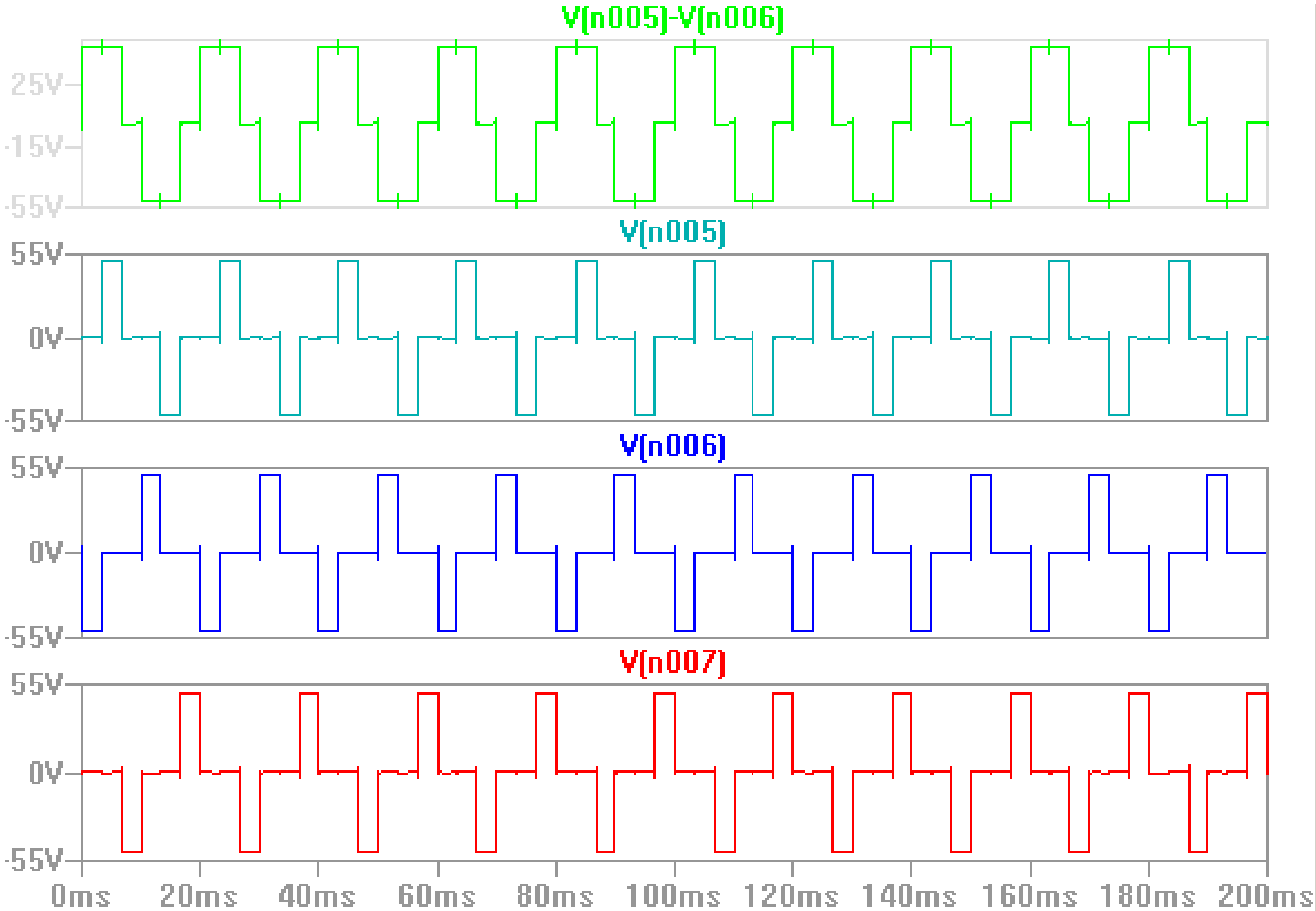


Figure 11. 3 phase quasi-square wave inverter output

Just as with the single phase quasi-square inverter, this output is also rich in low frequency (odd) harmonics.

The trouble with harmonics

Harmonics cause increased line loss, interfere with other devices, additional stresses (due to resonance) on attached devices. Figure 12 shows three phase waveforms and their associated 3rd, 5th and 7th harmonics.

The third order harmonics are in-phase, thus a 3-phase system may exhibit large currents in the neutral wire in the presence of significant 3rd harmonics. The fifth appear to be in reverse order to the fundamental components. The effect of this is to retard rotating machines (take away torque). In summary, the overall effect of harmonics is to reduce the efficiency of the transmission network and attached loads.

- CE regulations limit the amount of harmonics that a device can output.
  The European standard EN61000-3-2 defines emission levels for small appliances (domestic/light industrial etc.) Useful paper:
  http://www.yorkemc.co.uk/conferences/emcYork2003/potm/2004-01_SMPS-and-SELC.pdf

- Power factor: definition
  Power factor is defined as the ratio of real power to apparent power. A power factor of unity implies that 100% of the current drawn is contributing to real power. More formally, power factor may be defined as the cosine of the phase angle between the supply voltage and current drawn. Power factor may be “leading” (current phase is ahead of voltage phase) or lagging (current lags voltage). In electrical power courses, lagging power factor is usually associated with inductive loads (which may well linear you should note) while leading power factor is usually associated with capacitive (linear)loads. Non-linear loads also have an associated power factor – the definition in the same in this case: ratio of real power to apparent power. Harmonics that do not contribute to the load power thus represent an unnecessary burden on the electricity supplier (and a loss to the consumer).

Exercise: Using matlab, octave or similar, construct several cycles (at least 10) of quasi-square wave signal and note the harmonic content. How do the harmonics and fundamental magnitudes change when the central pulse width is changed?

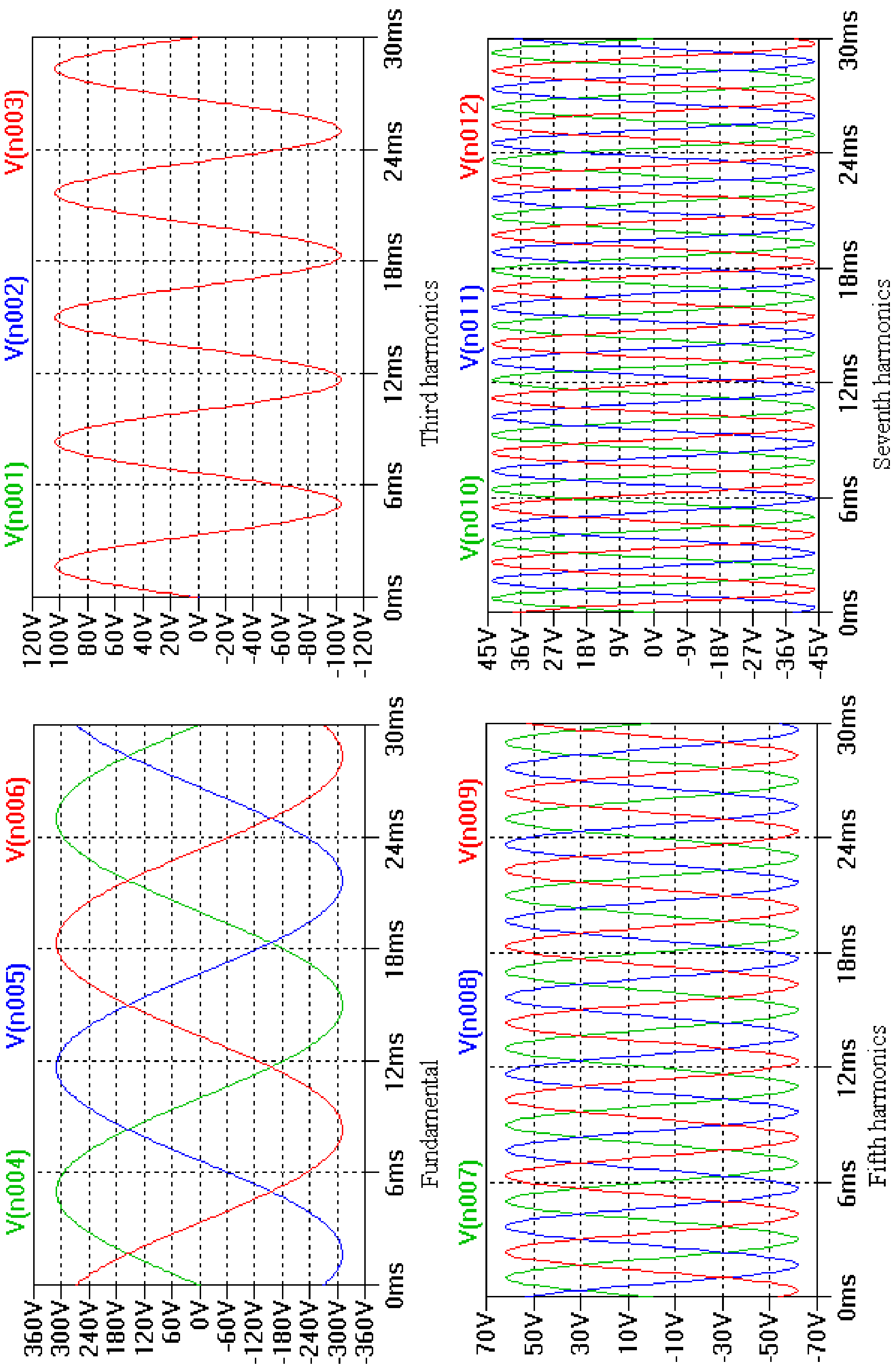


Figure 12. Phase relationships between 1st, 3rd, 5th and 7th harmonics. Note the thirds are all in-phase while the fifths are in reverse order to the fundamentals.

Sinusoidal Pulse Width Modulation.

Sinusoidal PWM helps to reduce the magnitude of low frequency harmonics. The process works as follows (can be done in analogue/digital hardware or software). A high frequency triangle or sawtooth waveform is compared with a low frequency sine wave. The triangle/sawtooth waveform is commonly referred to as the *carrier wave* ; the low frequency sine wave is called the *modulating wave*. See Figure 13.

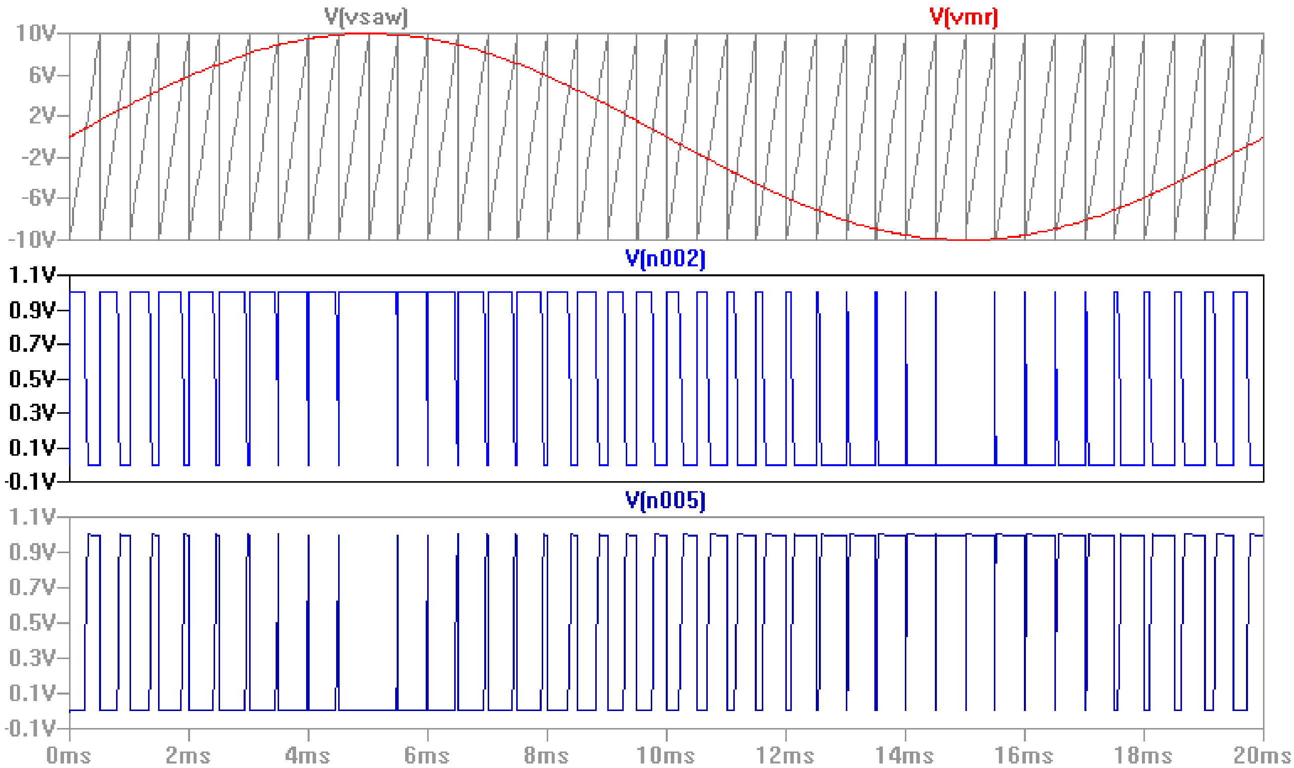


Figure 13. Sinusoidal PWM

When the modulating wave is greater than the carrier wave, one diagonal pair of IGBT's in the (single phase) inverter is turned on. When it is less, the other pair are turned on. The resultant inverter output voltage and current waveforms are shown in Figure 14.

Two ratios are talked about when it comes to Sinusoidal PWM (SPWM). The Amplitude Modulation Index (***ma***) and the Frequency Modulation index ***mf***. These are as follows:

$$ma = \frac{Magnitude of\ Modulating\ wave}{Magnitude\ of\ Carrier\ wave}$$

$$mf = \frac{Frequency\ of\ Carrier\ wave}{Frequency\ of\ Modulating\ wave}$$

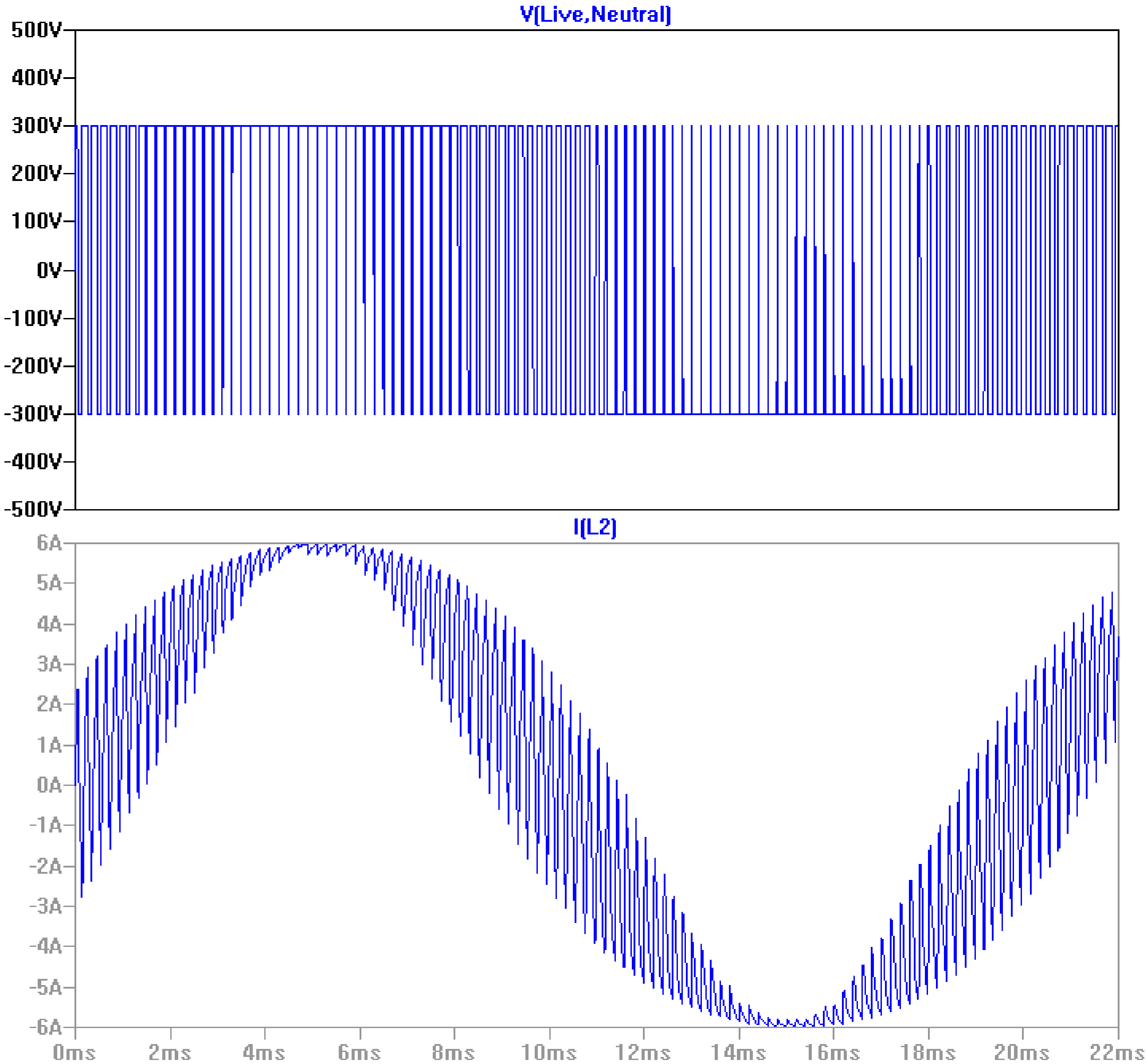


Figure 14. Sinusoidal PWM outputs for a single phase RL load.

Higher values of ***mf*** push the harmonic content further up the spectrum making it easier to filter. Higher values of **ma** lead to higher amplitude fundamental output voltage component (up to a point) however if the value of ***ma*** is significantly greater than 1 then the output tends to be more quasi-square square in nature leading to large low frequency harmonics again.

Note: The modulating wave frequency can be changed while leaving the carrier frequency unchanged. This has two effects. First it means that mf varies as the modulating wave changes (which may or may not cause problems). Second it means that the harmonics are clustered around the same frequency (the carrier frequency) regardless of fundamental frequency. This can help output filtering.

Exercise: Using matlab or octave construct at least 10 cycles of a sinusoidal PWM waveform and note the way the harmonics vary with ma and mf.

Inverter Applications 1: Variable Speed Drives

Figure 15. Variable speed drives

The three phase “squirrel cage” induction motor is extremely reliable, cheap to produce and has a high power density. They are widely used in industry in all sorts of applications. Their operation is as follows. A set of windings in the motor casing (stator) is driven from a three phase supply. In the simplest case there are 3 windings (one per phase). These windings are displaced 120 degrees from one another and they are energised in sequence by the AC mains. The net effect of this is to create a magnetic field that appears to rotate around the motor.

The squirrel cage rotor is simply a set of conducting bars shorted together at either end of the rotor. The bars may be shaped in particular ways to improve the torque behaviour of the machine. At startup, when the AC mains is applied to the stator, the rotor is initially stationary. From the rotor's perspective, the magnetic field appears to rotate rapidly around it inducing currents in the rotor conductors. These currents in turn lead to a force on the rotor which will cause it to rotate in the same direction as the field. Eventually the rotor will almost match the speed of the magnetic field (it can't quite match it because then there would be no induced current in the rotor).

Increasing the voltage applied to the motor simply increases the current flow in the windings which in turn strengthens the magnetic field producing higher torque.

The only way of controlling the speed of the induction machine (at least over a wide range) is to vary the frequency of the AC supply. This varies the speed of rotation of the magnetic field and hence the rotor. This is where inverters come in. Three phase inverters (Electronic Motor Drives or Variable Speed Drives (VSD's)) in this sort of application are now so cheap that some manufacturers are even building them in to the motors themselves.

The (per-phase) equivalent circuit of an induction motor consists mostly of an inductance representing the inductance of the stator and a resistance representing the mechanical power delivered by the machine. The impedance of the inductance varies with frequency; halve the frequency and you halve the impedance. If the frequency is low it is possible to deliver too much current to the machine which may damage it. To avoid this, induction motor drives usually vary the motor voltage in tandem with the frequency i.e. the ration of V/f is kept constant. There are exceptions to this. If the motor is driving a mechanical load that is difficult to start moving (high “stiction”) a temporary boost of torque can be supplied by increasing the motor voltage. This is referred to as “*voltage boost*”.

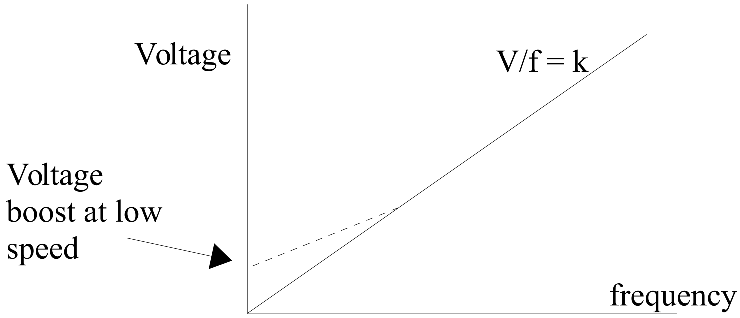


Figure 16. Voltage boost for induction motor drives.

Induction motor drives also incorporate other useful features:

Soft start: If an induction motor is started “Direct On Line” i.e. a contactor is closed to start it then a high starting current will flow (large rotor currents will be induced – similar to a transformer whose secondary is shorted). Not only is this undesirable, it is simply not permitted if the machine is over a certain size. People have used star-delta and/or resistance starters to avoid this problem in the past however the electronic motor drive can avoid this simply by slowly ramping up the output voltage and frequency.

DC Injection braking: An induction motor can be stopped quickly if a stationary (i.e. DC) magnetic field is applied. Many motor drives incorporate this (and even regenerative braking) as a feature.

Motor reversal: Motor direction can be switched.

Jogging: Some drives include a feature that allows an operator nudge a machine forwards or backwards. This can be useful when servicing the motor or the load to which it is attached.

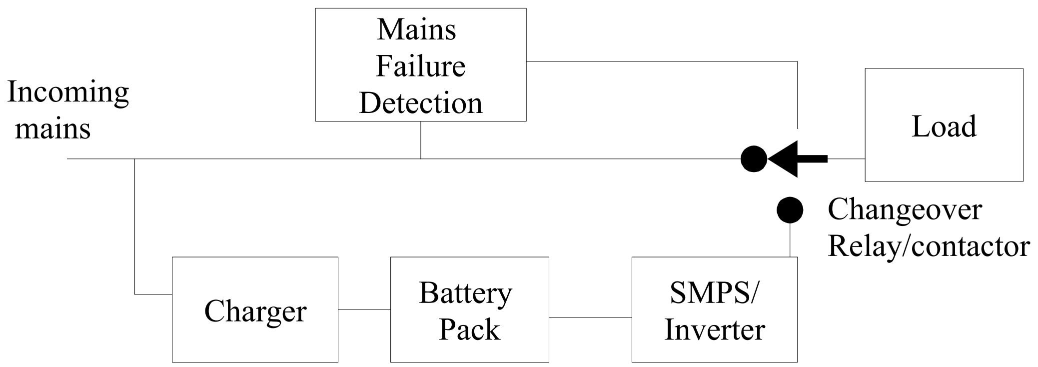
SCADA integration: Motor drives typically come with a current loop (4-20mA) or control voltage interface allowing them to be controlled by PLC's or other SCADA/computer systems.

Applications 2: UPS's

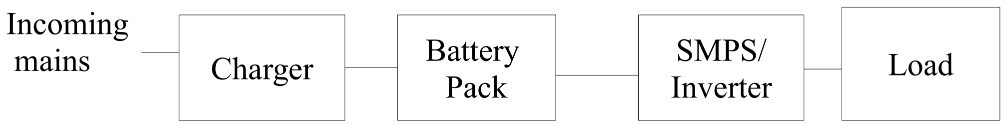
Uninterruptible power supplies protect systems against loss of power. They are commonly used in conjunction with computers, medical equipment and critical control equipment. The idea is that the UPS maintains power to the load for sufficient time to either allow the mains return or a backup generator to start up. Companies such as APC produce UPS's that range from 300VA to 1.6MVA. Static UPS's can use batteries or hydrogen fuel cells to store energy. Some UPS's make use of large flywheels to store energy.

UPS's can be connected in an offline manner (in parallel with the AC supply) or in an online manner (in series with the AC supply).

An offline (or standby) UPS is outlined below. The mains ordinarily directly feeds the load. The UPS maintains the charge on a battery back while the mains is available. If the mains fails, a monitoring circuit detects this and switches the load over to the inverter output of the UPS. This sort of supply is commonly used in small computer UPS systems. There is a momentary loss of power (1 or 2 cycles) during the changeover however computer power supplies have enough internal capacitance to ride through this.



An online UPS is outlined below. In this case, the load is always supplied by the inverter in the UPS.



When the mains fails, UPS's typically supply the load for only a few minutes. These few minutes can allow a standby generator to start up or allow systems to shut down in a controlled manner. UPS's for computers often (just about always) have a communications port that is connected to the computers informing them of their status. In the event of a power loss, software can respond to a message from the UPS and shut down a system.

The output waveshape from UPS inverters can be simply a quasi square wave whose edges have been “softened” by an LC filter or they can be as good as (or better than) the normal mains. The needs of the application will dictate this.
Question: A UPS has a 12V battery pack rated at 45Ah. Assuming a conversion efficient of 80% how long can the UPS maintain a 1kW load?

Applications 3: Grid connections from renewable resources

Some renewable energy sources such as wind and wave are quite variable in nature. This causes problems when they need to export power to a large grid as they have to synchronize output voltage and frequency with that grid. Induction generators can be connected directly to the grid if their excitation and rotor pitch is controlled carefully. Other generators may be connected indirectly. In these cases, the generator output is first rectified to DC, stepped up using a boost converter and then inverted back to a fixed frequency, fixed voltage AC.

We will come back to this in the next section of these notes.