



The VOLTECH HANDBOOK of PWM MOTOR DRIVES

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1. Introduction

Three-phase AC motors have been the work-horse of industry since the earliest days of electrical engineering. They are reliable, efficient, cost effective, and need little or no maintenance. In addition, AC motors such as induction and reluctance motors need no electrical connection to the rotor so can easily be made flameproof for use in hazardous environments such as in mines.

The main disadvantage of AC motors is that, when supplied directly from the three-phase AC line, they are essentially a constant speed drive. This is because the fixed frequency supply to the stator windings creates a magnetic field rotating at constant speed. This rotating magnetic field turns the rotor at nearly the same speed - the difference in speed is known as motor slip.

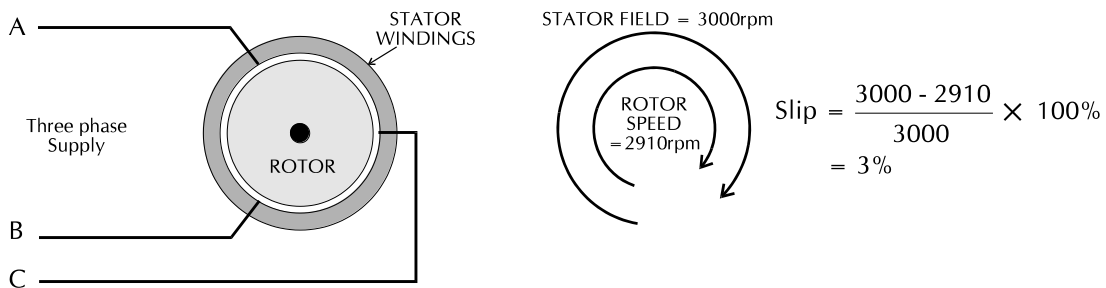


Figure 1

For efficient operation the motor works with a slip of just a few percent, i.e. the motor operates at constant speed.

Early attempts to provide an adjustable speed drive on an AC motor were by reducing the applied AC voltage using variable resistors or by an autotransformer in the AC line: -

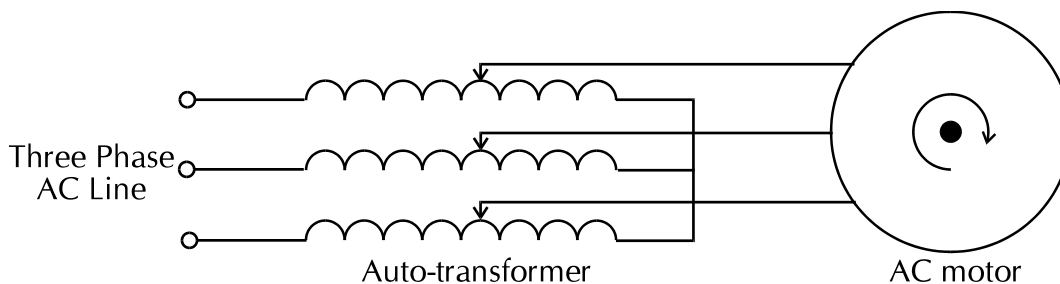


Figure 2

As the applied voltage is reduced, the motor provides less torque, so the motor slows down. Provided that the torque required by the motor is less at lower speeds, such as for a pump or fan, then this technique provides a variable speed drive. Even so, when the motor is operating at reduced speed, there is a very large slip between stator and rotor and the motor will be operating at much reduced efficiency. In addition, loads that require full torque at reduced speed cannot use this method of speed control.

For these reasons industrial variable speed drives have been dominated by DC motor drives. The commutator in the DC motor acts to provide a rotating field that is matched to the speed of rotation, so that speed control at full torque can be achieved merely by adjustment of the applied DC voltage. DC motors, however, are larger than AC motors, are more expensive, need much more maintenance, and are difficult to use in hazardous environments. They do however produce an excellent variable speed drive.

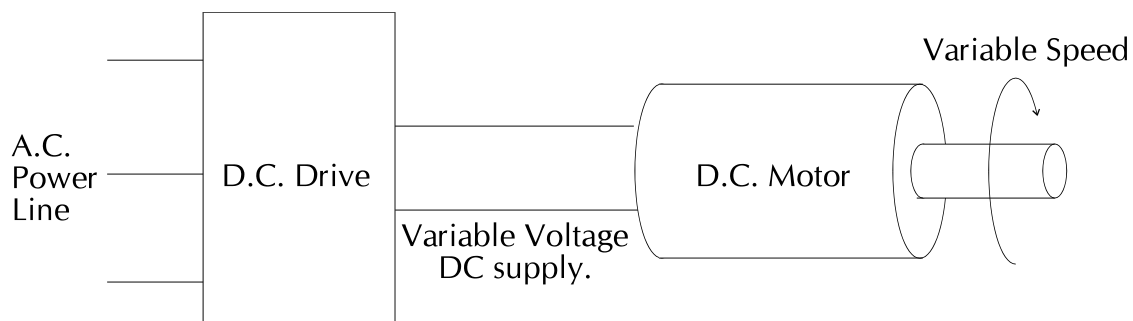


Figure 3

In order to provide proper speed control of an AC motor, it is necessary to supply the motor with a three-phase supply of which both the voltage and the frequency can be varied. Such a supply will create a variable speed-rotating field in the stator that will allow the rotor to rotate at the required speed with low slip. This AC motor drive can efficiently provide full torque from zero speed to full speed, can over speed if necessary, and can, by changing phase rotation, easily provide bi-directional operation of the motor. A drive with these characteristics is known as a PWM (Pulse Width Modulated) motor drive.

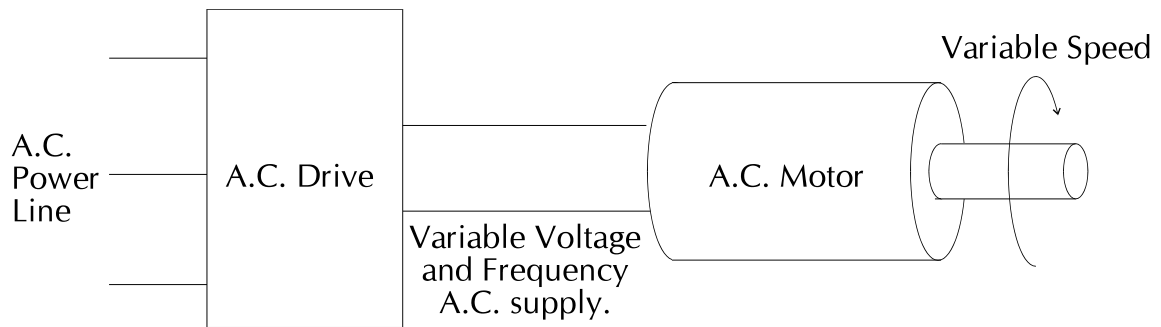


Figure 4

Although the principles of PWM drives has been understood for some years, advances in the technology of power semi-conductors, control electronics, and microprocessors has greatly stimulated the use of such drives. This has been further accelerated by the use of vector control methods, which give the AC drive the capability and flexibility of a full DC motor drive. PWM motor drives have become the dominant method of variable speed motor control, and are being used not only in industry, but in applications as diverse as electric vehicles and domestic air conditioners.

PWM drives produce complex waveforms, both on their output to the motor, and also in the electrical supply to the drive. This Application Note is designed to simplify electrical measurements on these drives.

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2. Principles of PWM motor drives

A block diagram of the essential elements of a PWM motor drive is shown in figure 5.

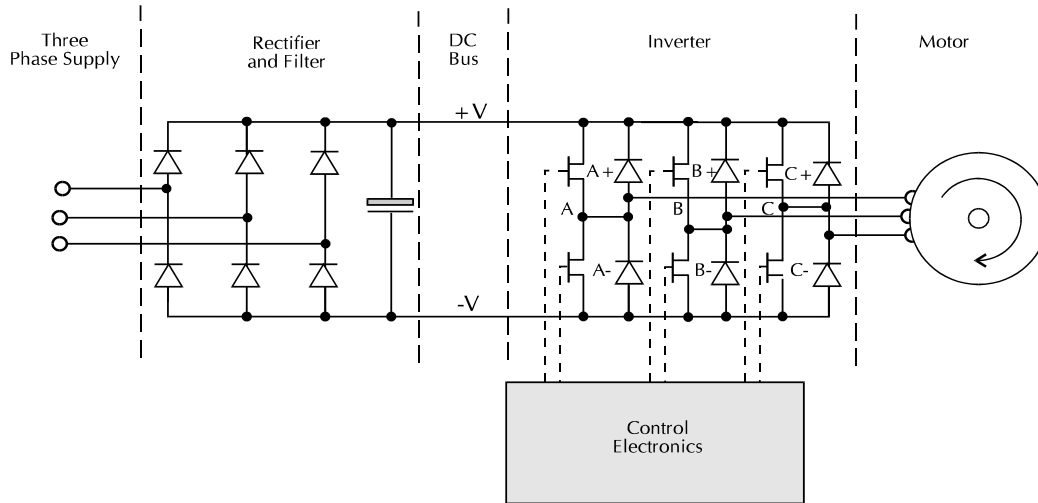


Figure 5

The three-phase supply is rectified and filtered to produce a dc bus, which powers the inverter section of the drive. The inverter consists of three pairs of semiconductor switches (MOSFET, GTO, power transistors, IGBT etc, with associated diodes). Each pair of switches provides the power output for one phase of the motor.

Within each pair of semi-conductor switches, (for example A), the output is connected either to +V via switch A⁺ and its anti-parallel diode, or to -V via A⁻ and its diode. In this way there is always a bi-directional path for current flow to the motor windings for both positive and negative output voltages: -

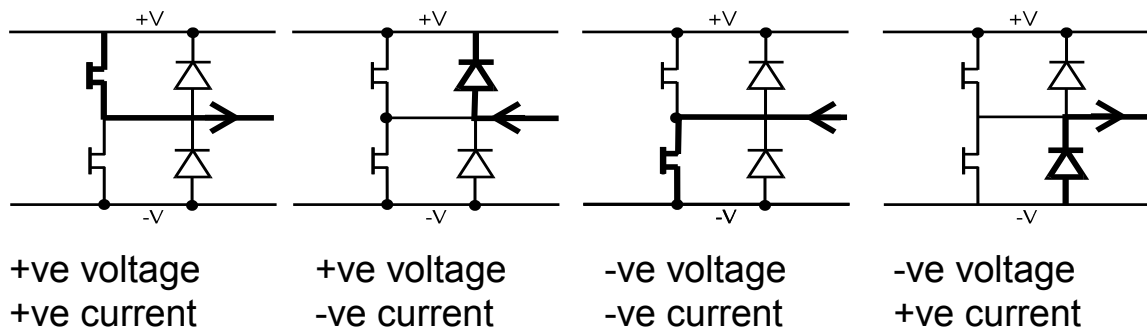


Figure 6

Each pair of semiconductor switches is driven by the control electronics so as to generate a high frequency square wave carrier pulse waveform at each of the phase outputs: -

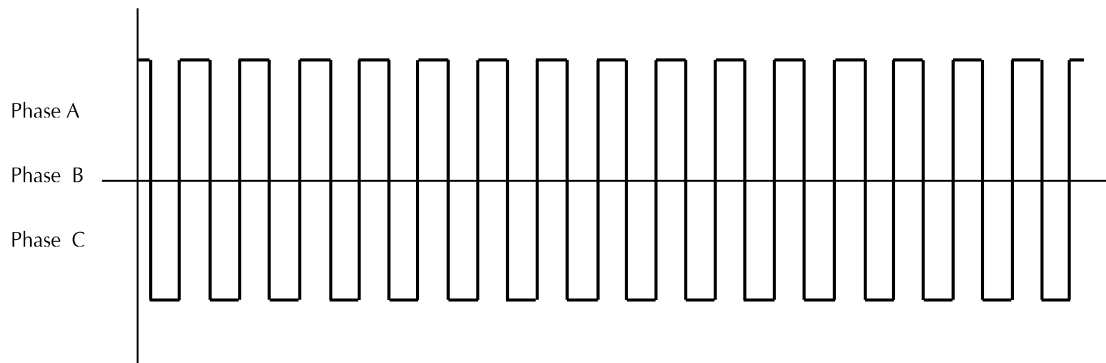


Figure 7

As the carrier is identical on all three phases, the net voltage appearing across any phase of the motor windings due to the carrier alone will be zero e.g.: -

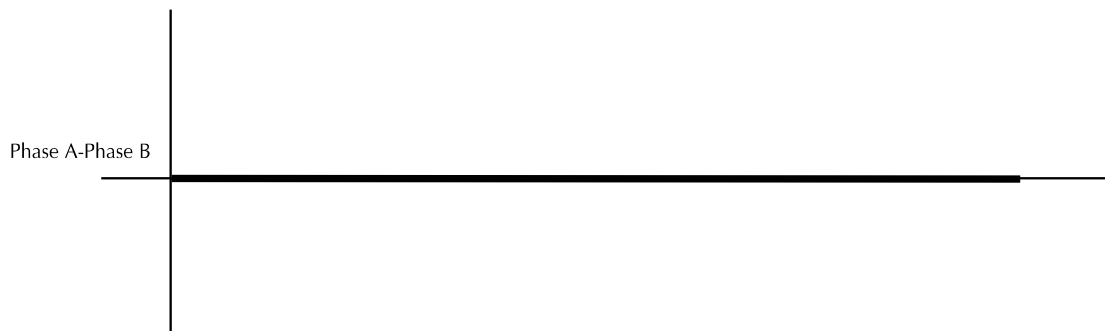


Figure 8

The carrier is said to be un-modulated, and no drive power is applied to the motor.

In order to drive the motor, the control electronics generates three low frequency sine waves, 120° apart, which modulate the carrier pulses to each pair of switches. The width of positive and negative pulse within each carrier cycle is modulated according to the amplitude of the low frequency sine waveform of that phase. For example: -

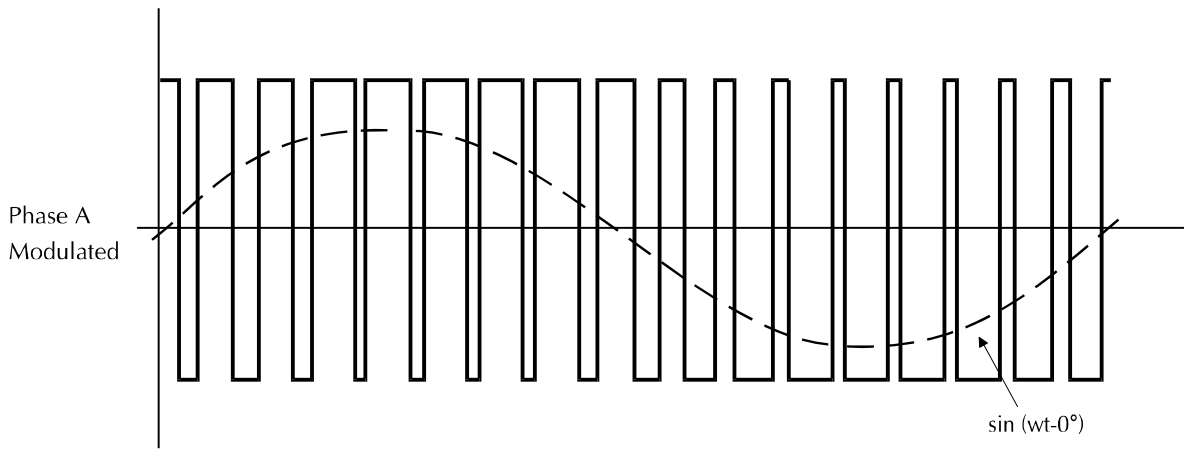


Figure 9a

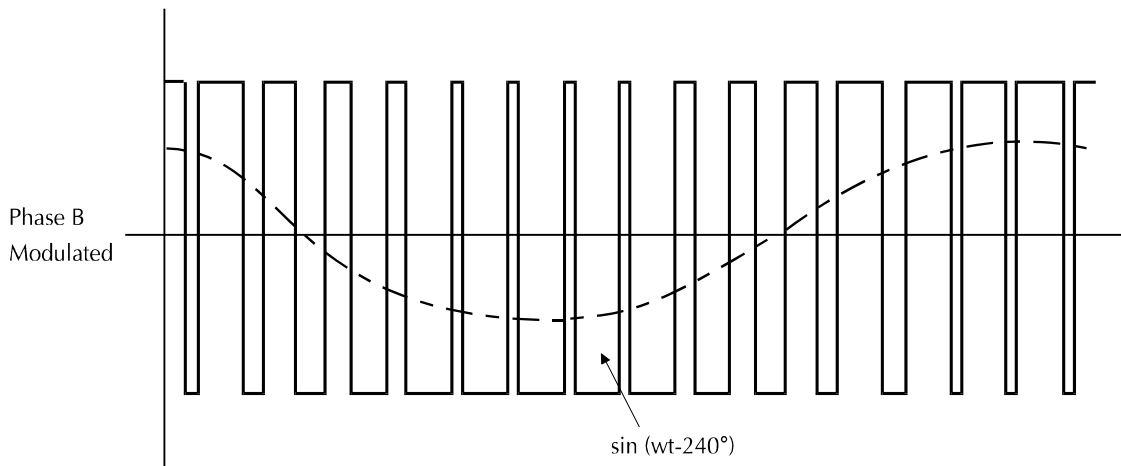


Figure 9b

The voltage appearing across one phase of the motor winding is therefore: -

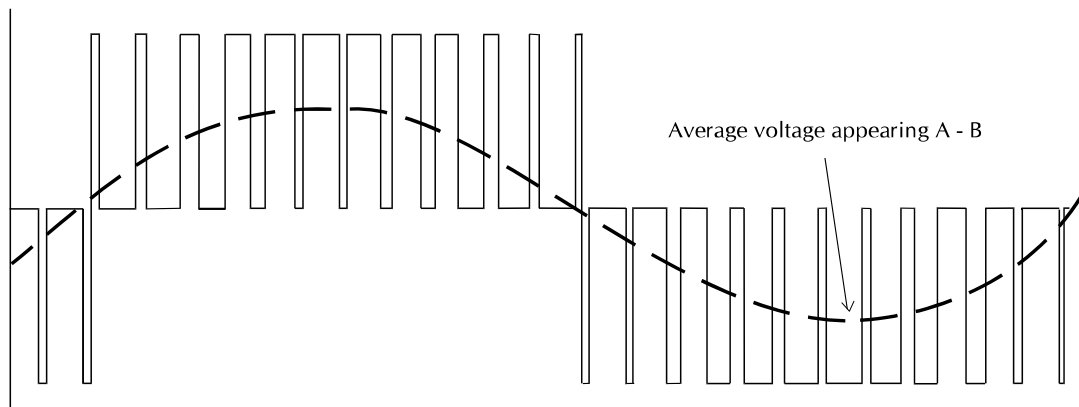


Figure 10

It can be seen that the average voltage presented to the motor winding is approximately sinusoidal. The two other phases of the motor winding will have similar average voltages spaced 120° apart.

It is clear that although the pulse-width-modulated voltage waveform applied to a motor winding contains a component at the required frequency, it also contains a number of other, higher frequency components. For example, the phase-to-phase waveform in figure10 has a frequency spectrum as follows:

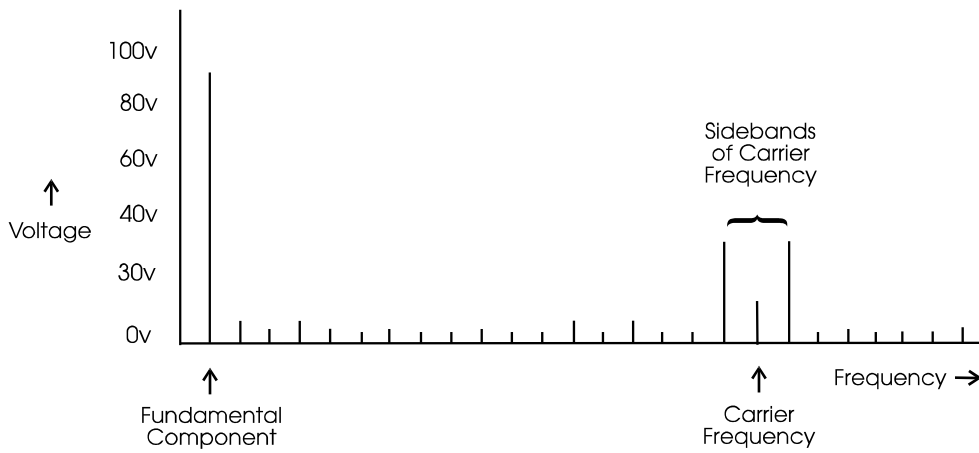


Figure 11

Fortunately, to a large extent, the motor appears as an inductor to the output voltages of the inverter. As an inductor has higher impedances to higher frequencies, most of the current drawn by the motor is due to the lower frequency components in the PWM output wave-shape. This results in the current drawn by the motor being approximately sinusoidal in shape.

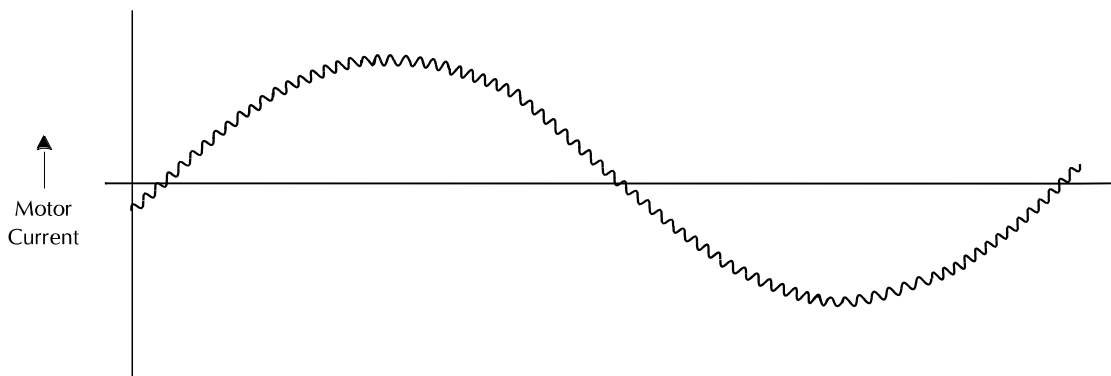


Figure 12

By controlling the amplitude and frequency of the modulating waveforms, the PWM drive can output to the motor a three-phase supply at the necessary voltage and frequency to drive the motor at any required speed.

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3. Characteristics of PWM motor drive

3.1 Voltage-frequency relationship

The characteristics of a PWM motor drive can best be understood by considering a simplified equivalent circuit of one motor phase (figure 13):

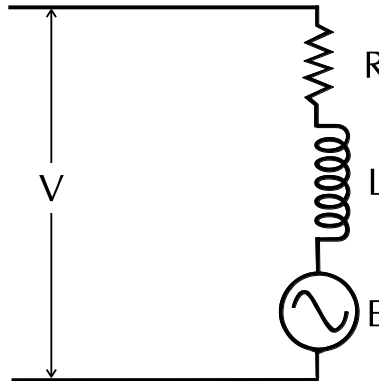


Figure 13

In this circuit, R and L represent the resistance and inductance of the motor as seen by the supply, and E represents the back EMF produced by motor rotation.

The magnitude of the back EMF, and its frequency, is proportional to the motor speed. The PWM drive must therefore adjust both the voltage and the frequency to adjust the speed, with an output voltage slightly higher than the back EMF to force current through the impedance of R and L. In fact the drive electronics needs to produce a voltage/frequency characteristics as shown in figure 14. The offset in this characteristic is to overcome the voltage drop in this impedance and allow the drive to deliver the required current even at low or zero speed.

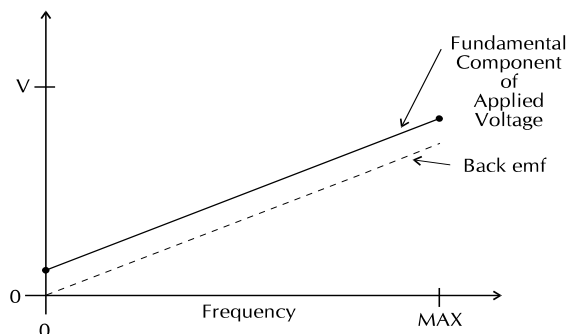


Figure 14

3.2 Choice of Carrier frequencies

Most PWM drives operate with a fixed carrier frequency that is several times higher than the highest output frequency that is to be used. As industrial drives operate with an output frequency from a few Hertz up to about 100Hz, they use a carrier frequency in the range of 2kHz upwards.

As power semiconductors improve, the trend is to increase carrier frequencies up to ultrasonic frequencies (18kHz+), and beyond, but this brings both advantages and disadvantages: -

High Carrier Frequencies	
Advantages	Disadvantages
Lower losses in motor (current more sinusoidal) No audible noise due to carrier	Higher switching losses in inverter Potential for more radiated radio frequency noise.

The choice of carrier frequency is therefore a compromise, and careful measurements must be made on both the input and the output of the drive to make the optimum choice.

3.3 Effect of harmonic and carrier frequency components in the PWM output

It was shown earlier, that although the PWM output voltage contains a large number of frequency components other than the fundamental (or wanted component) that these components are generally of higher frequency and suppressed by the inductance of the motor winding.

In practice, as shown by the equivalent circuit of figure 13, the motor is not a simple inductor, but is dominated by the back EMF.

Unfortunately, as the back EMF generated by the motor is essentially a sinusoidal voltage at the fundamental frequency, it provides no opposition to the flow of current at the harmonic and higher frequencies. For this reason these currents are larger when compared to the fundamental than would be the case if the motor were a pure inductor.

It is important therefore, that the strategy employed in the modulation of the carrier frequency is such as to produce in the windings a current that is as sinusoidal as possible. In particular, care must be taken to minimize the level of low order harmonic voltages produced, as the impedance of the motor to these voltages will be very low. In practice then the drive produces in the motor: -

- a). A 'wanted' component of current at the fundamental frequency.
- b). 'Unwanted' components of current at frequencies that are multiples of the fundamental frequency (these are harmonics) and also components of current at frequencies related to the carrier frequency.

The 'unwanted' components in the motor current have two effects on the motor: -

1. Components of current other than the fundamental represent additional currents in the motor stator and rotor windings, creating additional heat and reducing motor efficiency.
2. The 'unwanted' components create magnetic fields in the stator that may have negative or zero phase sequence, producing negative or braking torque. This can substantially reduce the amount of power available from the motor.

The effects of these unwanted components on the operation of the motor can be expressed by measurements of the fundamental and total output power of the inverter, by harmonic analysis of the voltage and current waveforms, and by torque/speed measurements on the motor.

The only useful power delivered to the motor is at the fundamental frequency - any power associated with the harmonics or carrier frequency does not contribute to the useful work done by the motor. The most efficient PWM drives are those that not only minimize losses in the converter, but also generate the most pure current waveforms to minimize power and torque losses in the motor itself.

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4. Measurements required on PWM motor drives

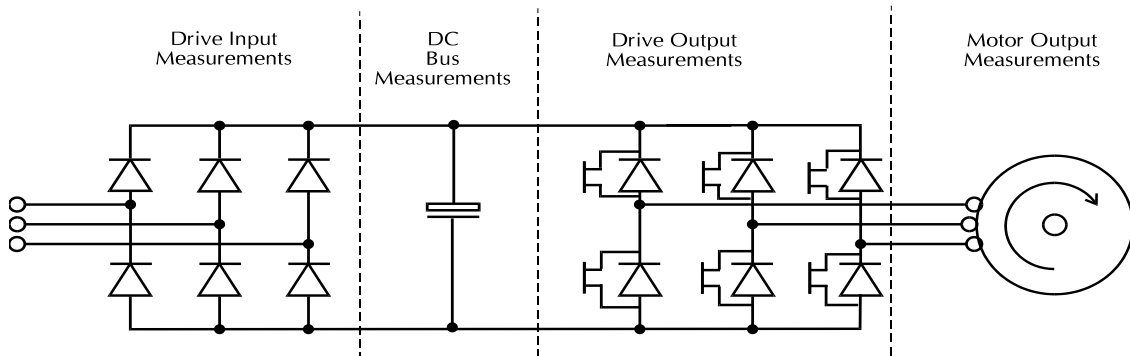


Figure 15

The following are examples of useful measurements to be made on PWM motor drives: -

Drive Section	Parameters	App Note Section
Motor Output Measurements	Speed, Torque, Shaft Power	Section 5
Drive Output Measurements	Total Output Power & Power Factor Fundamental Output Power & P F RMS Output Voltage and Current Fundamental Output Voltage and Current Harmonic voltages, currents & powers. Output Frequency	Section 6
Drive DC Bus Measurements	DC Bus Voltage, Current and Power	Section 7
Drive Input Measurements	Input Voltage and Current Input Power and Power Factor Input VA and VARs Input Harmonic Currents (including checking to harmonic specifications such as IEC61000-2-2)	Section 8
Efficiency Measurements	Efficiency of each section of PWM drive, motor efficiency and overall efficiency	Section 9
Measurements Under Dynamic Load Conditions	Real time analog outputs representing voltage, current, watts and power factor of drive output.	Section 10

The following sections 5 – 10 show measurements and screen shots from the PM6000 VPAS software (Voltech Part Number: 28-312). A 30 day trial of the software can be downloaded from Voltech's web site (www.voltech.com). To install this software double click onto PM6VPAS.exe (this is a self extracting auto install file).

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5. Motor Output Measurements

Motor output measurements can be made by installing torque and speed transducers on the output shaft of the motor: -

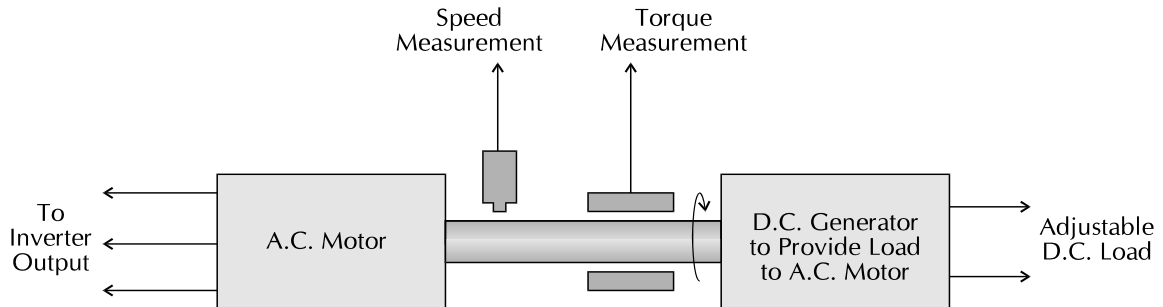


Figure 16

5.1 Sensors

Torque and Speed transducers produce an electrical signal that is proportional to the motor speed and the motor torque. By measuring these the motor's output power or mechanical power can be determined.

5.2 Torque

5.2.1 What is Torque?

Torque is a force that tends to rotate or turn things. You generate a torque any time you apply a force using a spanner or wrench. Tightening the nuts on the wheels of your car is a good example.

When you use a spanner or wrench, you apply a force to the handle. This force creates a torque on the nut, which tends to turn the nut. English units of torque are pound-inches or pound-feet; the SI unit is the Newton-meter. Notice that the torque units contain a distance and a force. To calculate the torque, you just multiply the force by the distance from the center. In the case of the nuts, if the spanner or wrench is a foot long, and you put 200 pounds of force on it, you are generating 200 pound-feet of torque. If you use a 2-foot wrench, you only need to put 100 pounds of force on it to generate the same torque.

The torque of a motor is the rotary force produced on its output shaft, it is a twisting force that rotates or turns an object, like a wheel. The motor torque is measured in Newton-meters (Nm) or Foot-Lbs (1 Foot-Lb = 1.3558Nm). Torque ratings vary from less than one Nm for small motors, to several thousand Nm for large motors.

5.2.2 Measuring Torque

Torque can be measured by rotating strain gauges as well as by stationary proximity, magnetostrictive and magnetoelastic sensors. All are temperature sensitive. Rotary sensors must be mounted on the shaft, which may not always be possible because of space limitations.

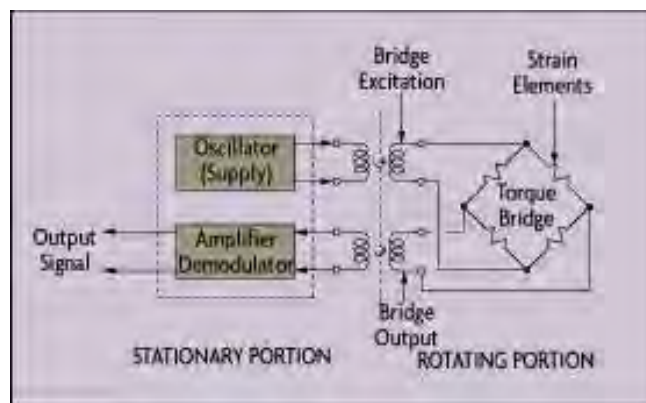


Figure 17

A strain gauge can be installed directly on a shaft. Since the shaft is rotating, the torque sensor can be connected to its power source and signal conditioning electronics via a slip ring. The strain gauge can also be connected via a transformer, eliminating the need for high maintenance slip rings. The excitation voltage for the strain gauge is inductively coupled, and the strain gauge output is converted to a modulated pulse frequency (Figure 17).

The maximum speed of such an arrangement is 15,000 rpm. Strain gauges also can be mounted on stationary support members or on the housing itself. These "reaction" sensors measure the torque that is transferred by the shaft to the restraining elements. The resultant reading is not completely accurate, as it disregards the inertia of the motor.

Alternatively torque transducers can be purchased to suit the motor that they are intended for as they are sold with minimum and maximum Newton-meters (Nm). Many of these transducers have two outputs, one for torque and one for speed and are available as non-rotary (no attachment to motor shaft) and rotary sensors (attached to motor shaft).

5.2.3 Using the PM6000 VPAS Software to Measure Torque.

Note: See section

5.5 USB-6009 Connections, for information on making analog measurements with a PM6000.

Figure 18 shows the USB-6009 set-up via the PM6000 VPAS software. The sensor used was a DC 0 - 10V output scaling with $0.4V = 1Nm$.



Figure 18

Figure 19 shows the output of the torque set up.

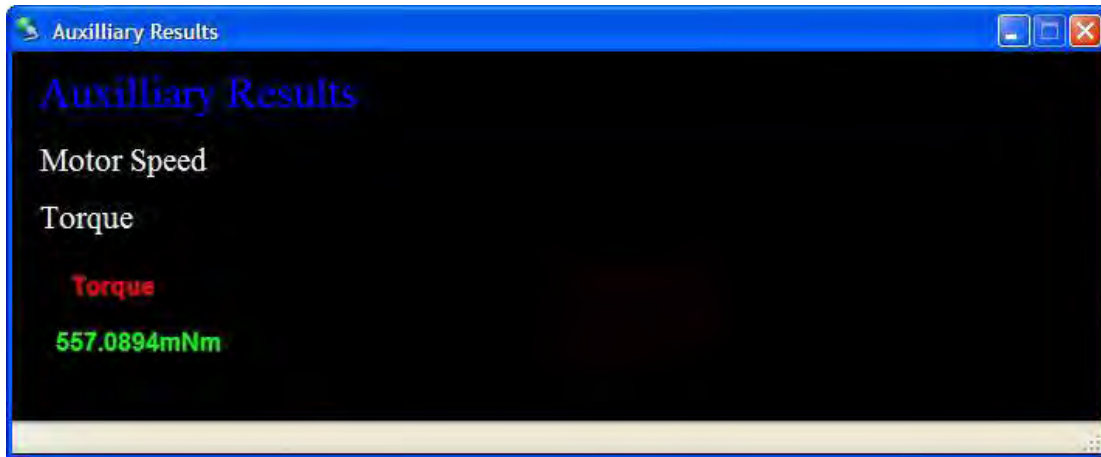


Figure 19

5.3 Speed

5.3.1 What is Speed?

Motor speed is commonly described as revolutions per minute (abbreviated **rpm**, **RPM**) and is a unit of frequency i.e. the number of full rotations completed in one minute around a fixed axis.

5.3.2 Measuring Speed

A speed sensors output is sometimes an analog output proportional to speed, but more commonly the output is TTL pulse produced by a disc on the motor shaft. The holes are aligned with a light source and photosensitive diode or transistor (i.e. on, off producing a positive and negative going TTL pulse or square wave as the shaft rotates). By measuring the frequency of the TTL signal from the rotating disc, and applying a scaling factor, the motor speed, in RPM, can be determined.

For example, if the rotating disc produces n pulses per revolution, the RPM can be calculated as:

$$\text{Pulses per second} \times \frac{60}{n}$$

5.3.3 Using the PM6000 VPAS Software to Measure Speed.

Note: See section

5.5 USB-6009 Connections, for information on making analog measurements with a PM6000.

Figure 20 shows the USB-6009 set-up via the PM6VPAS software. The rotating disc used had 18 holes and so a scaling factor of 60/18 or 3.333 was used.



Figure 20

Figure 21 shows the output of the speed set up.

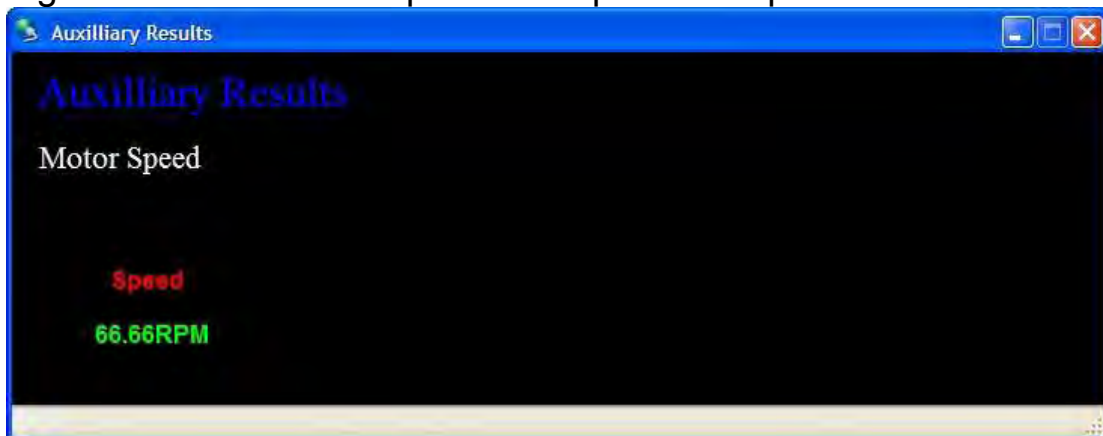


Figure 21

5.4 Motor Output Power

The speed and torque transducers produce electrical signals proportional to the motor speed and motor torque. From these measurements the motor output power can be calculated.

$$\begin{aligned}\text{Motor Output Power (W)} &= \text{Torque (Nm)} \times \text{Speed (radians/sec)} \\ &= \text{Torque (Nm)} \times \text{Speed (RPM)} \times \pi/30\end{aligned}$$

Note :

$$1 \text{ Lb-ft} = 1.3558 \text{ Nm}$$

$$1 \text{ HP} = 745.7 \text{ W}$$

5.5 USB-6009 Connections

The USB-6009 is a multi function I/O providing an interface with the PM6000 alongside PC software called PM6VPAS, which allows the correct measurements of any analog input within the limitations of the device. These can include torque, speed, mechanical power and efficiency. The output of each sensor is either an analog voltage or a TTL pulse. THE USB-6009 caters for both types of signal.

If your speed sensor output is a TTL pulse then connect it to pins 29 and 32. If your speed sensors output is an analog voltage (+/- 20V max.) then connect your sensor to CH1's differential input, pins 2 and 3.

Your torque sensor will be either differential or non-differential therefore connect this sensor to CH2 pins 4 and 5 or pins 5 and 6 (+/- 20V max.).

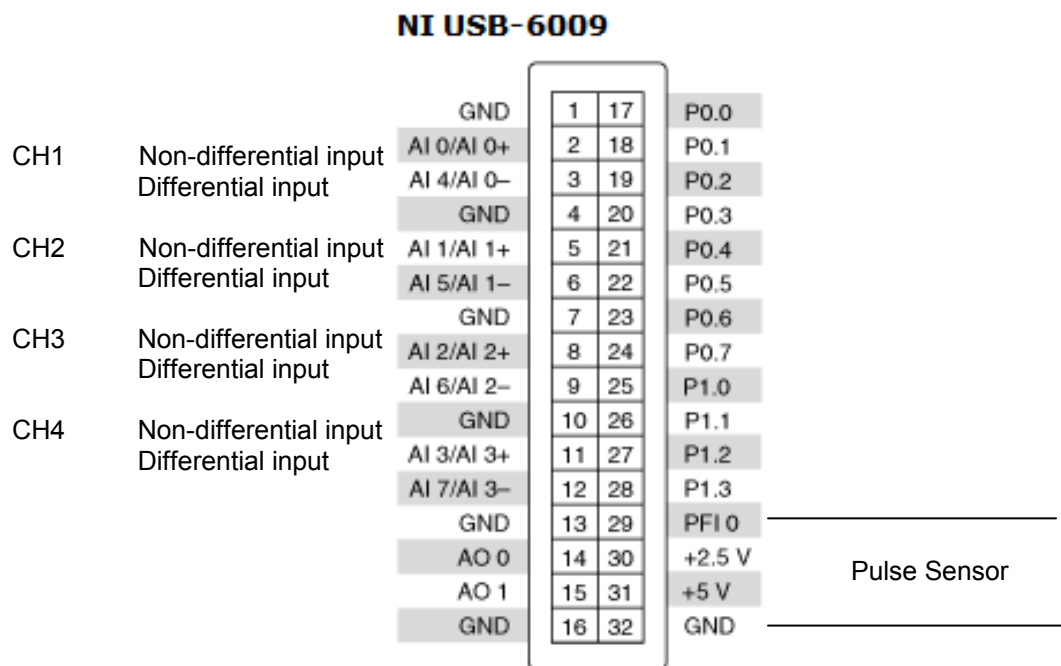


Figure 22

If you set channel 1 on the PM6000 VPAS to be a pulse input, then you cannot use channel 1 on the USB-6009 as an input. The same applies for channels 2, 3 and 4.

5.6 Mechanical Power

The power of a motor is the product of its torque and speed. The PM6000 VPAS software computes the motor power using the formula in section 5.4 to display the power of the motor output as shown in figures 23 and 24.

Figure 23 shows the USB-6009 set-up via the PM6000 VPAS software. The sensor used was as in Torque (section 5.2) and Speed (section 5.3). Note the scaling factor on the mechanical power reading is $\pi/30$.



Figure 23

Figure 24 shows mechanical power, in Watts.



Figure 24

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6. Drive Output Measurements

The output waveform of a PWM drive is very complex, consisting of a mixture of high frequency components due to the carrier and components at low frequency due to the fundamental.

The problem this poses for most power analyzers is that they can either measure at high frequencies, in which case low frequency information in the waveform is lost; or else they filter the PWM waveform to measure at low frequencies, in which case high frequency data is lost.

The difficulty occurs because the waveform is being modulated at low frequency. High frequency measurements, such as total rms voltage, total power etc, must therefore be made at high frequency but over an integral number of cycles of the low frequency component in the output waveform.

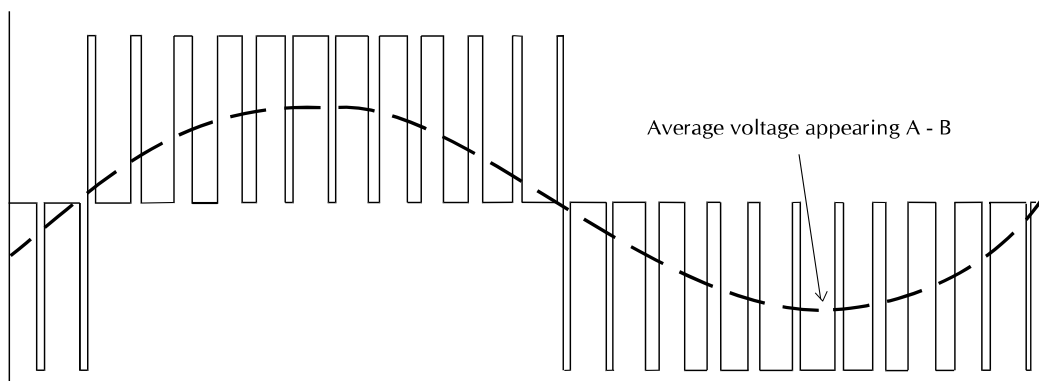


Figure 25

The PM6000 overcomes this problem by using a special operating mode for PWM output measurements. The data is sampled at high speed, and TOTAL quantities, including all harmonic and carrier components, are computed in real time. At the same time, the sampled data is digitally filtered to provide low frequency measurements such as FUNDAMENTAL and measurement of output frequency.

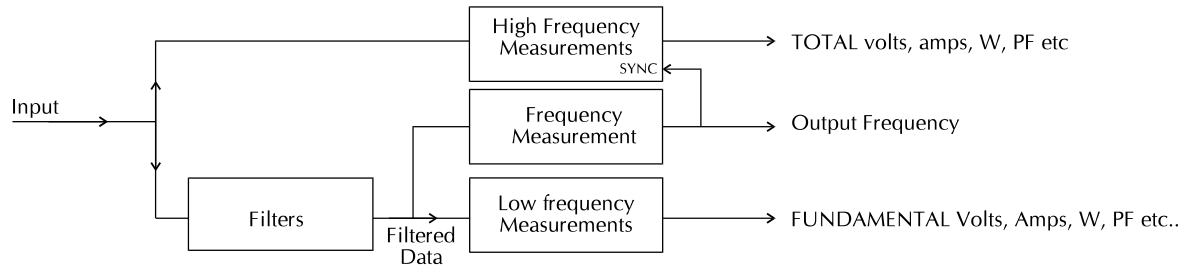


Figure 26

As well as the advantage of getting both low and high frequency results from the same measurement, this technique allows the high frequency measurements to be synchronized to the low frequency signal, which is the only way of providing high frequency measurement results that are both accurate and stable.

There is a choice of three filters to select according to the output frequency range to be measured (see figure 27): -

Filter	Application
5Hz	PWM Drives down to 5Hz output
1 Hz	Low speed measurement down to 0.5Hz
0.1Hz	Very low speed measurement down to 0.1Hz



Figure 27

The choice of filter does not effect measurement of the higher frequency components as these measurements are made on unfiltered data. Low frequency measurement results are available within the bandwidth of the selected filter.

6.1 Drive output measurements using the PM6000

The instrument is wired to the output in the 3 phase 3 wire configuration. (also known as two wattmeter method - refer to Appendix B for the theoretical proof that the power delivered to a system via 'n' wires may be measured with 'n-1' watt-meters). For PWM drives up to 30A rms output current, the PM6000 may be wired directly into the drive output as shown below.

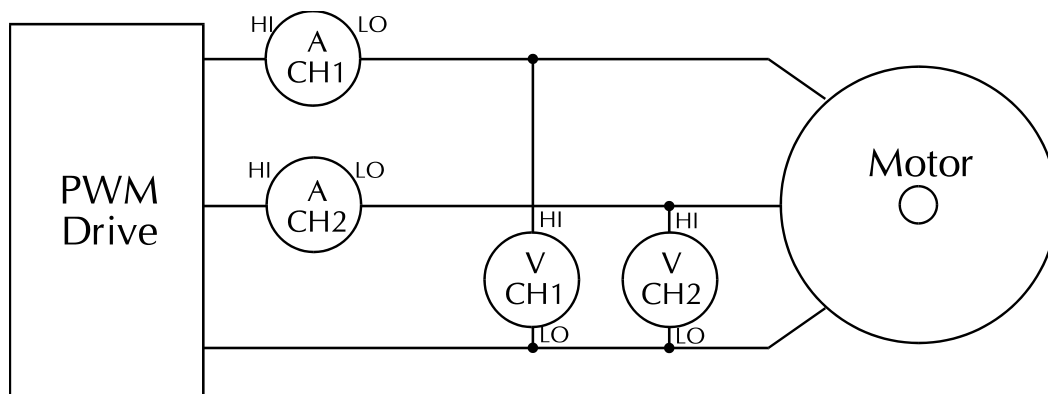


Figure 28

Drives with greater than 30A rms output current may be wired to the PM6000 as suggested in Appendix C.

In addition, since the PM6000 can have as many as 6 channels fitted, additional channels are available as independent channels to make simultaneous measurements of other sections of the circuit such as the DC bus within the PWM drive, as described in section 7.

It is a particular advantage of the PM6000 that it can be wired directly to PWM outputs for measurement on lower current drives. This is because, while AC current transformers and Hall - effect CT's provide good accuracy with higher currents, they tend to give poor results with currents of just a few amps. Best accuracy at low current is achieved by using a direct connection to shunts, but this causes problems for most power analyzers as the shunt measuring system cannot tolerate the high common mode

voltages that exists on PWM drive outputs. The voltage across the shunt may be only a few milli-volts, but the shunt potential is moving up and down with respect to the ground by hundreds of volts at several kV per microsecond. The PM6000 input circuitry provides superb rejection of these common mode voltages, which cause other analyzers to give totally erroneous readings.

Although only two channels of the PM6000 are used for measurements using the two wattmeter method, the instrument will vectorially compute and display values for the current in the third (unmeasured) wire. This is a valuable check on the balance of the load.

The instrument will now measure the output power with the selected filter. Verify that the measured frequency is correct. If the PM6000 is having difficulty with measuring the frequency, ensure that the correct filter frequency range has been specified.

Note that the V_{rms} , A_{rms} , and Watts figures are measured from pre-filtered values and therefore include all high frequency components whereas the fundamental values will measure only the values, which contribute to work in the motor. It is normal to have a large difference between the rms and fundamental voltage, and usually there would be a smaller difference for current and watts as the inductive motor filters the current.

The high frequency losses may be estimated by the difference between the total watts and the fundamental watts read on the SUM channel. This represents electrical power delivered by the PWM drive, which does not contribute to the mechanical output power and therefore adds to the heating of the motor:

High Frequency Losses = Total Watts - Fundamental Watts

This is a useful measurement when comparing PWM drives.

7. Drive DC Bus Measurements

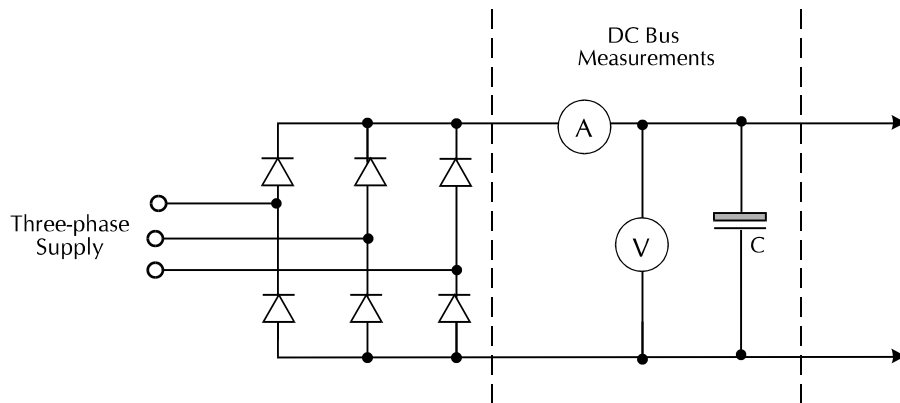


Figure 29

Although the link between the input and the output section of the PWM drive is referred to as the dc bus, the voltage and current in this bus are far from pure dc, so care must be taken in making the necessary measurements.

DC bus measurements are best made on the input side of the storage capacitors, as shown in figure 29 as the current here is essentially low frequency capacitor charging pulses from the ac supply, and free from the high frequency current pulses that may be drawn by the inverter section.

If dc bus measurements are made on their own, CH1 of the PM6000 can be used. However, dc bus measurements are often made in conjunction with other three phase three wire measurements such as the input or output of a drive. In this case channels 1 and 2 could be used for the drive input, channel 3 could be used for the dc bus and channels 4 and 5 could be used for the drive output.

Suggested measurements for DC bus.

Measurement	Reason
W	Total power in dc bus. Can be used in efficiency calculations.
Arms	RMS charging current in DC bus. Useful for sizing conductor or fuses.
ADC	DC component of current in dc bus. This is smaller than Arms.
VDC	Mean voltage across storage capacitor.
Vpk	Peak voltage across storage capacitor.

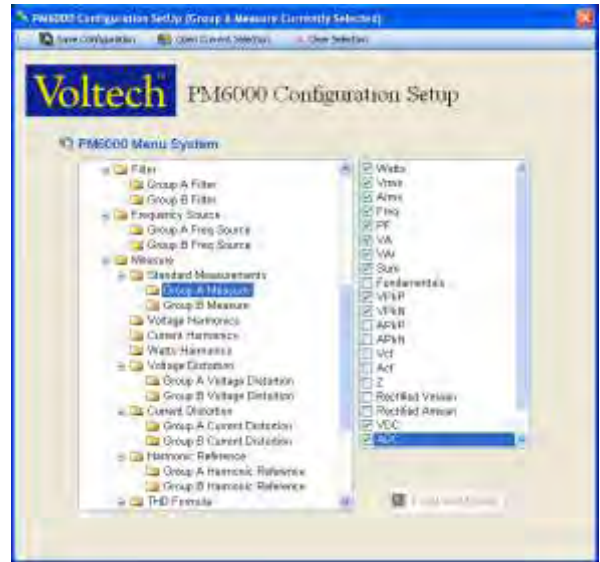


Figure 30

8. Drive Input Measurements

The input circuitry of most PWM motor drives is essentially a three-phase diode rectifier bridge with capacitor filter: -

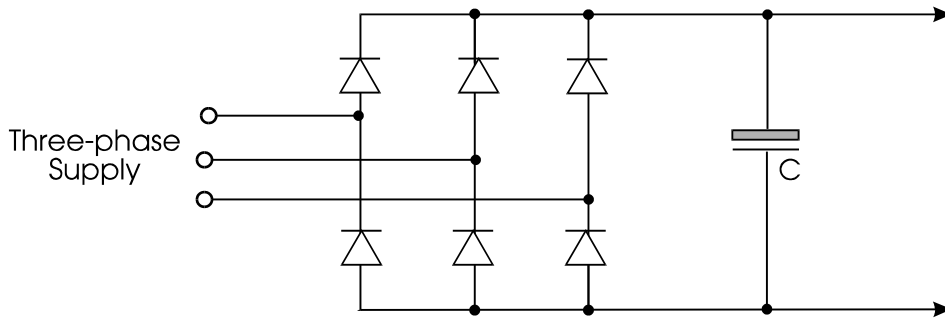


Figure 31

The input current to such a circuit consists, on each input phase, of pulses of current that charge the storage capacitor: -

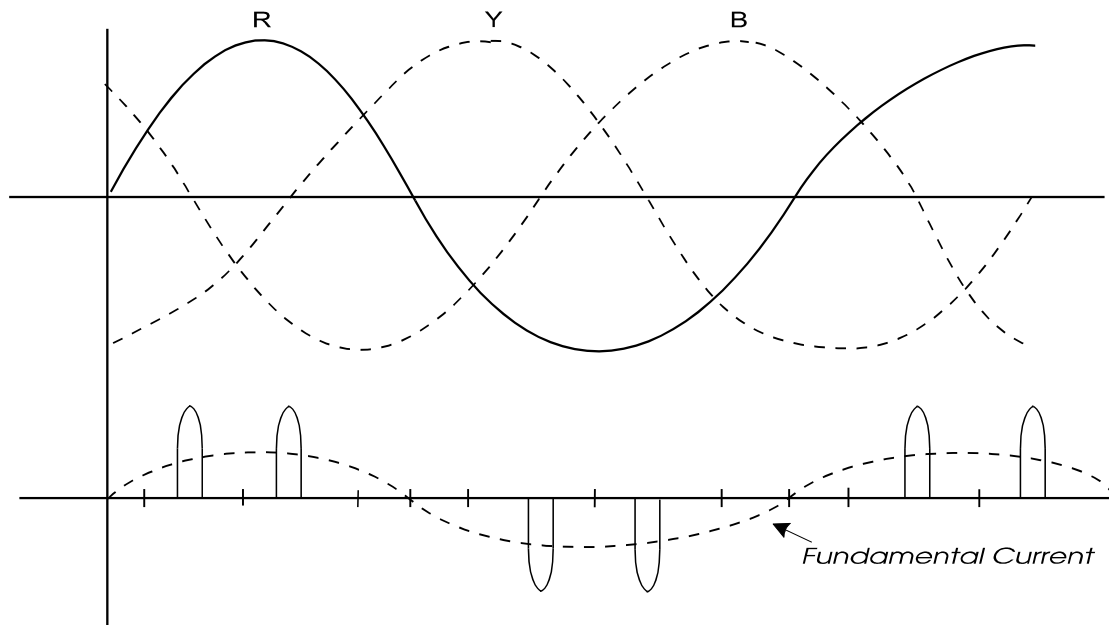


Figure 32

The input current is therefore a distorted current waveform, with a fundamental component at supply frequency, but with considerable harmonic content.

If the inverter section of the drive presented a constant-current load to the input circuitry, the input current on each phase and would be then a distorted waveform at constant amplitude: -

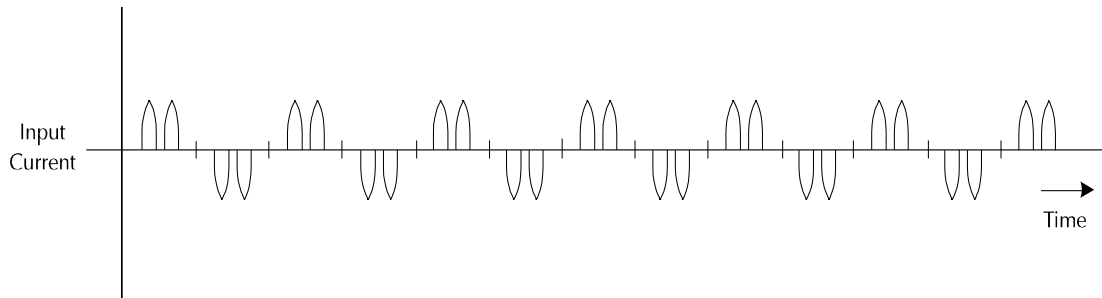


Figure 33

The input current drawn is essentially independent of the PWM output frequency since, as shown in Appendix D, the instantaneous power drawn by the drive is a constant, and therefore the current required from the input to charge the capacitor on the dc bus is a constant.

The PM6000 is wired to the input in 3-phase 3-wire configuration as shown in Figure 34 (also known as two wattmeter method - refer to Appendix C for the proof that the power delivered to a system via 'n' wires may be measured with 'n-1' watt-meters).

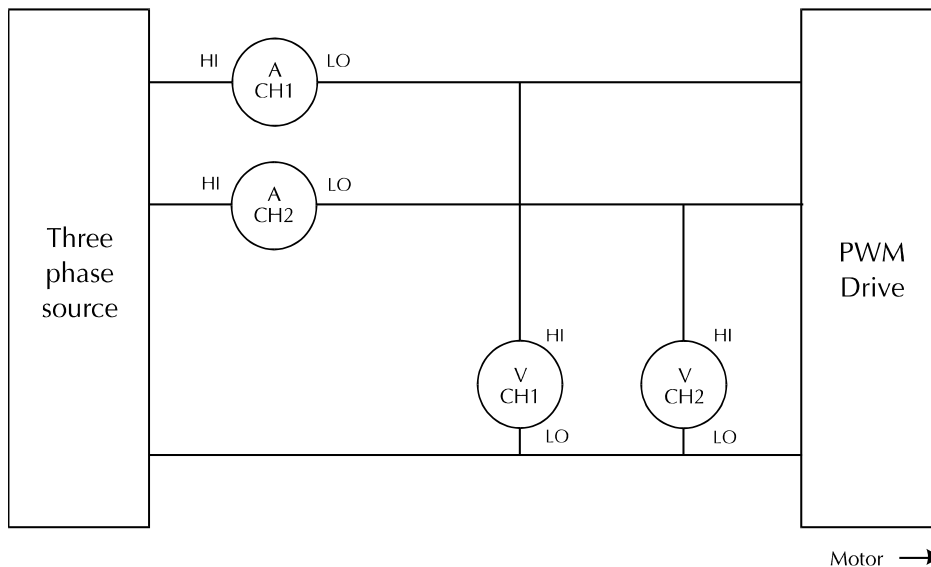


Figure 34

In this wiring configuration it is possible to use a third channel of the PM6000 as an independent drive channel to measure, for example, the dc bus within the PWM drive.

Connect the PM6000 channel 1 and 2 to the inout of the PWM drive in the three phase three wire configuration as shown in Figure 34.

If the readings vary too much, due, for example to a single phase PWM drive being measured, set the averaging to a value of 10 or greater.

The PM6000 will now measure the input parameter, including power and harmonic content. The frequency displayed will be the ac supply frequency.

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9. Loss and Efficiency Measurements

On any system, measurements of losses and efficiency are always best made by making simultaneous measurements on the input and output of the system.

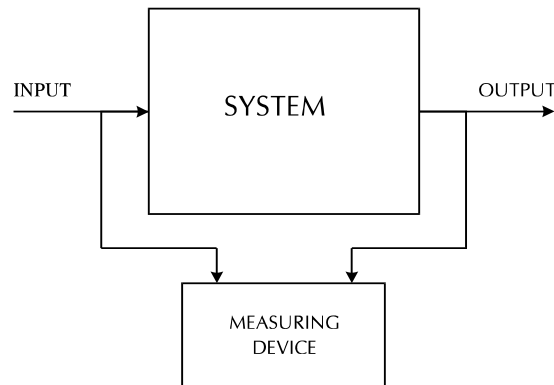


Figure 35

This is particularly important for systems with high efficiency, such as PWM drives. This is because, if separate measurements are made on input and output, and the system is shut down between measurements to transfer instrumentation, one cannot always be certain that exactly the same load conditions exist for both measurements. Any unnoticed difference in load conditions will appear as a major error in measured losses.

For example:

Set up Number 1 – Measure Input.

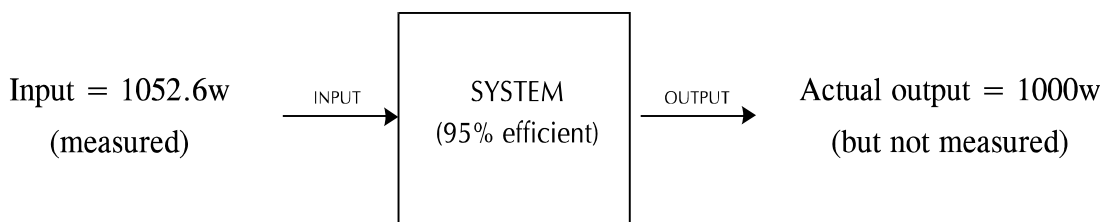


Figure 36

Switch off system, reconnect for output measurements, and switch on again: -

Set up Number 2 – Measure Output (but conditions have slightly changed).

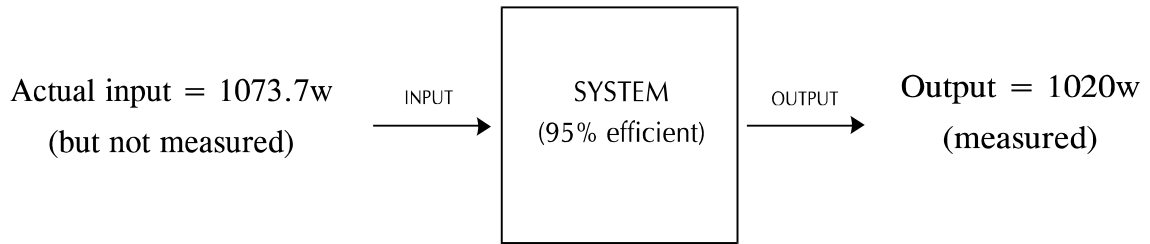


Figure 37

Apparent losses = $1052.6 - 1020\text{w} = 32.6\text{w}$.

Actual losses = $1073.7 - 1020\text{w} = 53.7\text{w}$.

This represents a very substantial error in measured losses!

A modern PWM drive is a high efficiency system, and it is recommended to make all measurements simultaneously to obtain the most accurate efficiency reading. A PM6000 5 channel instrument will allow measurements on all parts of the drive system simultaneously: -

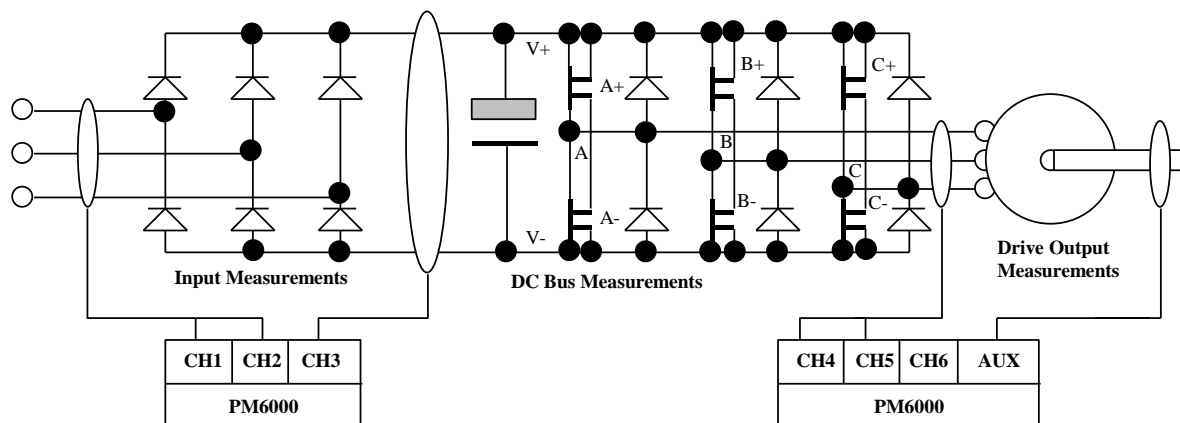


Figure 38

Using Voltech's PM6000 VPAS software the input group, the DC bus, the output group and the auxiliary measurements can all be displayed simultaneously allowing for accurate, real-time efficiency measurements, including mechanical power and efficiency.

10. Examining Detail Under Dynamic Load Conditions

The PM6000 VPAS software (visit www.voltech.com for a 30 day trial), allows you to view a number of parameters from a system on your PC. Figure 39 shows an example of reading made on a three phase input, with detailed graphs of the voltage, current and Watts harmonics.



Figure 39

The data can also be logged directly to a file which will enable the user to analysis the performance of the PWM drive over time.

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Appendix A: PM6000 VPAS Operating Facts

Synchronization of results between groups and between torque/speed is 50mS. The PM6000 is read 50mS after the torque and speed has been measured. The same is true between groups.

Data logging provides two methods: -

- a). Interval data logging (minimum interval 5 seconds, maximum interval 1 hour, stops after a selected quantity of results).
- b). Continuous data logging (logs data from 1/3 second to 5 seconds, dependent on how many groups and how many results are being displayed). Example 300-500 results update approx. 1 update per second. 100 – 200 results update approx 1/3 to 1/2 second updates.

Software updates are dependent on the amount of groups and results being displayed. Example 300-500 results update approx. 1 update per second. 1 – 200 results update approx 1/3 to 1/2 second updates.

The total amount of readings that can be displayed is: -

- a). 3P4W group = 978 results (updates every 2 seconds).
- b). 3P3W group = 654 results (updates every 1.5 seconds).
- c). 1P2W group = 324 results (update every 1 second).

- d). Maximum number on 2 groups of 3P4W = 1956 results (updates every 4 - 5 seconds).

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Appendix B: Required number of watt-meters

Consider the situation shown below, where the circuit is powered by 'n' wires.

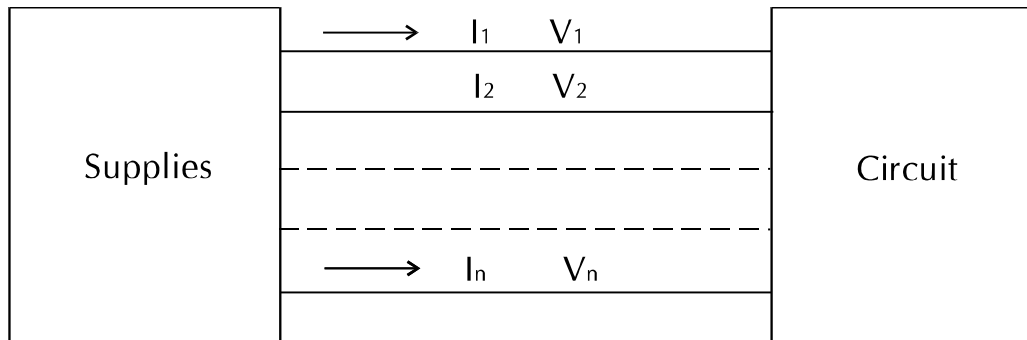


Figure B-1

Each wire will have an associated voltage (V_1 to V_n) with respect to a separate reference, and an associated current (I_1 to I_n). The total instantaneous power, P , will be given by:

$$P = V_1 I_1 + V_2 I_2 + \dots + V_n I_n$$

Applying Kirchoff's first law, that the total current flowing into a circuit must equal the current flowing out, allows us to write the n th current in terms of all the others:

$$I_n = - I_1 - I_2 - \dots - I_{n-1}$$

Substituting this expression for I_n in the equation for the power gives:

$$P = (V_1 - V_n) I_1 + (V_2 - V_n) I_2 + \dots + (V_{n-1} - V_n) I_{n-1}$$

This equation shows that the total power can be measured with $n-1$ watt-meters (i.e. voltmeter-ammeter pairs) connected as shown below, where the n th wire has now taken on the function of a "common" or "Lo" terminal.

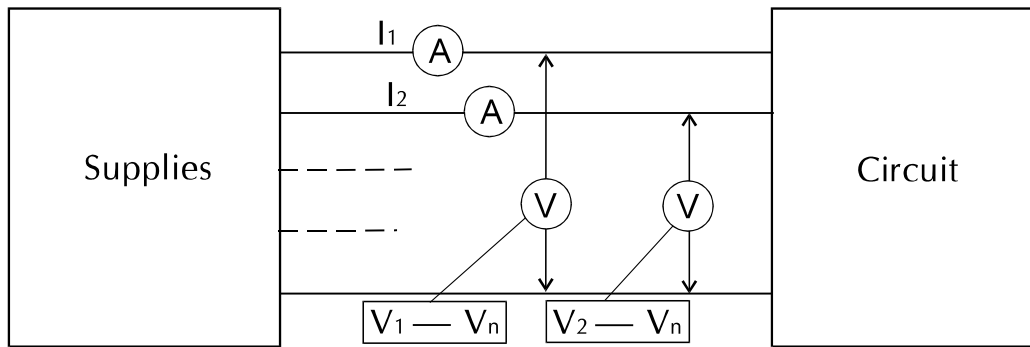


Figure B-2

It does not matter which of the wires is assumed to be the reference terminal, as the expression for power is symmetrical for all nodes.

Clearly, the general result which falls out from the final equation for the power measured is as follows: -

"In a circuit powered by several wires, the total associated power can be measured using a number of watt-meters equal to: - (the number of wires -1)."

Appendix C. Current Connections on PWM Drives

PWM motor inverters range in power output from a fraction of a kilowatt up to several hundred kilowatts, representing a wide range of motor currents.

Up to 30 Arms phase current, direct connection to the PM6000 current shunt input terminals (Ahi and Alo) can be made. For currents above this level, it is necessary to use either:

(i) A shunt connected to the PM6000 EXTERNAL current input connector. The output of the shunt should be in the range of 6mv to 2.5v peak for the range of measured current.

or

(ii) A current transformer with secondary connected to either the direct current input or the External input. The choice will depend on the secondary output of the CT; it may be voltage or current output, and it may be more convenient to convert a current output to voltage with a precision resistor if its level is too low for the direct current input (less than 20mA).

Both methods can be used successfully in motor applications, the measurements being scaled automatically by the PM6000 to give direct readings of motor current.

The PWM motor measurement environment presents a need for a wide range of frequency capability from the current transducer: Operation at motor frequencies from as low as 1 Hz need to be studied, and switching frequencies beyond 10kHz can be present in the current waveform.

Most current transformers are designed and rated for operation at frequencies above 45Hz, and not all have a good high frequency response. Accuracy and phase performance are degraded outside of the defined working range of the CT.

A range of current modules manufactured by the Swiss company LEM overcome these problems by using a field nulling technique in the core. This provides a wide dynamic range from DC to well beyond 100kHz, with accuracies better than 0.5% of nominal current.

These current modules have active inbuilt circuitry, which requires a power source to drive them.

The accuracy of the LEM modules are rated as percentage of the nominal current, so to measure currents lower than the nominal value, the best accuracy is achieved by winding several primary turns. For example, if an LT200-S is being used and a maximum current of 100A is to be measured, make 2 windings of the primary cable.

Appendix D. Instantaneous Power in a 3-phase system.

Consider a 3-phase load with an angular frequency ω where the current on each phase is lagging the voltage by a phase angle, θ .

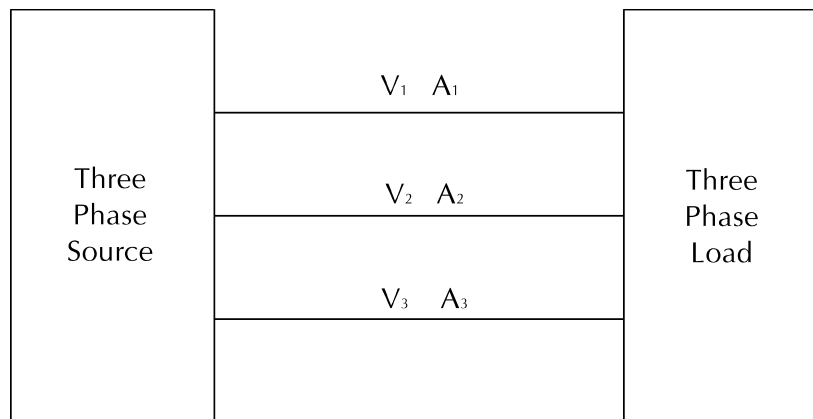


Figure D-1

Where:

$$V1(t) = V_p \sin(\omega t - 0)$$

$$V2(t) = V_p \sin(\omega t - \frac{2\pi}{3})$$

$$V3(t) = V_p \sin(\omega t - \frac{4\pi}{3})$$

and

$$A1(t) = A_p \sin(\omega t - 0 - \theta)$$

$$A2(t) = A_p \sin(\omega t - \frac{2\pi}{3} - \theta)$$

$$A3(t) = A_p \sin(\omega t - \frac{4\pi}{3} - \theta)$$

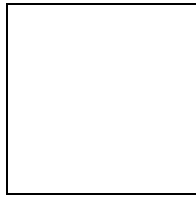
Where V_p and A_p are the peak of the voltage and current waveforms respectively.

The instantaneous total power $P(t)$ is given by:

$$\begin{aligned} P(t) &= V1(t) A1(t) + V2(t) A2(t) + V3(t) A3(t) \\ &= V_p A_p [\sin(\omega t - 0) \cdot \sin(\omega t - 0 - \theta)] \\ &+ V_p A_p [\sin(\omega t - \frac{2\pi}{3}) \cdot \sin(\omega t - \frac{2\pi}{3} - \theta)] \\ &+ V_p A_p [\sin(\omega t - \frac{4\pi}{3}) \cdot \sin(\omega t - \frac{4\pi}{3} - \theta)] \end{aligned}$$

$$\text{Now, } \sin A \sin B = \frac{1}{2} [\cos(A-B) - \cos(A+B)]$$

$$\therefore P(t) = \frac{V_P A_P}{2} \begin{bmatrix} \cos \theta - \cos(2\omega t - \theta) \\ + \cos \theta - \cos(2\omega t - \frac{4\pi}{3} - \theta) \\ + \cos \theta - \cos(2\omega t - \frac{2\pi}{3} - \theta) \end{bmatrix}$$



$$\begin{bmatrix} 3 \cos \theta - [\cos(2\omega t - \theta) + \cos(2\omega t - \frac{2\pi}{3} - \theta) \\ + \cos(2\omega t - \frac{4\pi}{3} - \theta)] \end{bmatrix}$$

Now, $\cos(2\omega t - \theta) + \cos(2\omega t - \frac{4\pi}{3} - \theta) + \cos(2\omega t - \frac{2\pi}{3} - \theta) = 0$ for any value of t . This term represents the summation of three vectors 120° apart.

$$\therefore P(t) = \frac{3V_P A_P}{2} \cos \theta.$$

This term is not a function of t , so the instantaneous power in a three-phase system is a constant.

