APPLICATION NOTE - 017
PWM Motor Drives – Theory and Measurement Considerations

Pulse Width Modulated (PWM) power electronic techniques represent a large and increasing proportion of modern power electronics. Like any form of power conversion, PWM drives or associated loads should be designed and tested to meet specific performance and efficiency criteria but given the complexity of waveforms associated with PWM applications, accurate measurement is not a simple task.

Newtons4th manufacture precision power analysers that are selected by customers around the world for use in the most demanding power electronic measurement applications. This experience has enabled Newtons4th to develop power measurement products that are ideally suited to meet the unique demands associated with this increasingly important sector of power electronics.

This application note describes the principal of PWM motor drives and explains particular considerations that should be taken into account when making power measurements in this application.

Why use PWM for speed variation?

When an AC motor is connected directly to an AC line (415V 3Φ for example) the motor speed is fixed and is calculated as follows

$$ns = \frac{120 * f}{p} - slip$$

ns = Motor speed (Hz)   f = fundamental frequency   p = no. of poles

This is a problem since many applications need to change the speed of the motor, for example changing the flow rate of a water pump by changing the speed of the propeller in a pump. This was traditionally achieved by reducing the voltage across the windings of the motor, which in turn reduced the current through the windings thus reducing motor torque. The speed of the motor would reduce proportionally to voltage if the load on the motor remained the same but this not an ideal solution since we know load is not always constant. Another reason this method of control is not ideal is that when the slip on a motor is too great, the efficiency of the motor is significantly reduced and if the load changes, so will motor speed. In light of this a more sophisticated solution was required.

PWM Fundamentals

While PWM techniques can be applied to single or multi phase applications, we will consider here the more commonly used three phase application where in the UK for example, the 3 Phase AC supply is 415V 50Hz. The PWM controller will rectify this AC voltage and produce

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around 600VDC, the DC bus will then transfer this signal to the inverter stage. The inverter stage utilises Mosfets, IGBT's or Thyristors as switching devices which are controlled by a processor that switches the devices on and off in a specific sequence to produce a sine wave fundamental component at the required frequency and amplitude. This voltage produces the correct rotational magnetic field to the rotor resulting in kinetic energy (rotation of the rotor).

Simplified PWM Diagram

Figure 1

The above diagram represents the 3 Phase input, rectification, the DC interconnecting bus and the Inverter stage, the output of which is transmitted to the motor and transferred into mechanical power.
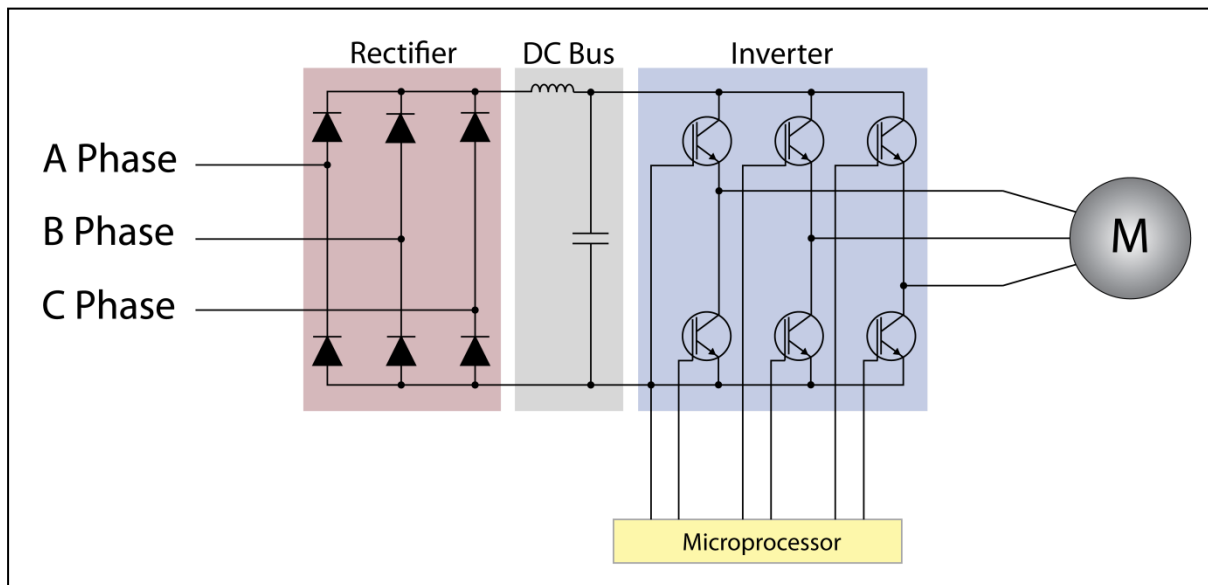

Figure 2

As depicted above, this is a 3 Phase in, 3 Phase out system. The circuitry on the DC bus will smooth the rectified signal as much as possible as ripple will cause inefficiencies. The inverter stage provides full control of the motor via the Microprocessor and the IGBT circuitry.

The Microprocessor will send gate signals to the switching devices (IGBT's above) in order to vary both the frequency and the voltage to the motor. This circuit utilises two IGBT's for each motor winding phase.

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Rectifier

The rectification stage of the circuit converts the 3 Phase input into a rectified DC output; this stage should ideally have low rectifier loss to maintain optimum efficiency prior to the DC bus.

DC Bus

The DC bus provides a transmission path between the Rectifier and Inverter, this stage also smoothes the ripple DC produced by the rectifier. This is often used as a measurement point for efficiency of the inverter stage. Typically the DC voltage level is 1.35 times the level of the 3Φ AC entering the rectifier, in this case we have 415V 3Φ so the DC bus would be around 560V DC.

Waveforms

Figure 3 depicts the various voltage waveforms at different stages in the circuit, as we can see the 50Hz AC input is rectified and smoothed.
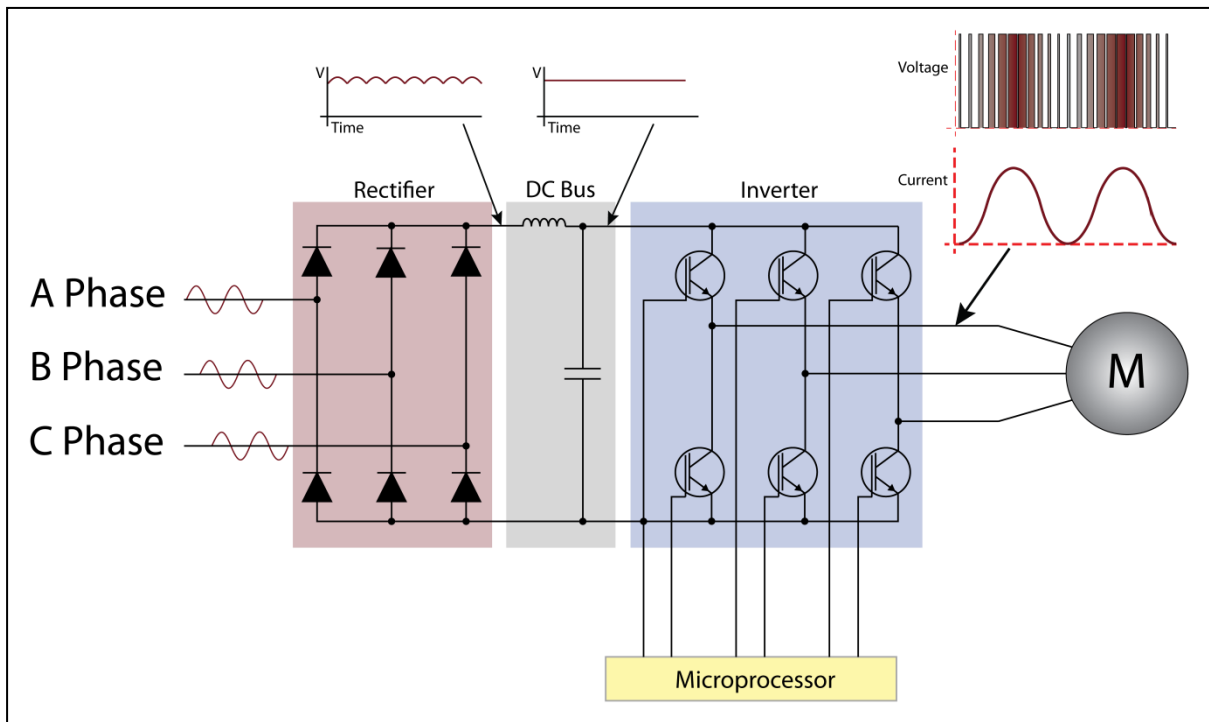
Figure 3

Inverter and Microprocessor

The IGBT's in the previous diagram are switched on and off by the signals from the microprocessor to create an average AC voltage as close as possible to a sinusoidal voltage waveform for the motor windings to convert into mechanical power with as little jogging

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(ripple torque) as possible. The voltage required to switch on an IGBT can be as high as 15V, when this is applied current will flow through the IGBT and toward the motor coils.

Figure 4 illustrates the PWM output waveform from the IGBT's. It shows a single phase, in essence the duty cycle of the IGBT's is varied which provides the equivalent of a sine wave output. Essentially the waveform is smoothed by the inductive nature of the motor winding.
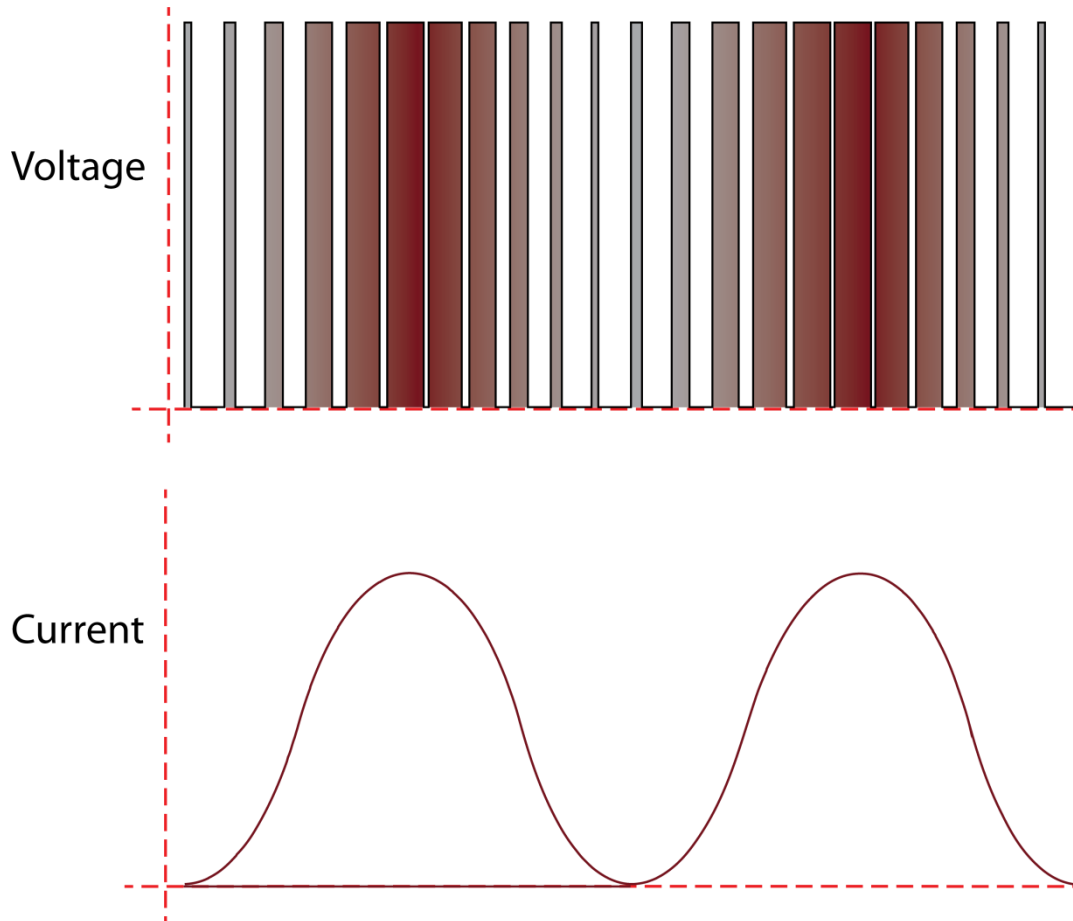

Figure 4

This modulation of the duty cycle is phase shifted by 120 degrees for each phase; both the fundamental frequency of the output and the voltage of the output can be controlled, with larger average duty cycles giving greater voltages and increased torque.

Anti Parallel Diodes

When the IGBT is switched off, a back emf produced in the inductive motor winding will be present which would produce a very high and potentially damaging voltage across the IGBT junction. To overcome this problem, anti parallel diodes are used that allow current flow from the motor winding to the DC bus when the IGBT is switched off. This back emf is a result of

relative motion between the armature which carries the current and an external magnetic field, this back emf is directly proportional to motor rotational velocity and opposite in polarity to the voltage applied by the inverter stage.
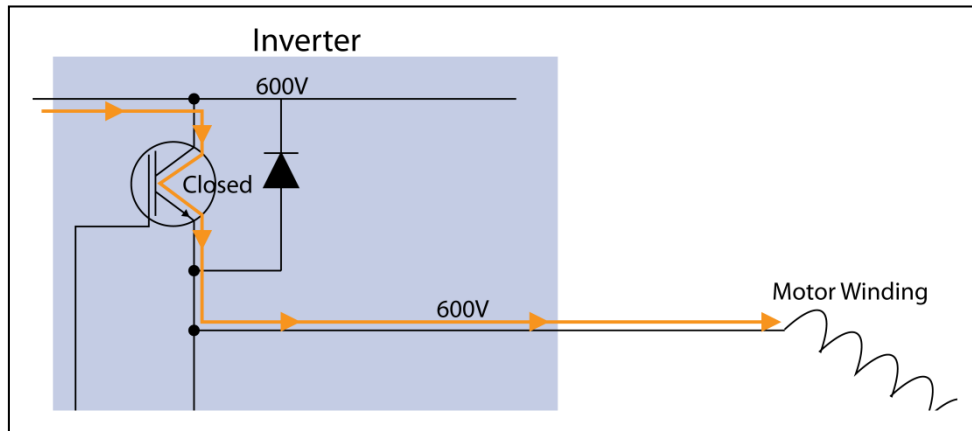

Figure 5.

Figure 5 illustrates the flow of current with the IGBT in the "On" position. As shown the potential of the DC will be equal to the current on the "motor" side of the Anti-Parallel diode, Current will flow through the IGBT and onto the motor windings.
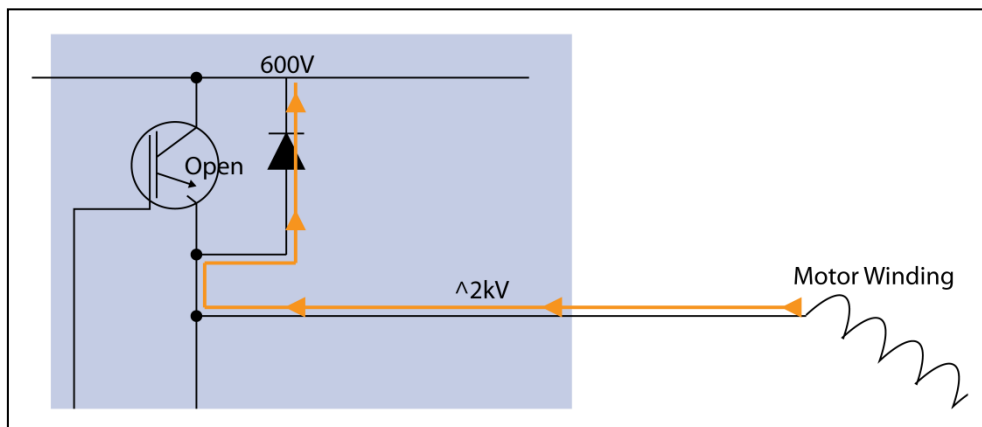

Figure 6.

However, figure 6 shows the current flow when the IGBT is turned off, as we can see the back emf produced by the collapsing fields in the motor winding can be very large, the potential voltage is higher than that of the DC bus and the diode passes this current.

Without this path the build-up of potential difference on the IGBT junction would be so high that the IGBT may be destroyed. When the lower IGBT's shown in figure 3 are off, the same process occurs but in reverse as the motor windings will be connected to the low (0V) side of the DC bus.

In order to drive current through the motor windings and increase motor speed and torque, both the frequency of the modulation and the voltage (by increasing average duty cycle) of

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the inverter stage must be increased. This is due to the relationship between the back emf and motor speed as they are proportional to each other, as motor speed increases so does back emf. In order to maintain current flow (and resulting torque) the supply voltage to the motor windings must be kept above this emf.

Harmonics

As we know, a square edge will consist of many harmonics. We also know that 'in phase' components of voltage and current will result in real power. For this reason, the true power output of a PWM system can only be established with measurement equipment that accurately measures power signals over a frequency range that includes all frequency components.

The diagram below shows real voltage and current harmonic measurement results on a PWM inverter drive with nominal 18kHz carrier and 50Hz fundamental. It can be seen that while the voltage and current harmonic profile differ as would be expected, low order harmonics of the fundamental and frequency points around the carrier frequency contain a both voltage and current components. It follows that these components will contribute to the total power and should therefore always be included in measurements that aim to quantify total power or system efficiency.

PWM Motor Drive Harmonic Analysis – 2nd to 375th Harmonic (50Hz Fundamental)
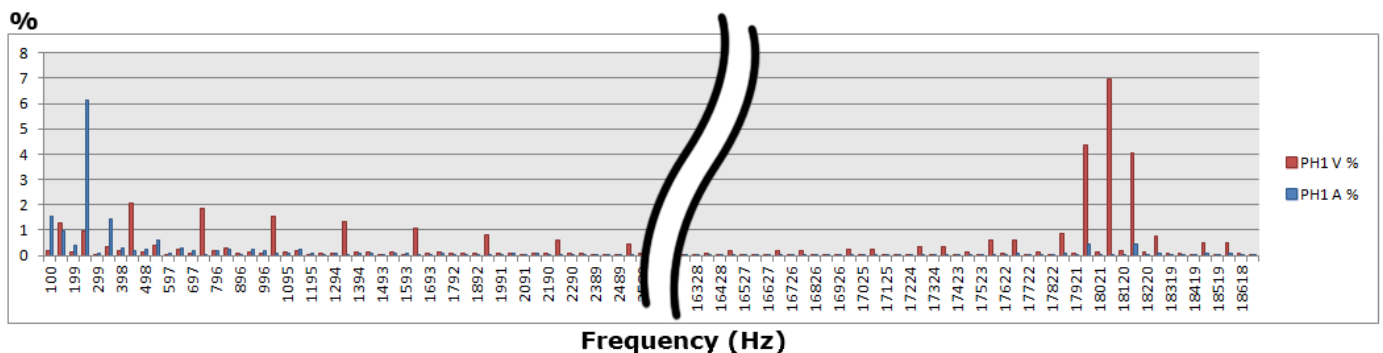*Measured on a PPA5530 Precision Power Analyzer*

Figure 7.

This application note was an introduction to pulse width modulation theory; a series of PWM related application notes including measurement approach and a guide to measuring efficiency of the various stages in a PWM Motor drive will be discussed in future application notes.

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