AN4220
Application note

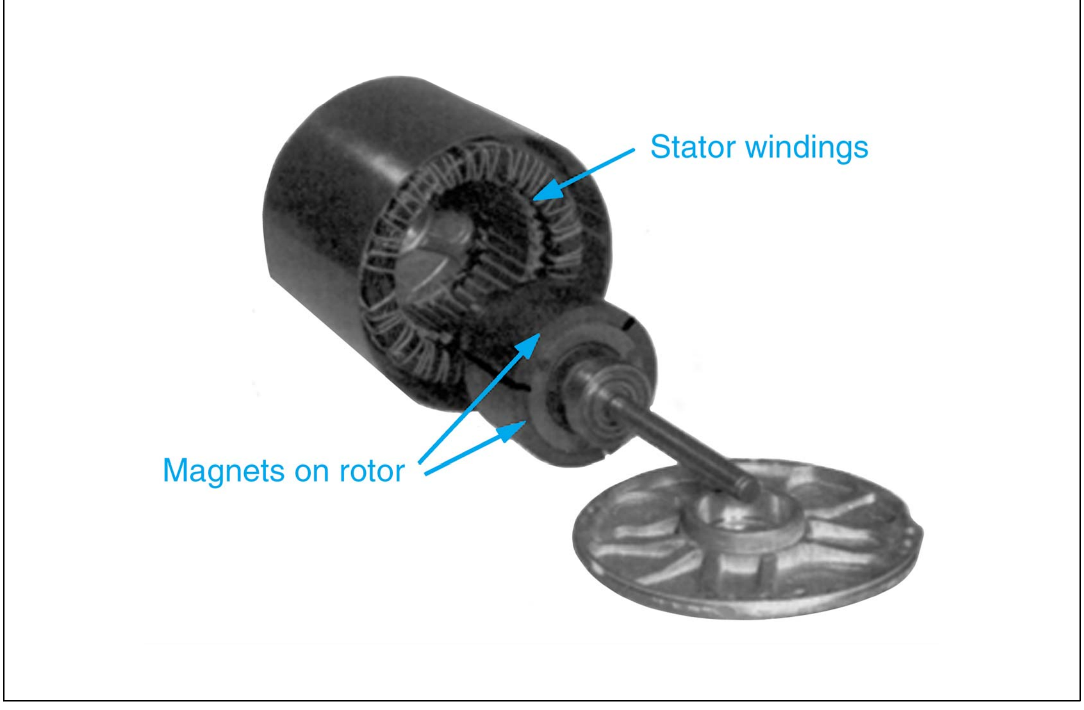
Sensorless six-step BLDC commutation

By Dennis Nolan

Introduction

A common "Permanent Magnet Brushless DC" (PM BLDC) motor consists of a 3-phase coil wound on a cylindrical shaped magnetic core (the STATOR) and a rotor/shaft assembly which is normally held in place by bearings which mount at either end of the stator. The rotor is a smaller cylinder which is fixed to the shaft, concentric with the stator, and carries several permanent magnets mounted around its perimeter as shown in *Figure 1*.

Figure 1. PM BLDC motor



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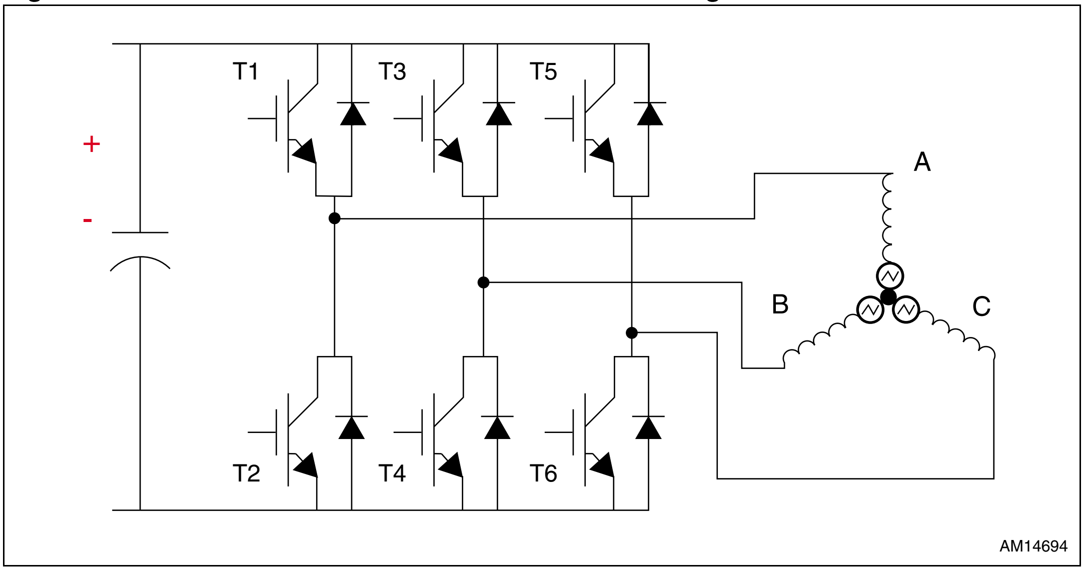
Description

A typical BLDC drive is a microcontroller controlled three phase inverter. To the drive, the motor looks like three coils connected at the center in a WYE configuration, as shown in *Figure 2*. The center point, or neutral, of the WYE is not usually brought out of the motor. Although it is less common, the three coils may also be connected in a triangular DELTA configuration. For the analysis, the DELTA configuration is harder to think about, and a mathematical transform exists that can convert a DELTA to an equivalent WYE so this application note will only discuss the WYE configuration. The three motor terminals are normally referred to as A, B, and C or U, V, and W. A conventional six transistor, three phase inverter bridge allows the motor drive to connect each terminal to either the positive DC bus, the negative DC bus, or leave the terminal open. Pulse width modulation switching techniques allow us to switch a terminal between the two available voltages at a high switching frequency so that the average voltage at the terminal can be set anywhere between zero and the full available bus voltage.

Figure 2. Schematic - coils connected in a WYE configuration



To understand the commutation sequence, one needs to first look at the back EMF characteristics of the motor and what generates torque. For a BLDC motor, the magnetic material on the rotor is specifically magnetized with a sinusoidal magnetic field strength pattern. If one were to take the probe of a magnetic flux meter and slowly move it around the perimeter of the rotor the field strength would display a sinusoidal pattern, where +1 represents the strongest “north” direction flux and -1 represents the strongest “south” direction flux. *Figure 3* is a pictorial representation of this flux pattern. The length of the arrows indicate the strength of the magnetic flux while the direction indicates north or south polarity.

We know that if we move a permanent magnet past a coil of wire a voltage will be induced in the wire. If we take care to move different magnets past the same coil at the same speed, the voltage induced will be proportional to the strength of the magnets.

If we now assemble our PM BLDC motor and mechanically spin the rotor (an electric hand drill will do nicely) and observe on an oscilloscope the voltage at A with respect to B we will observe a sine wave voltage, like shown in *Figure 4*. This is the back EMF (electromotive force) or BEMF of the motor. For a given motor, the amplitude and frequency of the BEMF are both directly proportional to the rotor speed. Each rotation of the rotor will produce an integer number of full BEMF cycles. The simplest rotor, with 2 poles, will produce one BEMF cycle for each rotation. This rotor has been magnetized with one peak “north” pole and one peak “south” pole at opposite sides of the rotor. Probably the most often encountered motor is a four pole motor. This rotor has north and south poles placed alternately every 90 degrees along the rotor. A four pole motor will generally be smoother in operation than a two pole, somewhat similarly to the way that a four cylinder internal combustion engine will be smoother than a two cylinder. The four pole motor will produce two electrical cycles for each rotation. If we cast ourselves in the role of the AB coil, we are sitting in one spot and “watching” the rotor move past. We “see” the magnetic flux level go up and down and this is reported in the BEMF that is produced. The “pickup coil” shown in *Figure 3* depicts this situation.

Figure 3. Flux pattern pictorial representation

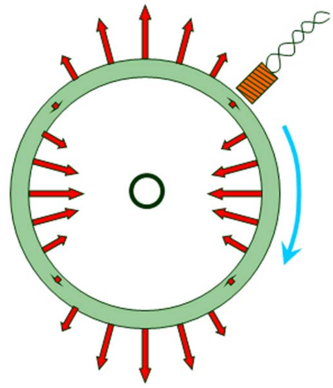
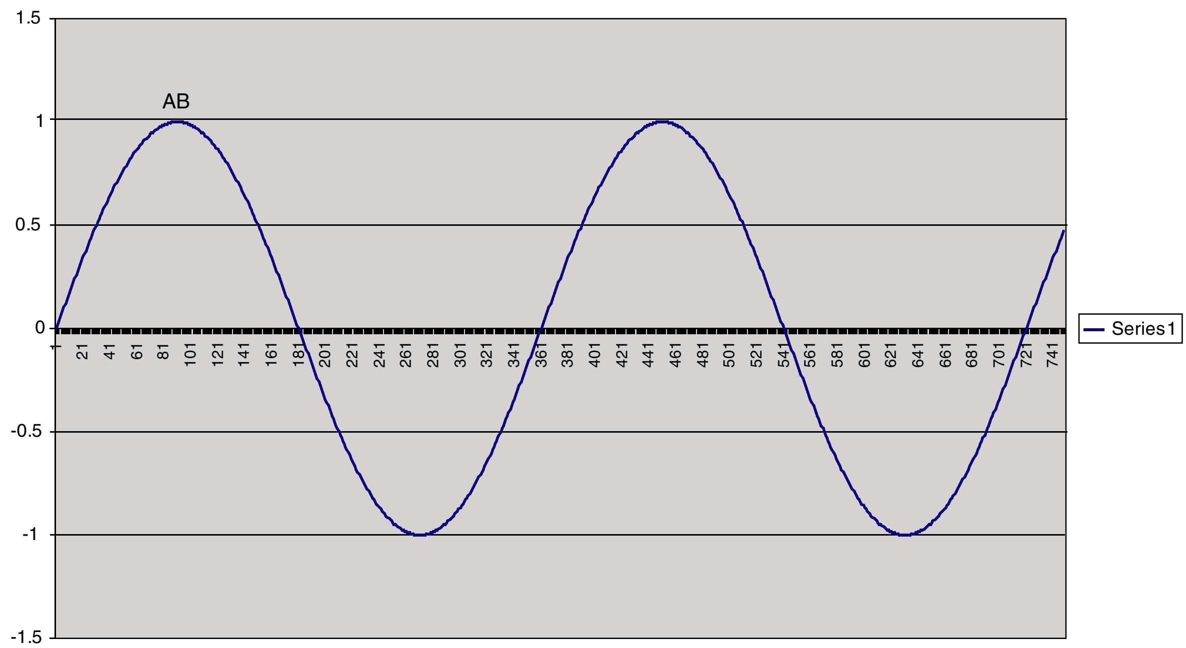


Figure 4. Motor single phase BEMF



Now it is also a well-known fact that, if an electric current flows through a coil of wire in the presence of a permanent magnet, a force will be produced (mutually on both the wire and the magnet) which is proportional to the strength of the magnet and the amount of current flowing (Amps) in the coil.

If we force a constant (DC) current to flow from terminal A to B, then the BEMF waveform (again referring to *Figure 4*) predicts the force (torque) that will be produced on the rotor as function of the rotor position. In fact, this curve represents the instantaneous value of TORQUE/AMP produced by a current through AB at any given rotor position. The reason for this is that the amplitude of the BEMF generated and the torque produced are both directly proportional to the same parameter, namely, the strength of the permanent magnet. If the rotor is at 100 degrees, for example, the motor will produce a torque that would tend to move the rotor clockwise toward 180 degrees. If the rotor were at 260 degrees, the motor would produce a negative, or counterclockwise, torque that would tend to move the motor back to 180 degrees. At 180 degrees the motor produces no torque so the rotor would remain stationary, until it is moved away from the zero torque position. The maximum torque is produced when the rotor is at 90 or 270 degrees.

Generally we want the motor to produce a relatively constant torque per amp of current applied and this clearly cannot be achieved by just energizing AB. If we want to produce clockwise torque we can apply a positive voltage to AB during the positive half of the BEMF cycle and then reverse the polarity during the negative half of the cycle (so that we won't produce counterclockwise torque). This would keep the motor turning, but with a very high “torque ripple” which is very undesirable and inefficient.

Adding the BEMF for BC and CA we see three sine waves spaced at 120 degrees, as shown in *Figure 5*. This is the classic 3-phase waveform, with the three waveforms evenly spaced out around the circle. The phase shift is determined by the physical spacing of the coils on the stator.

To get the best torque out of the motor, we want to energize the phases in a sequence so that each phase is energized when that phase could produce the maximum torque. Looking at *Figure 5*, we see that the time each phase has the highest positive BEMF is spaced 120 degrees apart so we could drive the motor with positive currents in each phase and switch the phase we are driving every 120 degrees. However we still have a significant torque ripple if we do this. Looking further we see that each phase has a negative peak spaced so that each negative peak is centered between two positive peaks. If we drive a negative current, for example drive phase CA with a negative current, we produce a clockwise torque during the time that phase CA has a peak negative BEMF.

The conventional six-step excitation of a PM BLDC motor energizes the motor in this sequence, with two of the terminals energized while the third terminal is left open and not conducting.

Figure 5. Motor 3-phase BEMF

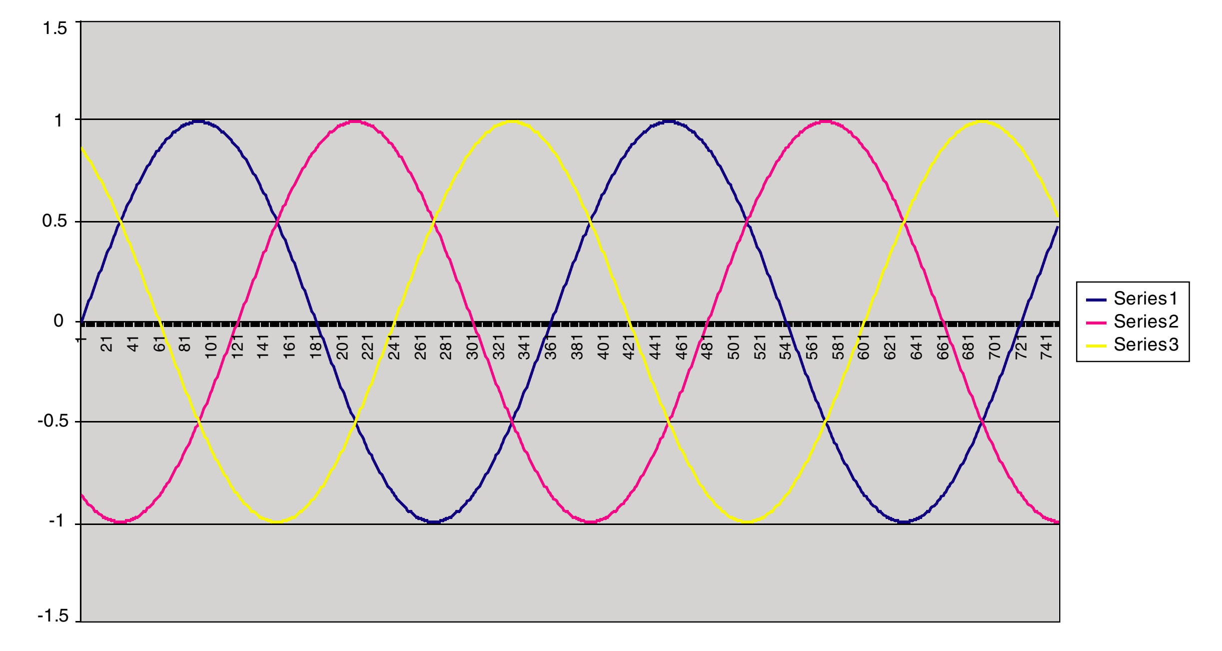


Figure 6 shows the entire 3-phase cycle broken up into 60 electrical degree intervals. Each interval is centered on the peak of one of the phases, and covers 30 degrees on either side. Aside from being the strongest part of the phase (in terms of torque per amp) it is also the flattest region. Looking at this region for AB, note that just as the torque per amp for phase AB is starting to decrease, phase CA is just entering its optimal region. Admittedly, CA is at a negative or counterclockwise peak here, but we have only to energize this phase in the negative direction (positive to A and negative to C) to effectively flip the torque around, as shown in *Figure 7*. When we reverse the polarity to CA we call it phase AC.

Figure 6. 3-phase cycle

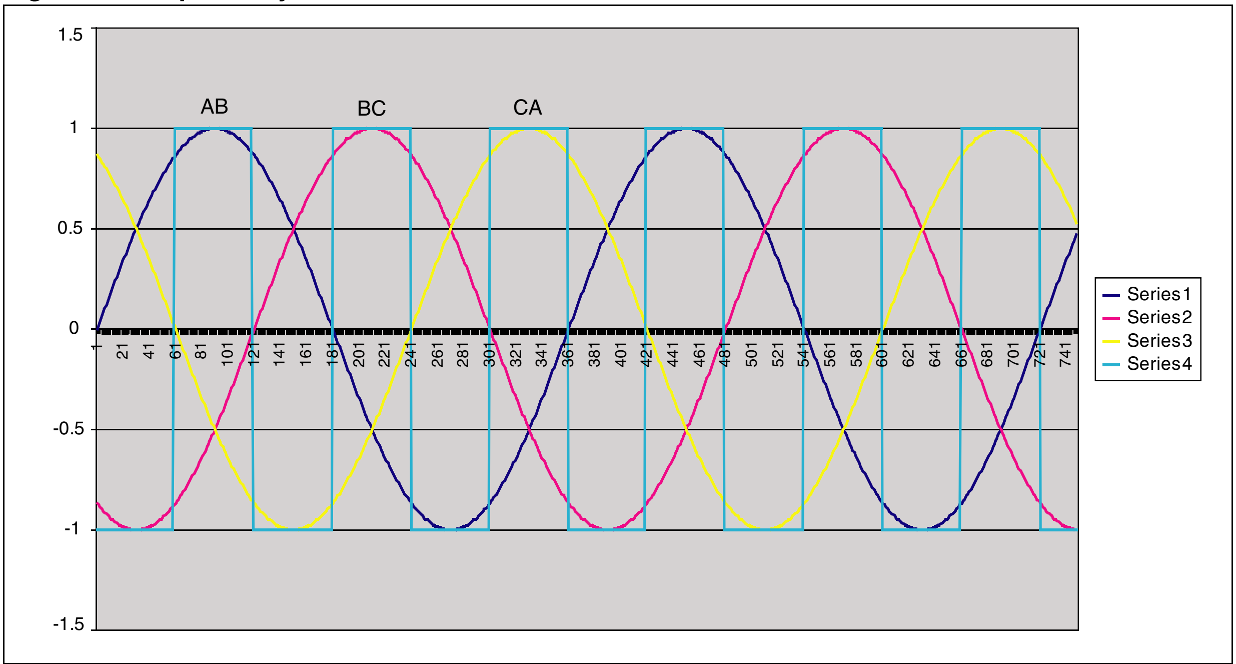
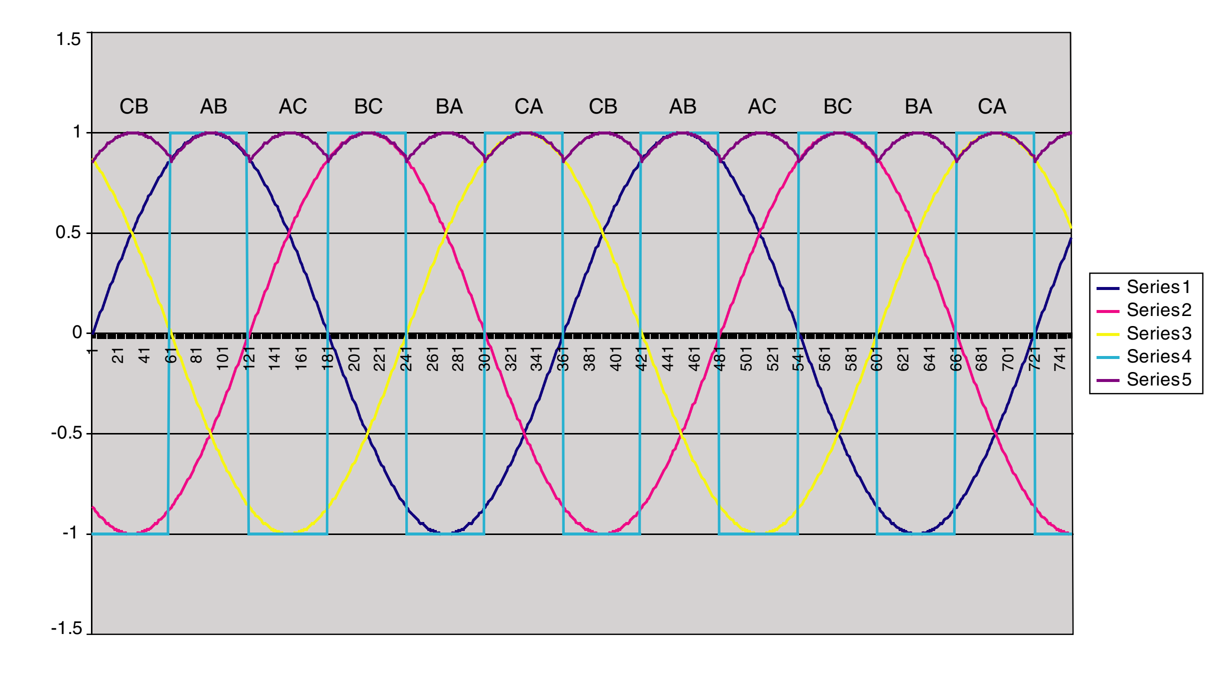


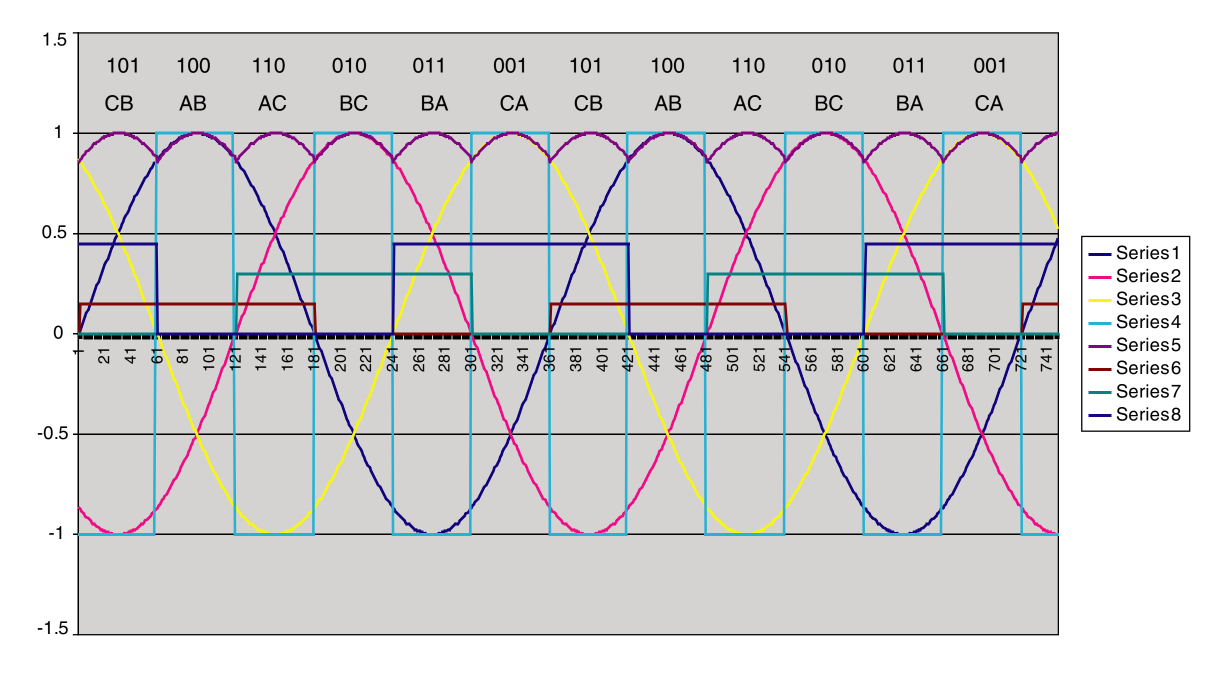
Figure 7 shows all six available commutation phases. The beauty of the three phase arrangement is that just when one phase starts to decline we can switch to another phase which is on the upswing. If we normalize the peak torque to 1.0, the minimum is 0.866 (the sine of 60 or 120 degrees). This gives rise to the commonly quoted statement that a six-step commutated BLDC has 13% peak-to-peak ripple. This level is found acceptable for most applications. Many will recognize that this resultant waveform is also the voltage waveform observed when a three phase voltage source is full wave rectified by a six diode bridge driving a resistive load.

Figure 7. Six available commutation phases



Now that we know when (relative to rotor position) each of the six phases should be energized, the question becomes how can the motor drive know when commutation should occur? The traditional method of sensing rotor position is with the use of Hall sensors. The sensors are semiconductor devices which operate from DC supply voltage in the range of 5 to 15 Vdc and are sensitive to the magnetic flux generated by the magnets on the rotor. In most motor designs, the rotor magnets are made somewhat longer than the stator so that the Hall sensors can be placed near the rotor and away from the magnetic influence of the stator so that the magnetic “signal” of the rotor can be clearly seen. Most Hall sensors are digital devices whose outputs are high in the presence of a north direction magnetic flux and low for a south direction. Since the motor BEMF polarity also corresponds to the polarity of the flux, Hall sensors can be placed around the stator so that they produce signals like those shown in *Figure 8*.

Figure 8. Hall sensor signals



Note that the brown signal in *Figure 8* corresponds to the polarity of phase AB, the green to phase BC and the blue to CA. If we take these three signals as a three bit digital word in the order AB, BC, CA we get the binary numbers shown above the phases in *Figure 8*. Each phase corresponds to a unique binary pattern. It is now a simple matter to either design hardware logic or a microprocessor lookup table to convert this three bit pattern into a six bit pattern that can be used to control the six transistor bridge. The three bit word can take on eight possible patterns but we only see six. Since a three phase set of sine waves are never either all positive or all negative at the same time, 000 and 111 never occur and are considered illegal codes. Some drives will shut down on a fault if an illegal code is encountered.

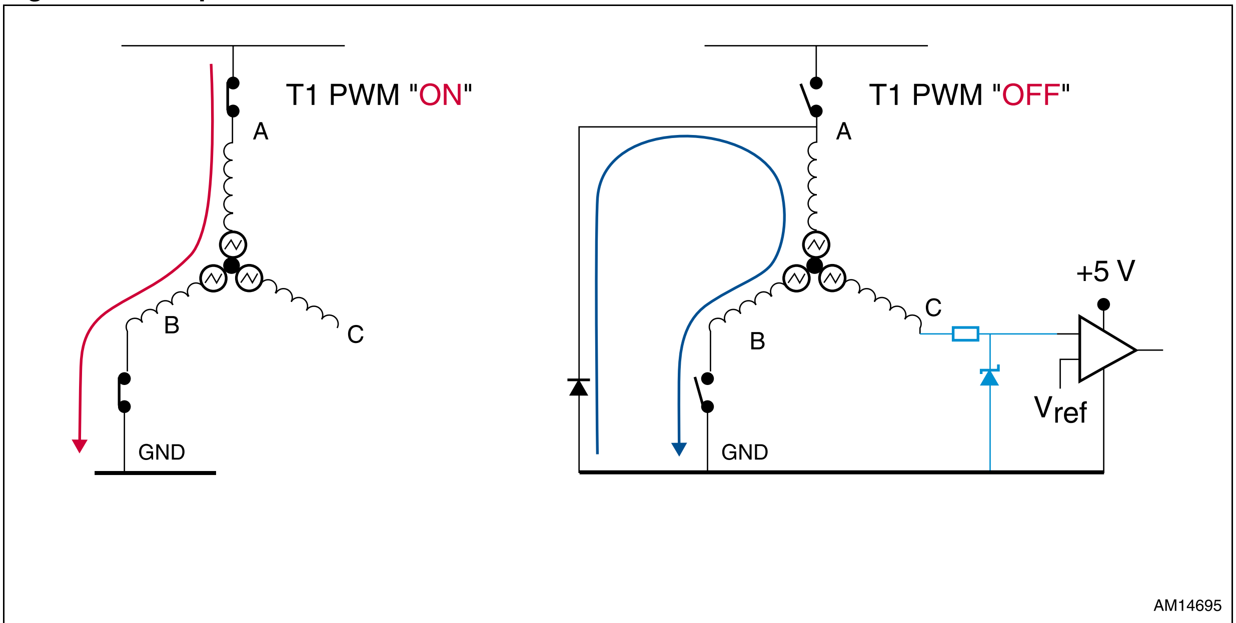
The technique just described is called a “sensored” drive because Hall sensors in the motor are required for proper operation. In the sensorless approach the drive derives the rotor position information it needs directly from the motor BEMF signals. These signals can be read from the three main wires delivering power to the stator so no additional wires are required. Hall sensor drives require five additional wires, two to carry power and ground and three for the individual signals. These wires add cost to the system as well as complexity (anyone who has ever tried to connect brand X's motor to brand Y's drive can attest that very strange things happen if the sensor wires get mixed up). The presence of sensors also adds cost to the motor and reduces reliability, since the motor often finds itself in an inhospitable environment. A sensorless motor has only steel, copper, insulation, and magnets, a more robust combination, especially in very high temperature environments.

Figure 8 shows that the key to knowing when to commutate is knowing when the BEMF voltages cross zero. If we were simply spinning the motor with a hand drill this would be easy. A basic voltage comparator circuit would produce signals identical to the Hall sensor signals previously discussed. The big problem, however, is that when the motor is being driven the motor terminals are being driven to either the positive bus rail or to ground and therefore we cannot “see” the BEMF. *Figure 9* depicts the basic scheme used in sensorless BEMF zero crossing detection. The method relies on two important facts. First, at any instant in time one of the three terminals is not being driven and no current is flowing in that wire and, second, because the other phase is being pulse width modulated in order to regulate speed, during the off part of the PWM cycle the other two terminals are both effectively tied to ground. During this interval it is possible to get a quick look at the BEMF of the unenergized phase and determine its polarity. If we select a common switching frequency of 20 KHz, then we will get a new sample of the polarity of the unenergized phase every 50 microseconds. We will therefore know, within a 50 microsecond resolution, when the polarity change or zero crossing occurs. This information is then used to drive the software commutation state machine.

In practice, all three motor terminal voltages are connected back to input channel pins of the microprocessor's analog to digital converter. During each PWM cycle, just at the end of the PWM off time, the voltage of the floating terminal is sampled. This ADC sample is compared with a very low threshold value (essentially zero) and the resulting logic level drives the commutation state machine. The action of the ADC conversion and logic comparison functionally replaces the voltage comparator shown in *Figure 9*. A complete derivation of the formula for motor terminal voltage during PWM off time is given in *Appendix A*.

Looking at *Figure 9*, we see that when the neutral is at ground, we are actually sensing the line to neutral BEMF of the unenergize phase. However, the BEMF signals in *Figure 7* are the line to line BEMF. Fortunately there is a defined relationship between the line to neutral and line to line BEMF. In this case the sensed line to neutral BEMF leads the line to line BEMF by 30 degrees. So, the commutation time is typically delayed by 30 degrees relative to the sensed zero crossing. See *Appendix B* for more detailed discussion on commutation delay.

Figure 9. Proposed direct back EMF detection

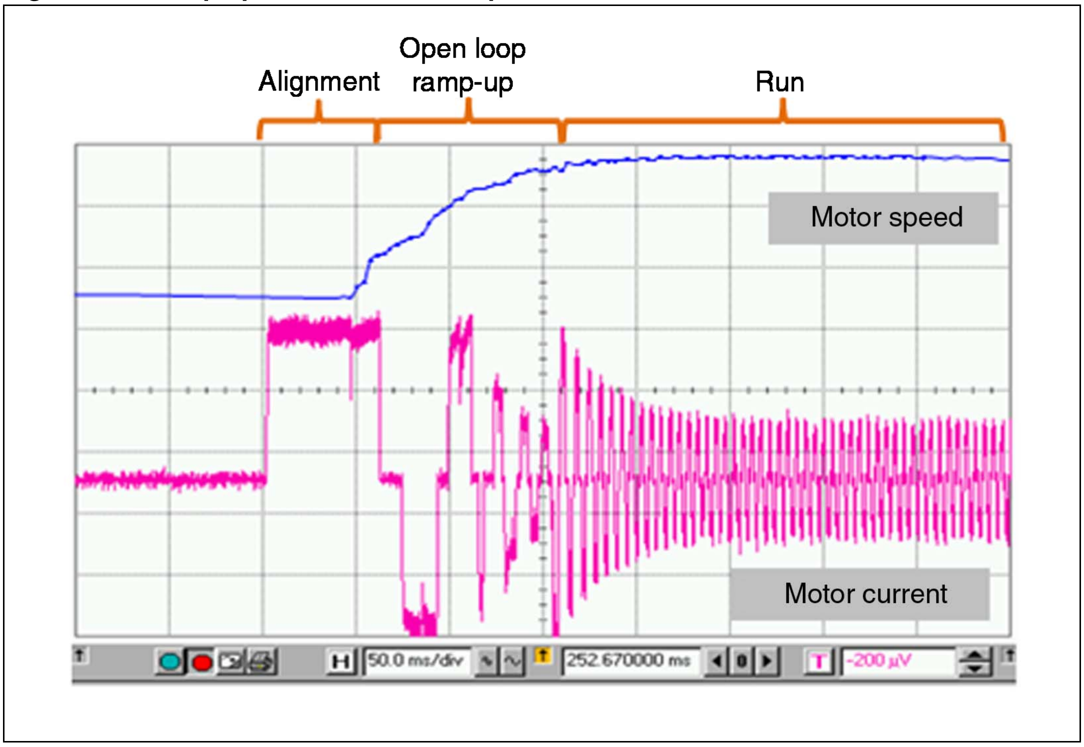


1. PMV is applies on high-side switches.
2. Back EMF is detected during “off” time of the PWM.

There is one additional problem to be overcome with the sensorless approach, starting the motor. If the rotor is not turning, no BEMF signal is generated and so the sensorless drive has no information about the position of the rotor. Since we cannot tell where the rotor is, our best bet is to tell the rotor where to go. If we circulate a DC current through phase AB, for example, we know that torque will be produced (although we cannot predict the direction) and this will cause the rotor to move. The rotor will move to one of the two zero crossing points on our plot. Note that only one of these two zero crossing points is a stable point. This is because at the positive slope crossing, any movement in the clockwise direction would produce clockwise torque which will produce more clockwise movement, etc. At the negative slope point, however, movement in either direction will result in a torque in the opposite direction, so the rotor will stay put. This procedure of circulating DC current in a phase in order to bring the rotor to a known position is referred to as prepositioning or alignment (since the rotor is aligning itself with the field created by the stator not unlike the way that a compass needle aligns itself with the earth's magnetic field).

Now that we know where the rotor is, we know that the proper next phase should be BC and this should be followed by BA, CA, CB, etc. When should we switch phases? We do not know and, until we have built up enough speed we will not have any information from the BEMF. The procedure we use here is to operate in an open loop stepping mode where the phases are advanced on a fixed time schedule that has been predetermined based on the expected acceleration rate of the motor. The step times generated in this manner will not be exactly correct, but we do have some margin for error and it should not be necessary to do more than six to ten steps in this manner until we have built up sufficient speed that the BEMF signal can be read and utilized. When the commutation state machine determines that it is receiving an adequate BEMF signal, the mode of operation is automatically switched to a synchronized commutation. For most systems, this “open loop ramp-up” will take well less than a second. *Figure 10* shows a scope plot of the motor speed and motor current during alignment, ramp-up, and synchronized commutation.

Figure 10. Scope plot of motor startup



Appendix A Derivation of motor terminal voltage formula

Figure 11 provides a detailed equivalent circuit of the motor and inverter bridge during PWM off time that we will reference in order to analyze the circuit. Since no current flows in phase C we have:

Equation 1

$$V_c = e_c + V_n$$

From phase A, if the forward voltage of the diode is ignored we have:

Equation 2

$$V_n = 0 - ri - L\frac{di}{dt} - e_a$$

From phase B, if the voltage drop of the transistor is ignored we have:

Equation 3

$$V_n = 0 + ri + L\frac{di}{dt} - e_b$$

Adding *Equation 2* and *Equation 3* we get:

Equation 4

$$2V_n = -e_a - e_b \quad \text{or} \quad V_n = \frac{-(e_a + e_b)}{2}$$

In a balanced three phase system, ignoring possible harmonics, we can assume that:

Equation 5

$$e_a + e_b + e_c = 0 \text{ or } e_c = -(e_a + e_b)$$

Substituting *Equation 5* into *Equation 4* yields:

Equation 6

$$V_n = \frac{e_c}{2}$$

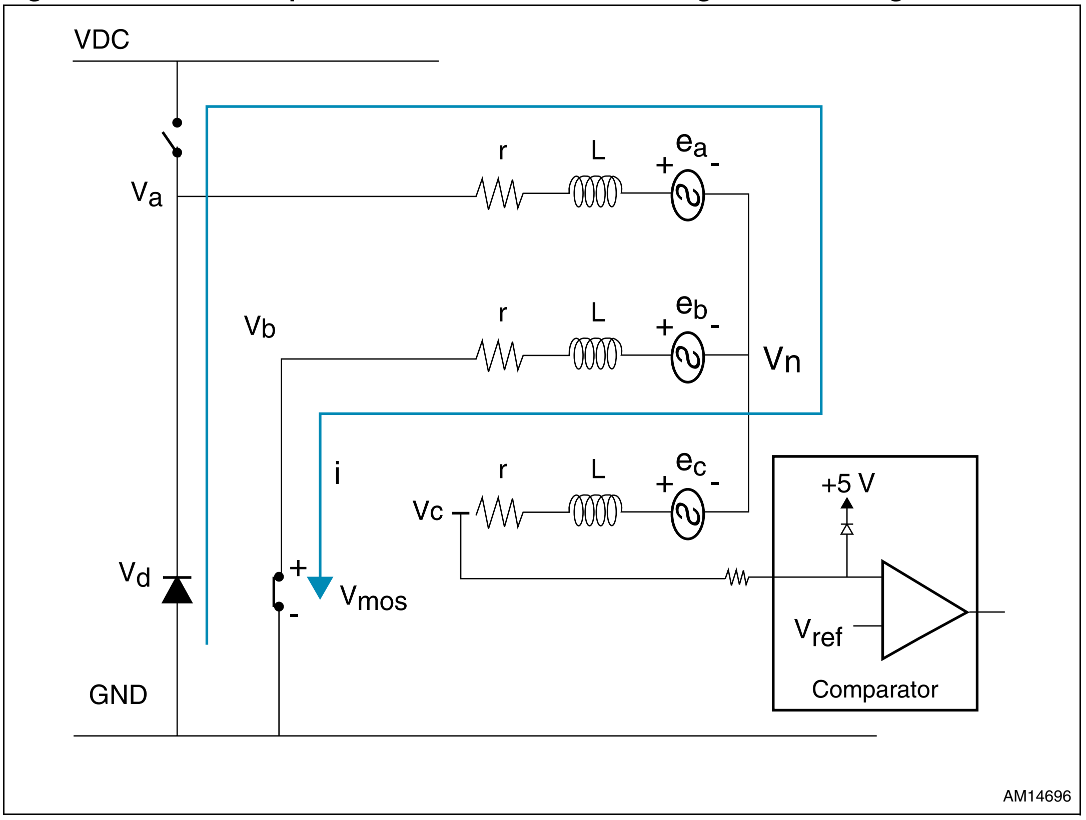
Substituting *Equation 6* into *Equation 1* yields:

Equation 7

$$V_c = e_c + \frac{e_c}{2} \quad \text{or} \quad V_c = 1.5e_c$$

Thus, the signal we see at the motor terminal of the floating phase during PWM off time is directly proportional to the phase BEMF, just 1.5 times bigger.

Figure 11. Detailed equivalent motor and inverter bridge circuit during PWM off time



Appendix B Commutation delay

Referring to *Figure 11* and the derivation of *Appendix A*, it is clear that the BEMF signal that is “visible” during the PWM off time is that of the line to neutral BEMF voltages, e_{an} ,e_{bn}, and e_{cn}. The signals shown in *Figure 8* are the line to line BEMF voltages e_{ab}, e_{bc}, and e_{ca} and it is the zero crossings of these signals that mark the proper bridge commutation times. Fortunately, the phase relationship between these signals is well known and advantageous for our purposes. e_{an} leads e_{ab} by 30 degrees, e_{bn} leads e_{bc} by 30 degrees, and e_{cn} leads e_{ca} by 30 degrees. Since we detect the time of each line to neutral zero crossing, the time between these zero crossings gives us the time interval associated with 60 electrical degrees, which changes with the speed of the motor. Since the zero crossing of the line to neutral that we sense leads the line to line, we need only to delay the commutation of the bridge by a nominal value of one half of the zero crossing to zero crossing time (which is referred to as a step time) in order to get our commutations at the proper time.

Please note that while the theoretical commutation delay time is one half of the step time, it is often found advantageous to make some adjustment to this setting. This is very often done in the case of high motor speeds. The ultimate objective of commutating the motor at the correct time is to maintain close to a unity power factor, which assures optimal torque production. Power factor, however, is determined by the phase relationship of the phase currents to the line to neutral BEMF. The inverter bridge is a voltage source device and we control the timing of the applied voltage. When motor speeds and commutating frequencies are relatively low, applying the driving voltage to the motor in sync with the BEMF will also place the motor current reasonably in phase. As operating frequencies go up, however, the inductive nature of the load can cause the motor current to start to lag the BEMF. To compensate for this, many motor drives will implement a speed dependent phase advance of the commutation timing. Since the commutation is nominally delayed by 30 degrees, we can easily get up to 30 degrees of effective phase advance by reducing the delay. It is also possible to retard the commutation beyond the nominal, but this is rarely done.

Appendix C Demagnetization time allowance

The concept of demag time is developed and explained in *Appendix D*. *Figure 12* presents a plot of motor terminal voltage where the effects of the demag interval can be clearly seen just after bridge commutation and before the floating phase voltage characteristic is observed. It is also possible to observe the demag interval by looking at an oscilloscope plot of phase current. As each phase goes from conducting (in either polarity) to zero current, a finite time interval can be observed as the magnitude of the current falls to zero. In the design of a sensorless commutation state machine it is important to make allowance for this demag time interval. Immediately after commutation of the bridge we would like to move forward to the state where we start sampling the BEMF of the floating phase but we must introduce a time delay state long enough to allow the current to fall to zero. This is because our entire analysis of being able to “see” the BEMF is based on the phase current being zero. If current is still flowing, a freewheeling diode is conducting and we will “see” nothing but DC bus of ground. In short, we would get fooled.

In practice, the demag allowance “blanking” time, when we do not look at BEMF, is usually set as a fixed proportion of the current step time. A good nominal value is usually around 25% of a step time. The actual length of demag time is approximately directly proportional to motor inductance and motor current level and inversely proportional to motor BEMF level (speed) since it is primarily motor BEMF that “drives” current out of the exiting phase. It is interesting to note that if demag time ever exceeds one half of a step time we have a “drop dead” situation where the sensorless system will no longer function properly. This is because the BEMF zero crossing normally occurs at the mid point of the commutation step. If the demag time extends beyond this half way point we cannot “see” the zero crossing because it is masked by the phase current that is still flowing.

Fortunately, it is uncommon for motor demag times to exceed half a step time. Although step times keep getting shorter as motor speed increases, BEMF is also increasing and these two items tend to cancel out. The worst offending motors tend to be lower cost motors that use weak magnets and compensate by having lots of turns of wire in the stator. This causes the inductance to be high, which increases demag time. The worst case for excessive demag time is generally found with low speed (BEMF), high current, and a high inductance motor. There are some bridge switching techniques, generally referred to as “fast demag” which can help to remedy this situation by modifying current circulation path during demag so that the decaying current flows back out through the DC bus rather than just circulating through the bridge. This will cause the voltage forcing current out of the exiting phase to be BEMF plus Vbus rather than just BEMF. The details of such techniques are beyond the scope of this paper.

In any case, to be thorough, a sensorless system should be evaluated to be sure that the demag time is within the allowance. A default setting around 25% of a step time works well for most systems, but it may need to be increased. Of course, it should never be set to greater than one half of a step time and, in practice, probably not more than 40%.

Appendix D Motor terminal voltage oscilloscope plots

Figure 12 presents an oscilloscope plot of the motor terminal voltage with respect to system ground (negative side of the DC bus). Superimposed on the plot is a representation of the line to neutral BEMF as would be seen if the motor was simply being rotated with a mechanical driver of some type. During the two floating phases we can clearly see that the low point (during PWM off time) of the voltage forms an envelop that follows the BEMF. The start of the left hand side floating interval is marked by a spike up to the DC bus level. This is caused by commutation of the bridge when the low side transistor of that phase turns off and the motor current immediately transfers into the freewheeling diode on the top side. Since the high side diode is conducting, the motor terminal voltage is “nailed” to the DC bus and the voltage will stay there until the phase current decays to zero. This interval is referred to as the clearing or demagnetization time. After the demag time, actual BEMF would be negative but, because of the freewheeling diodes in the low side of the bridge, the voltage is clamped to one diode drop below ground and appears flat. At the point where the BEMF polarity becomes positive, we can see the low side of the voltage envelop starts to rise, and this is the time instant that we detect as the rising BEMF zero crossing. The observant reader will probably notice that the high side of the envelop (during PWM on time) also appears to follow the BEMF. In fact, this is the case, and it is possible to design a system that samples BEMF during the on time rather than the off time, using a comparison threshold equivalent to one half of the DC bus, rather than near zero. It is possible to extend the analysis presented in *Appendix A* to show that, during on time, the terminal voltage is essentially BEMF plus Vbus/2.

As one would expect, during the conducting phase, the terminal voltage is either Vbus or zero since it is being actively driven. The start of the right hand side floating phase is marked by another demag interval. In this case, the commutation is marked by the high side transistor turning off, which causes current to transfer into the freewheeling diode on the low side. Voltage will thus be “nailed” to ground until the current decays to zero. During this interval, we follow the voltage waiting for the falling edge zero crossing.

Figure 13 presents the broader view with the motor terminal voltage of all three phases. The square wave trace at the bottom of the plot is a diagnostic output from the controlling microprocessor which marks each zero crossing as it is detected.

Figure 12. Oscilloscope motor plot

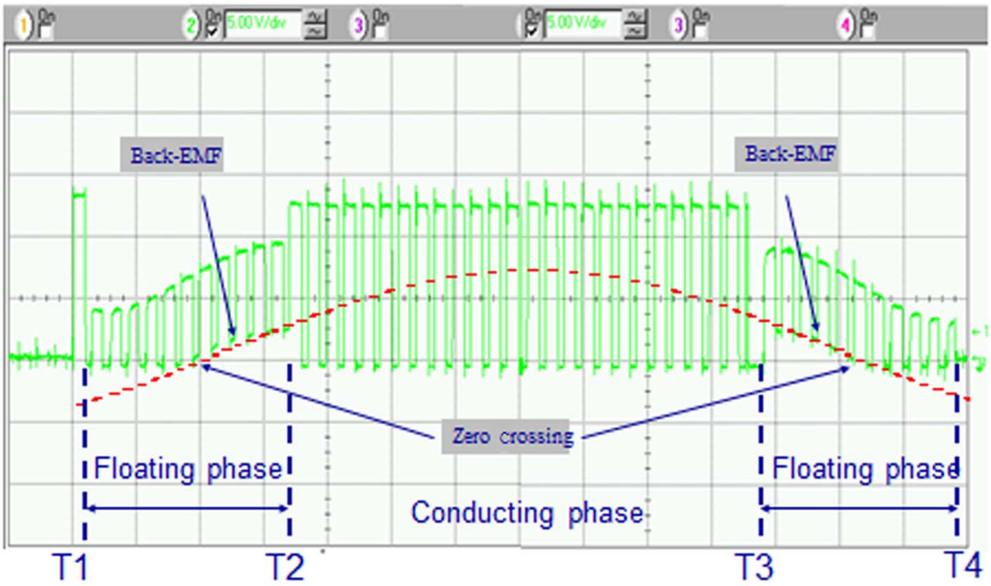
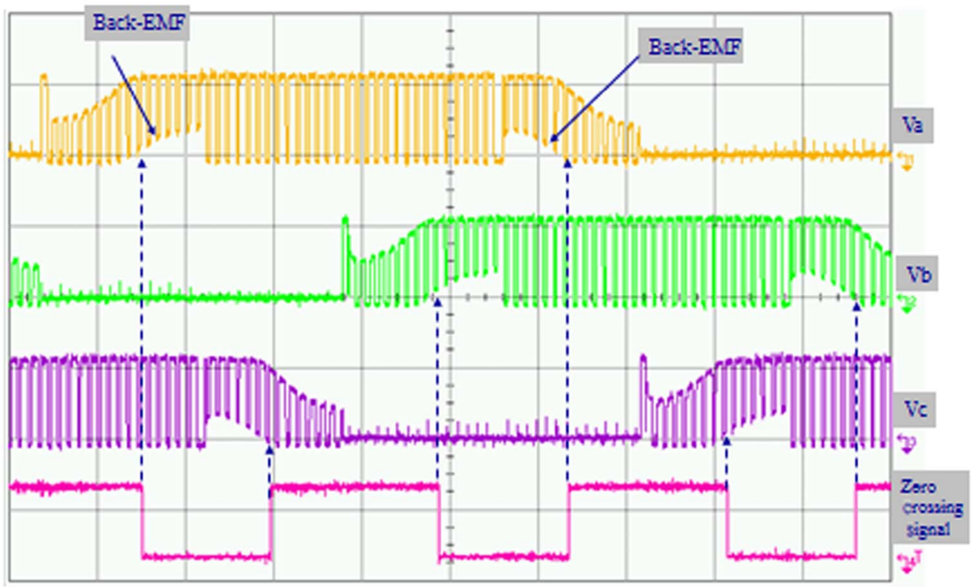


Figure 13. Broader view with the motor terminal voltage of all three phases



Revision history

Table 1. Document revision history

Date	Revision	Changes
11-Jan-2013	1	Initial release.