DSP Solutions for BLDC Motors

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ABSTRACT

This report presents generic considerations on the control of Brushless Permanent Magnet DC motors using the TMS320C24x. This new family of DSPs enables single chip, cost effective, modular and increased performance solutions for BLDC drives. A complete solution proposal is presented below: control structures, power hardware topology, shaft position sensors, control hardware and remarks on energy conversion efficiency can be found in this document. In addition, this report deals with sensorless algorithms as an alternative to position sensors for speed control.

1. Introduction

The economic constraints and new standards legislated by governments place increasingly stringent requirements on electrical systems. New generations of equipment must have higher performance parameters such as better efficiency and reduced electromagnetic interference. System flexibility must be high to facilitate market modifications and to reduce development time. All these improvements must be achieved while, at the same time, decreasing system cost.

Brushless motor technology makes it possible to achieve these specifications. Such motors combine high reliability with high efficiency, and for a lower cost in comparison with brush motors. This paper describes the use of a Brushless DC Motor (BLDC). Although the *brushless* characteristic can be apply to several kinds of motors - AC synchronous motors, stepper motors, switched reluctance motors, AC induction motors - the BLDC motor is conventionally defined as a permanent magnet synchronous motor with a trapezoidal Back EMF waveform shape.

To drive these motors, Texas Instruments offers a new DSP controller family, referenced TMS320C24x, specifically designed for the needs of digital motor control. In a single chip solution, this device combines a fixed-point DSP core with micro-controller peripherals. This component is able to perform sophisticated control schemes as well as algorithms which can act as a substitute for position sensors.

2. The DSP in BLDC Motor Control

Motor drives are traditionally designed with relatively inexpensive analog components. The weaknesses of analog systems are their susceptibility to temperature variations and component aging. Another drawback is the difficulty of upgrading these systems.

Digital control structures eliminate drifts and, by using a programmable processor, the upgrades can be easily accomplished by software.

Digital Signal Processors go further. Their high performance allows them to perform high resolution control and minimize control loop delays. These efficient controls make it possible to reduce torque ripples and harmonics, and to improve dynamic behavior in all speed ranges. The motor design is optimized due to lower vibrations and lower power losses such as harmonic losses in the rotor. Smooth waveforms allow an optimization of power elements and input filters. Overall, these improvements result in a reduction of system cost and better reliability.

3. The TMS320C24x Family

As the first DSP optimized for digital motor control, the TMS320C240 is a single chip solution based on a 20 MIPS 16-bit fixed-point DSP core associated with several micro-controller peripherals such as a Pulse Width Modulation (PWM) generator and Analog to Digital Converters (ADC).

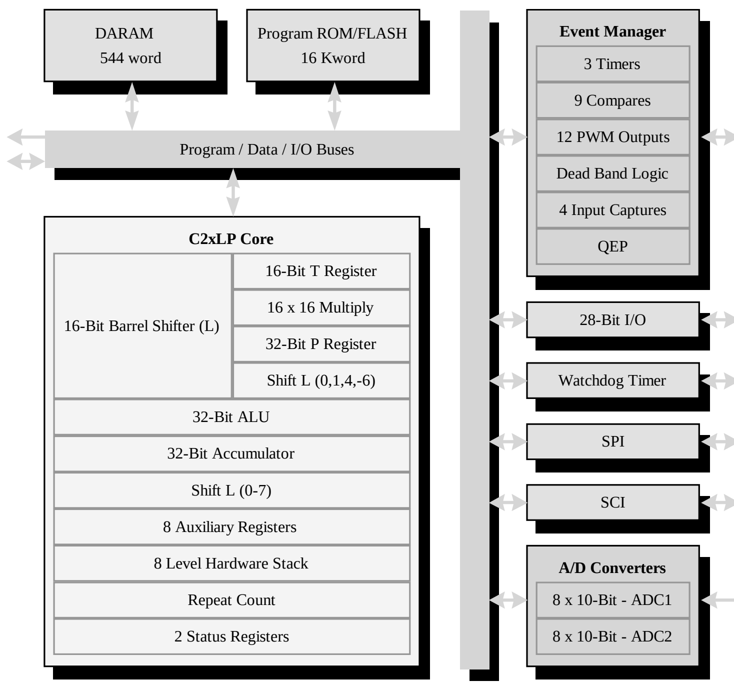

Figure 1: TMS320C240 Architecture

The C2xLP DSP core is a derivative of the TMS320C5x technology using the limited instruction set of the TMS320C2x. The source code is compatible with TMS320C2x devices and upward compatible with TMS320C5x devices. Main instructions are executed in a single cycle time of 50ns including the multiply/accumulation instruction.

The Harvard architecture shares the memory between program space and data space, allowing high performance. The TMS320C240 provides 16K words of program ROM and 544 words of DARAM. A Flash version is available, the TMS320F240, with 16K words of program memory.

A dedicated Event Manager module works in an intelligent manner with a minimum CPU load. Up to 12 PWM outputs are available. Three different time bases can be used to generate output signals. The PWM generator circuit supports asymmetrical or symmetrical modes as well as space vector modulation. Three independent pairs of PWM can be complemented and a programmable dead-band is also available. Up to 4 input captures are available. A Quadrature Encoder Pulse (QEP) circuit measures the position and the direction from 2 input signals. This system is often used in motor control to detect the rotor shaft position.

The TMS320C240 has two 10-bit Analog to Digital Converters (ADC). Each ADC has 8 channels and one sample and hold, enabling two simultaneous conversions. The device includes a watchdog timer to monitor software and hardware operations. A Serial Communication Interface (SCI) supports communication between CPU and other asynchronous peripherals. A high speed synchronous Serial Peripheral Interface (SPI) is available for communication between the CPU and external peripherals or another micro-controller. And, up to 28 individually programmable I/O pins are available.

4. The BLDC Motor

4.1 The AC Synchronous Motor

The BLDC motor is an AC synchronous motor with permanent magnets on the rotor (moving part) and windings on the stator (fix part).

Permanent magnets create the rotor flux. The energized stator windings create electromagnet poles. The rotor (equivalent to a bar magnet) is attracted by the energized stator phase, generating a rotation. By using the appropriate sequence to supply the stator phases, a rotating field on the stator is created and maintained. This action of the rotor - chasing after the electromagnet poles on the stator - is the fundamental action used in synchronous permanent magnet motors. The lead between the rotor and the rotating field must be controlled to produce torque. This synchronization implies knowledge of the rotor position.

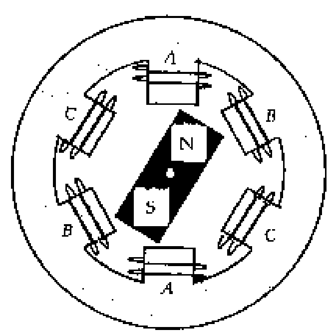

Figure 2: A 3-Phase Synchronous Motor with a Single Permanent Magnet Pair PoleRrotor

On the stator side, three phase motors are the most common. These offer a good compromise between precise control and the number of power electronic devices required to control the stator currents. For the rotor, a greater number of poles usually create a greater torque for the same level of current. On the other hand, by adding more magnets, a point is reached where, because of the space needed between magnets, the torque no longer increases. The manufacturing cost also increases with the number of poles. As a consequence, the number of poles is a compromise between cost, torque and volume.

4.2 The BLDC Motor Control

The key to effective torque and speed control of a BLDC motor is based on relatively simple torque and Back EMF equations, which are similar to those of the DC motor. The Back EMF magnitude can be written as:

$$E = 2NlrB\omega$$

and the torque term as :

$$T = \left(\frac{1}{2} i^2 \frac{dL}{d\theta}\right) - \left(\frac{1}{2} B^2 \frac{dR}{d\theta}\right) + \left(\frac{4N}{\pi} Brl\pi i\right)$$

Where N is the number of winding turns per phase, l is the length of the rotor, r is the internal radius of the rotor, B is the rotor magnet flux density, ω is the motor's angular velocity, i is the phase current, L is the phase inductance, θ is the rotor position, R is the phase resistance.

The first two terms in the torque expression are parasitic reluctance torque components. The third term produces mutual torque, which is the torque production mechanism used in the case of BLDC motors. To sum up, the Back EMF is directly proportional to the motor speed and the torque production is almost directly proportional to the phase current. These factors lead to the following BLDC motor speed control scheme:

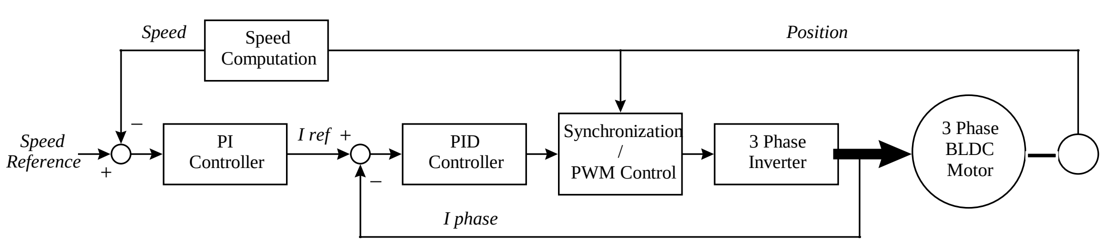

Figure 3: Speed and Current Control Loop for a BLDC Motor

The BLDC motor is characterized by a *two phase ON* operation to control the inverter.

In this control scheme, torque production follows the principle that current should flow in only two of the three phases at a time and that there should be no torque production in the region of Back EMF zero crossings. The following figure describes the electrical wave forms in the BLDC motor in the *two phases ON* operation.

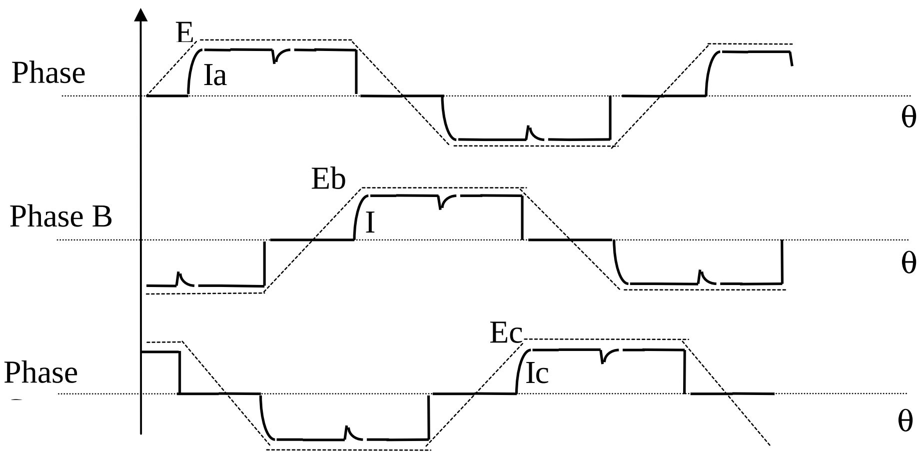

Figure 4: Electrical Waveforms in the Two Phase ON Operation

This control structure has several advantages:

- Only one current at a time needs to be controlled.
- Only one current sensor is necessary.
- The positioning of the current sensor allows the use of low cost sensors as a shunt.

We have seen that the principle of the BLDC motor is, at all times, to energise the phase pair which can produce the highest torque. To optimize this effect the Back EMF shape is trapezoidal. The combination of a DC current with a trapezoidal Back EMF makes it theoretically possible to produce a constant torque. In practice, the current cannot be established instantaneously in a motor phase, as a consequence the torque ripple is present at each 60 degree phase commutation.

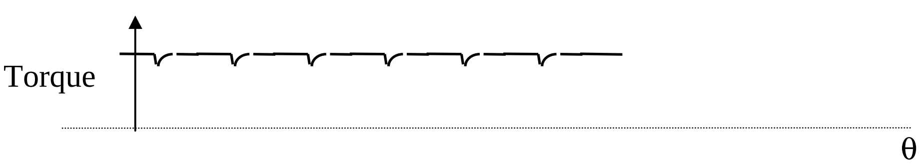

Figure 5: Torque Ripple in a BLDC Motor

If the motor used has a sinusoidal Back EMF shape, this control can be applied but the produced torque is:

- Firstly, not constant but made up from portions of a sine wave. This is due to its being the combination of a trapezoidal current control strategy and of a sinusoidal Back EMF. Bear in mind that a sinusoidal Back EMF shape motor controlled with a sine wave strategy (*three phase ON*) produces a constant torque.
- Secondly, the torque value produced is weaker.

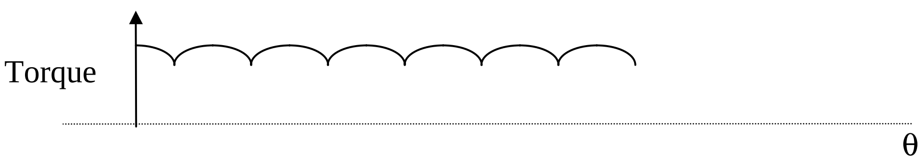

Figure 6: Torque Ripple in a Sinusoidal Motor Controlled as a BLDC

5. System Topology

5.1 Three Phase Inverter

The BLDC motor control consists of generating DC currents in the motor phases. This control is subdivided into two independent operations: first, stator and rotor flux synchronization, then control of the current value. Both operations are realized through the three phase inverter depicted in the following scheme.

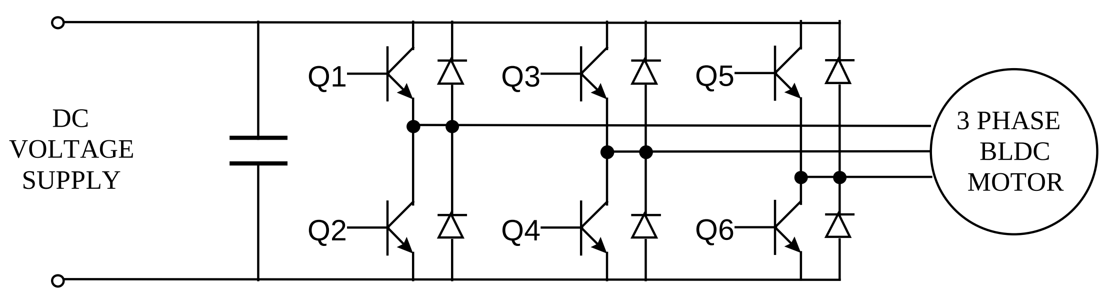

Figure 7: Three Phase Inverter

The flux synchronization is derived from the position information coming from sensors, or from sensorless techniques. From the position, the controller defines the appropriate pair of transistors (Q1 to Q6) which must be driven.

The regulation of the current to a fixed 60 degrees reference can be realized in either of the two different modes:

5.1.1 The Pulse Width Modulation (PWM) Mode

The supply voltage is chopped at a fixed frequency with a duty cycle depending on the current error. Therefore both the current and the rate of change of current can be controlled. The two phase supply duration is limited by the two phase commutation angles. The main advantage of the PWM strategy is that the chopping frequency is a fixed parameter; hence, acoustic and electromagnetic noise are relatively easy to filter.

There are also two ways of handling the drive current switching: hard chopping and soft chopping.

In the hard chopping technique both phase transistors are driven by the same pulsed signal: the two transistors are switched-on and switched-off at the same time. The power electronics board is then easier to design and is also cheaper as it handles only three pulsed signals. A disadvantage of the hard chopping operation is that it increases the current ripple by a large factor in comparison with the soft chopping approach.

The soft chopping approach allows not only a control of the current and of the rate of change of the current but a minimization of the current ripple as well. In this soft chopping mode the low side transistor is left ON during the phase supply and the high side transistor switches according to the pulsed signal. In this case, the power electronics board has to handle six PWM signals.

5.1.2 The Hysteresis Mode

In the hysteresis-type current regulator, the power transistors are switched off and on according to whether the current is greater or less than a reference current. The error is used directly to control the states of the power transistors. The hysteresis controller is used to limit the phase current within a preset hysteresis band. As the supply voltage is fixed, the result is that the switching frequency varies as the current error varies. The current chopping operation is thus not a fixed chopping frequency PWM technique. This method is more commonly implemented in drives where motor speed and load do not vary too much, so that the variation in switching frequency is small. Here again, both hard and soft chopping schemes are possible. Since the width of the tolerance band is a design parameter, this mode allows current control to be as precise as desired, but acoustic and electromagnetic noise are difficult to filter because of the varying switching frequency.

5.2 Shaft Position Sensors

The position information is used to generate precise firing commands for the power converter, ensuring drive stability and fast dynamic response. In servo applications position feedback is also used in the position feedback loop. Velocity feedback can be derived from the position data, thus eliminating a separate velocity transducer for the speed control loop.

Three common types of position sensors are used: the incremental sensors and the three Hall effect sensor.

- The *incremental sensors* use optically coded disks with either single track or quadrature resolution to produce a series of square wave pulses. The position is determined by counting the number of pulses from a known reference position. Quadrature encoders are direction sensitive and so do not produce false data due to any vibration when the shaft begins rotation. The Quadrature Encoder Pulse unit of the TMS320C24x DSP handles encoders output lines and can provide 1, 2 or 4 times the encoder resolution. Speed information is available by counting the number of pulses within a fix time period.

- The *three Hall effect sensors* provide three overlapping signals giving a 60° wide position range. The three signals can be wired to the 'C24x DSP Input Capture pins, thus speed information is available by measuring the time interval between two Input Captures. The time interval is automatically stored by the TMS320C24x into a specific register at each Input Capture. From speed information it is numerically possible to get the precise position information needed for sharp firing commands.
- The *resolver* is made up of three windings (different from the motor's windings): one linked to the rotor and supplied with a sinusoidal source and two other orthogonal coils linked to the stator. A Back EMF is induced by the rotating coil in each of the two stator resolver windings. By decoding these two signals it is possible to get $\cos(\theta)$ and $\sin(\theta)$ where θ is the rotor position. The resolver resolution depends only on the AD conversion.

5.3 Current Sensors

A characteristic of the BLDC control is to have only one current at a time in the motor (*two phases ON*). Consequently, it is not necessary to put a current sensor on each phase of the motor; one sensor placed in the line inverter input makes it possible to control the current of each phase. Moreover, using this sensor on the ground line, insulated systems are not necessary, and a low cost resistor can be used.

6. Enhanced Sensorless Algorithms

A way to reduce system cost is to replace expensive components such as position sensors. In the following paragraphs, we present several solutions which can be easily implemented in a TMS320C24x.

6.1 Direct Back EMF measurement

The first step in the development of a BLDC control without any position sensor is the detection and analysis of the motor back-EMF. For trapezoidal motors, the direct back-EMF analogue measurement is the most popular method. The motor is fed two phase ON, with 60º commutation periods, and detection of the commutation instant is performed by sensing the back-EMF in the non-fed phase. Actually, the BLDC motor voltage equation can be written as :

$$u = Ri + L\frac{di}{dt} + e$$

where u is the phase voltage, R is the phase resistance, L the phase inductance and e the Back EMF term. This Back EMF term can be written as follows (sinusoidal waveform or first harmonic of a trapezoidal Back EMF) :

$$e = kw\sin(p\theta)$$

where p is the number of pole pairs. Thus for a 120° commutation the current is zero during two sixths of the mechanical period, making the terminal voltage equal to the Back EMF term in these zero current periods. In particular, the Back EMF zero crossings give specific positions for each period and can be used in the same way as Hall effect sensor signals to switch the power inverter.

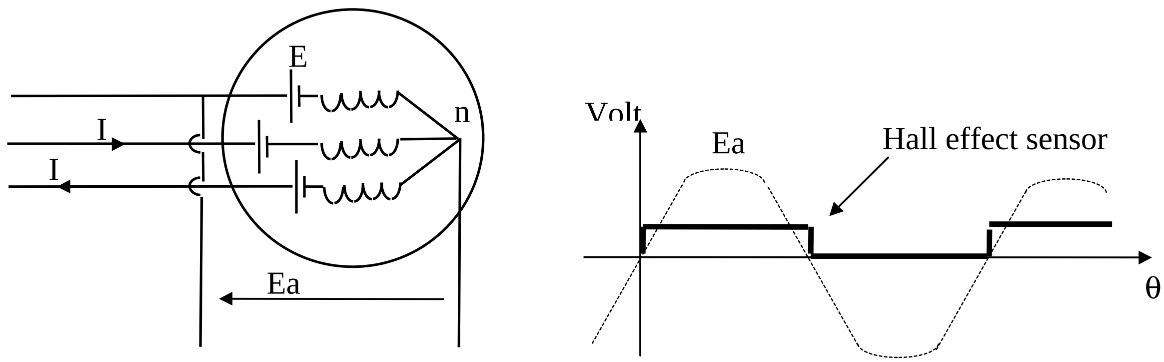

Figure 8: Direct Back EMF Measurement

This simple method makes it necessary to get the neutral point out of the star connected stator and to avoid the magnetic circuit saturation effects. The solution presented below answers the two above mentioned problems. It only requires measurement of the three terminal voltages.

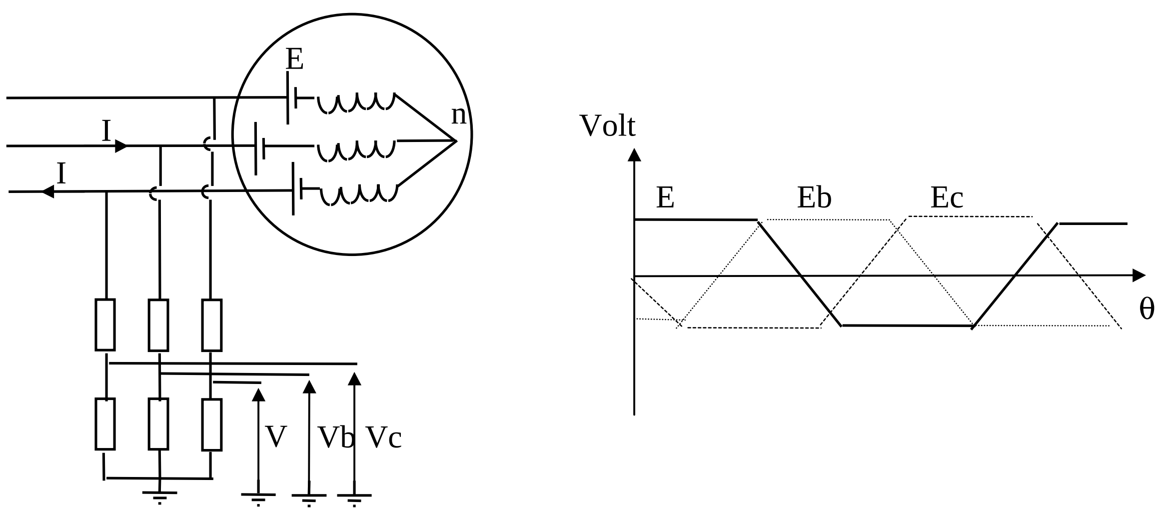

Figure 9: Back EMF measurement

Assuming that phase A is the non-fed phase it is possible to write the following equations for the three terminal voltages:

$$Va = Ea + Vn$$

$$Vb = Eb + RI + L\frac{dI}{dt} + Vn$$

$$Vc = Ec - RI - L\frac{dI}{dt} + Vn$$

When the Back EMF of the non-fed phase A is equal to zero, the following relationship between the terminal voltages arises:

$$Va = \frac{Vb + Vc}{2}$$

This can be used to obtain the six commutation points. This method is applicable even with poor quality windings (containing iron) and heavy loads.

The reliability of this method depends on the measured signals. As the magnitude of the Back EMF signal increases and decreases with the speed, this method is usable only after a specific minimum speed. This critical speed is around 5% of the rated speed. This control strategy implemented on the TMS320C24x allows a single chip, low cost, efficient and fast BLDC drive solution.

6.2 Indirect Back EMF Determination

For a 180° commutation or for a 120° high frequency commutation the Back EMF detection cannot be realized. An indirect Back EMF measurement is necessary using either an electronic approach or a Luenberger type sensor (digital approach) to solve the terminal voltage equation according to the Back EMF term. An explanation of the second control technique can be found in the *DSP Solution for Permanent Magnet Synchronous Motor* Texas Instruments Application Report. The electronic approach is only usable for large motors, for which the resistive term is relatively small compared with the inductive one, thus making it possible to neglect the resistance thermal effect. By sensing the phase current and deriving it through an operational amplifier (connected as a differentiator circuit which is very sensitive to commutation noises), the difference between the terminal voltage and the Back EMF term can be determined (as we get the terminal voltages from the ADC and from the differentiator the Ldi/dt term). The rotor position and the rotor speed can be deduced from this difference signal as in the digital solution. The main drawbacks of this control approach are the more limited range of motors for which this method is applicable, and the fact that it is a multi-chip solution which is temperature and age sensitive.

6.3 Open Loop

In the above mentioned methods the initial rotor position and the rotating direction have to be known. Furthermore, the Back EMF waveform is not detectable at low speed operation because its level is too low. Two ways of solving this problem are possible: the first solution is to implement a position determination at 0 rpm by sensing the phases' reluctance and the second solution is to design an open-loop algorithm. In this case, the initial rotor position is determined by magnetically stalling the rotor. The speed sufficient to get a reliable Back EMF signal is reached thanks to a similar stepper motor speed control. This control also determines the direction of rotation.

6.4 Saturation Effects

Although BLDC motors are more and more often wound with non saturating iron-less copper, most of the Permanent Magnet Motor Drives have to encounter the saturation of the magnetic circuit. This saturation means that the stator flux magnitude does not remain linear with phase current but becomes flat from a specific required current as depicted below:

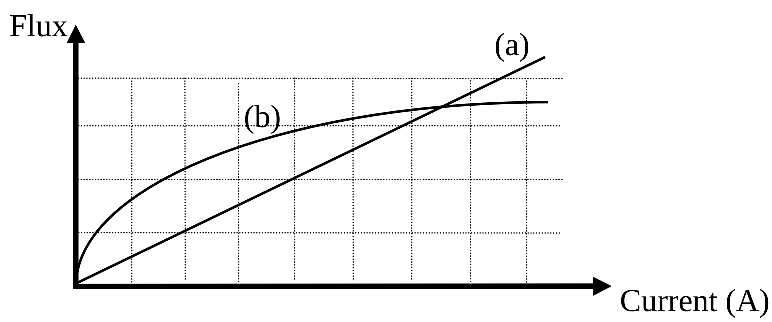

Figure 10: Saturation Curves for an ironless windings (a) and for magnetic material (b)

This effect modifies the Back EMF waveform shape and magnitude (as seen in chapter 4.2.) and has to be taken into account in the control structure otherwise neither flux synchronization nor magnet over-temperature protection are any longer possible. The TMS320C24x real time capabilities allow accurate input terminal voltage control and thus a control of the magnetic circuit saturation.

7. Results

In this section some first results are presented concerning a DSP-Controller solution for a complete 100W 12V BLDC drive sensorless speed control without the neutral point brought out of the motor. The control uses a symmetric Pulse Width Modulator at 20 kHz. The speed control loop is implemented using a standard PI regulator block and the current control using a first order recursive filter. The current is sensed by means of a low cost shunt resistor and the shaft position sensor is removed. This control also uses three ADC inputs to measure the terminal voltages. The proposed control is implemented using Texas Instruments Assembler language with fixed precision numerical representation. The control algorithm is synchronized by the PWM Period Interrupt that generates interrupts. The speed is controlled once every few current control cycles and the speed feedback is computed from the Back EMF zero crossing detection. The dV/dt due to phase commutation are managed by the CPU to avoid misinterpretation of the measured terminal voltage.

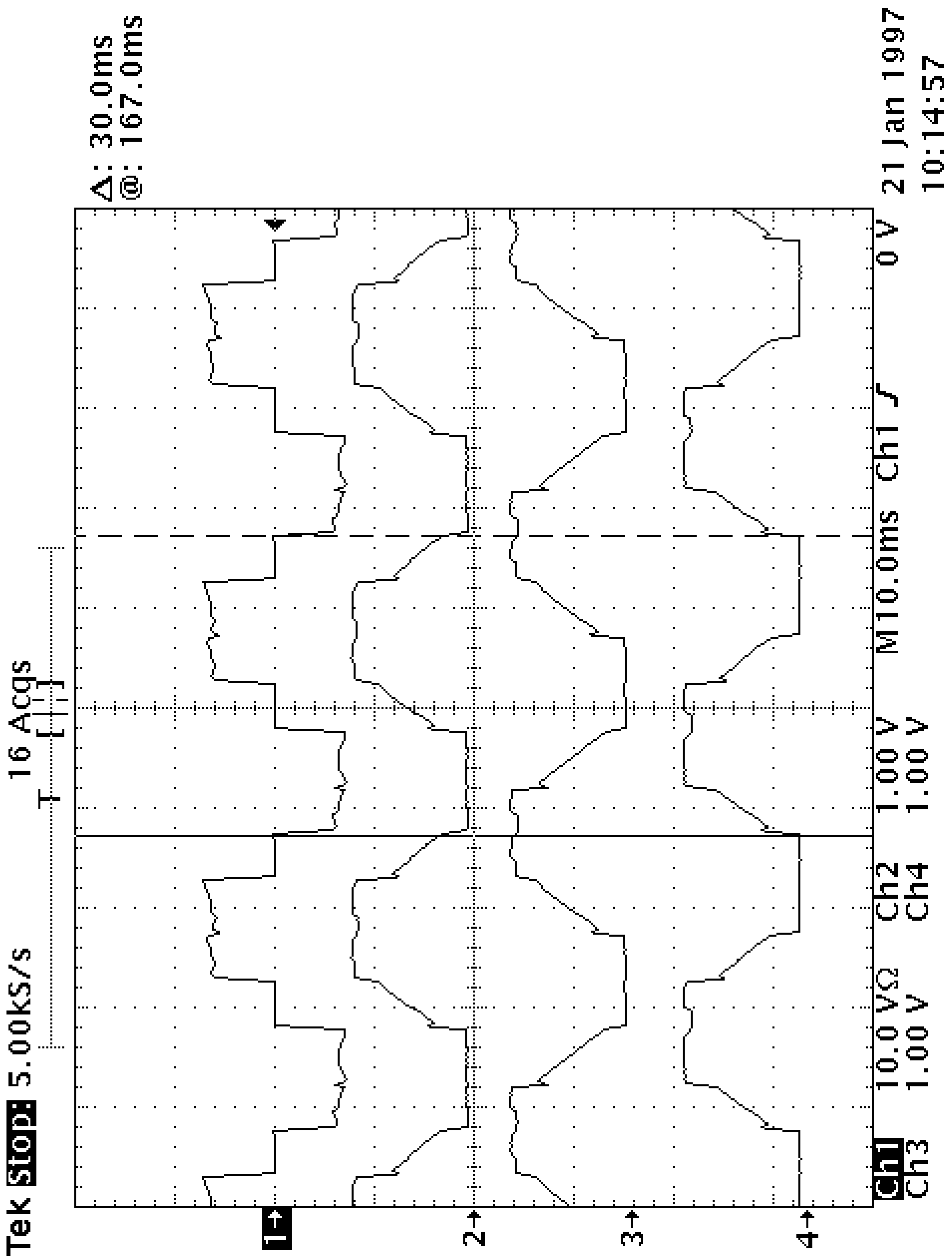

Table 1: Results

Channel 1	Channel 2	Channel 3	Channel 4
A phase current	Half Bridge voltage1	Half Bridge voltage2	Half Bridge voltage3

Speed référence	: 2000 rpm
Speed reached	: 2000 rpm
Speed ripple	: <0.5%
Torque	: 0.1 N.m (20% of max torque)
Power	: 20W

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