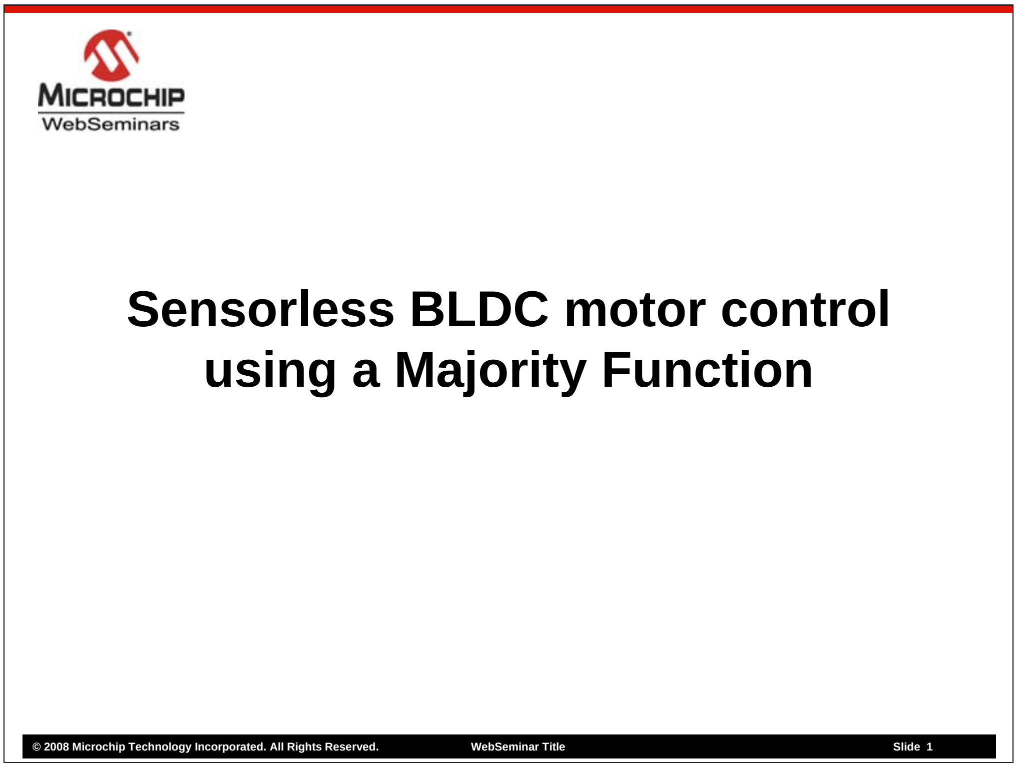


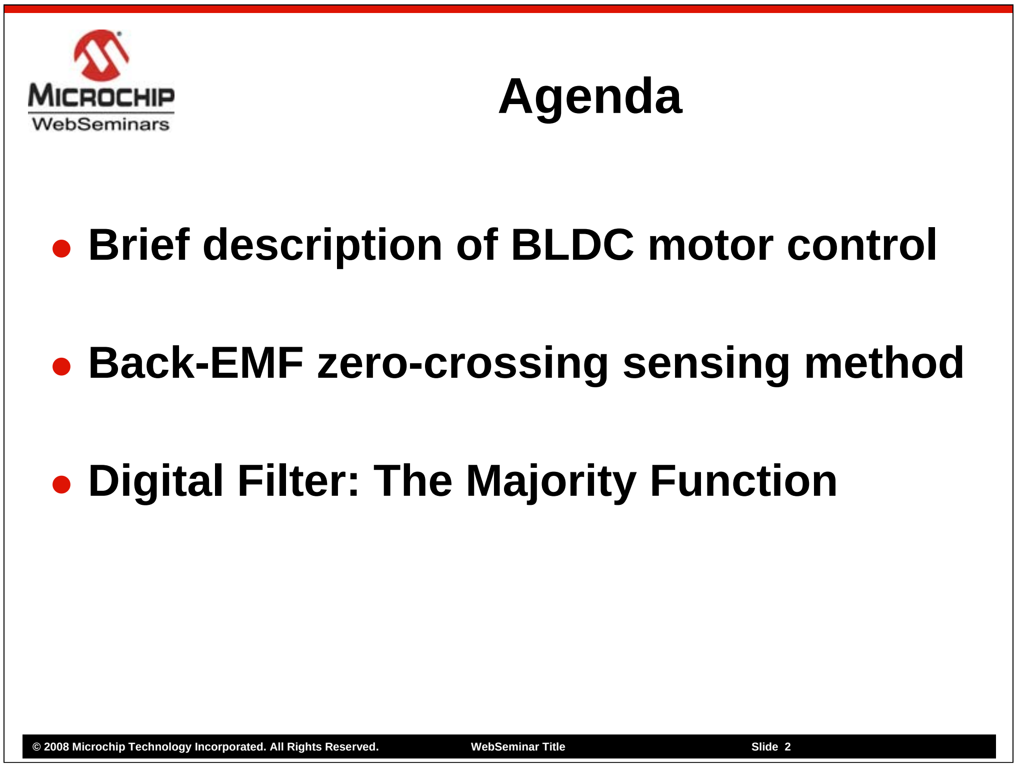
MICROCHIP WebSeminars

Sensorless BLDC motor control using a Majority Function

WebSeminar Title Slide 1

Welcome to the Sensorless Brushless DC motor control using a Majority Function Web Seminar.

My name is Daniel Torres and I am an applications engineer for the dsPIC® Digital Signal Controller Division at Microchip.

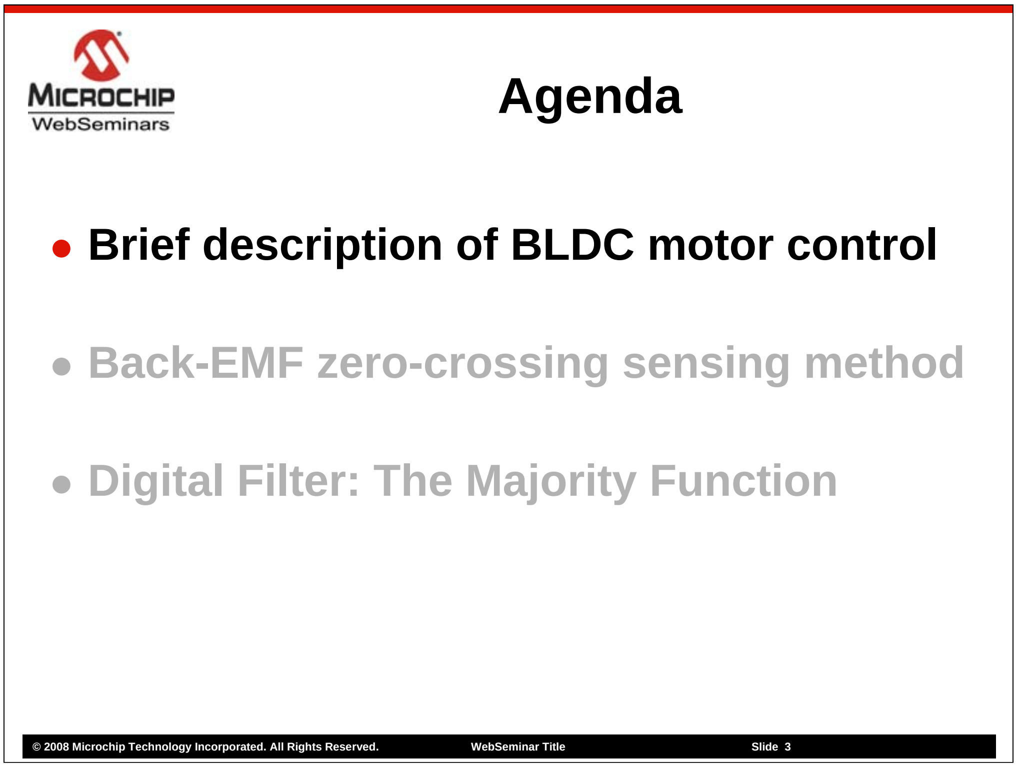


Agenda

- Brief description of BLDC motor control
- Back-EMF zero-crossing sensing method
- Digital Filter: The Majority Function

Here is the Agenda for today’s seminar.

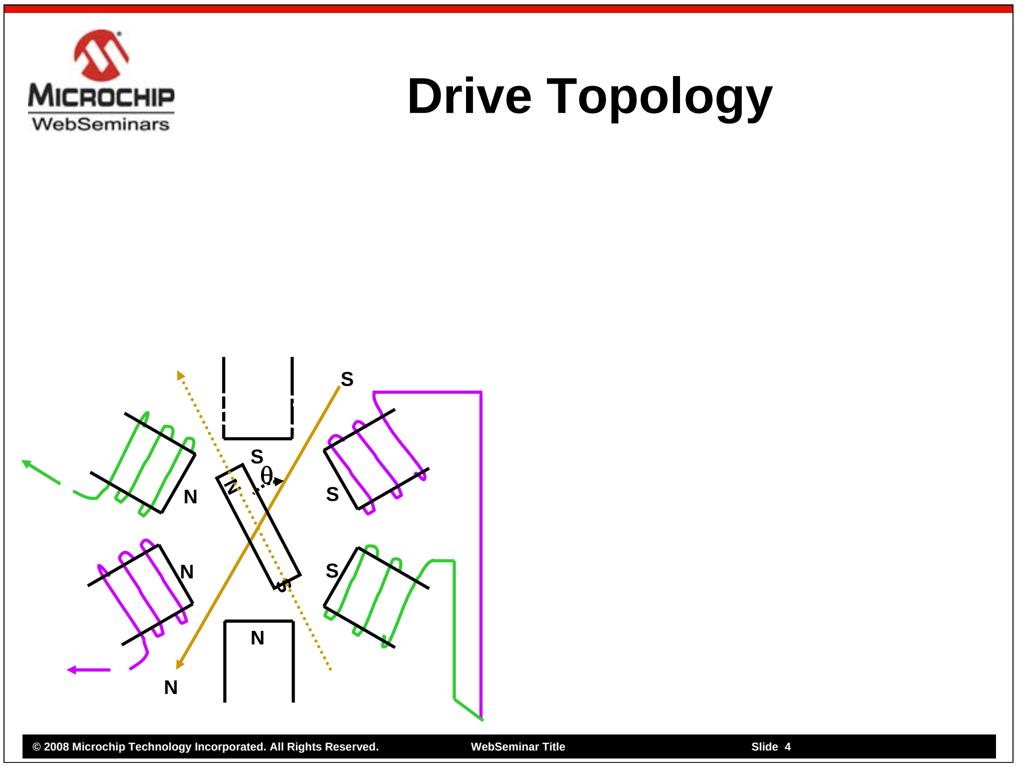
We will recall the principles of controlling a brushless DC motor Secondly we will discuss the back-EMF sensing method used in this sensorless technique we will cover the principles of the digital filter, the so-called “majority function”. The last section of this seminar discusses the motor start-up sequence and the sensorless operation.



Agenda

- **Brief description of BLDC motor control**
- **Back-EMF zero-crossing sensing method**
- **Digital Filter: The Majority Function**

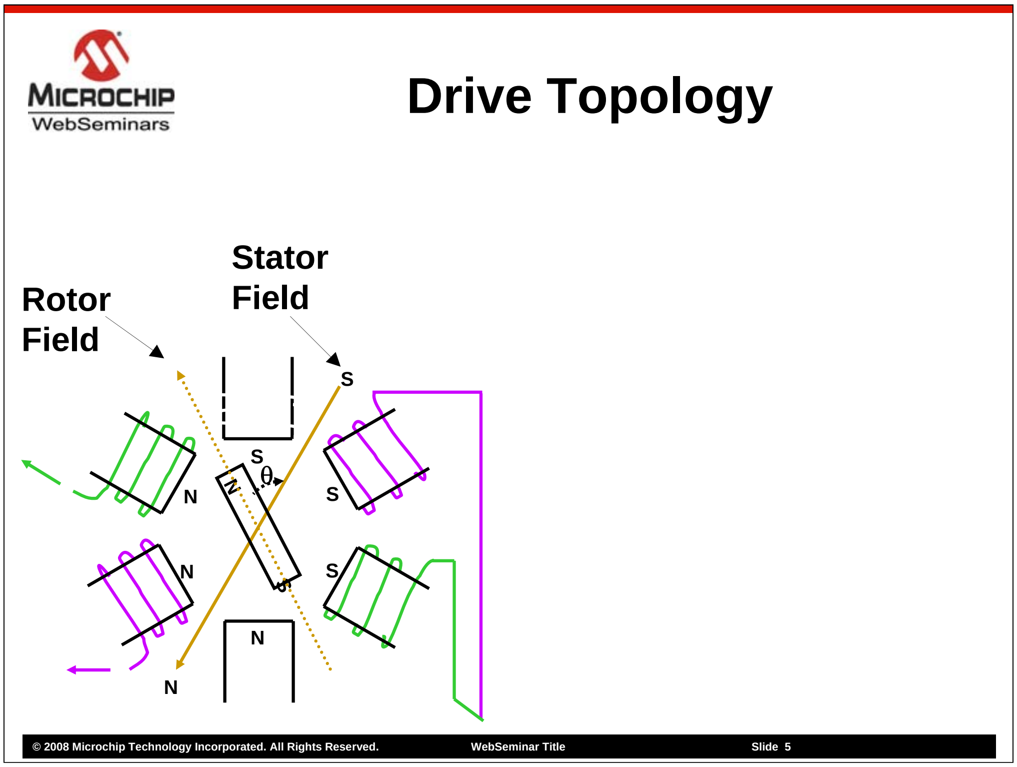
Brief description of the brush-less DC motor control. In this section we will discuss the principles of controlling a brushless DC motor; the six-step commutation control technique, and it is relationship with the back-EMF zero-crossings.



Drive Topology

WebSeminar Title Slide 4

A brushless DC motor has windings on stator and alternate permanent magnets on rotor.

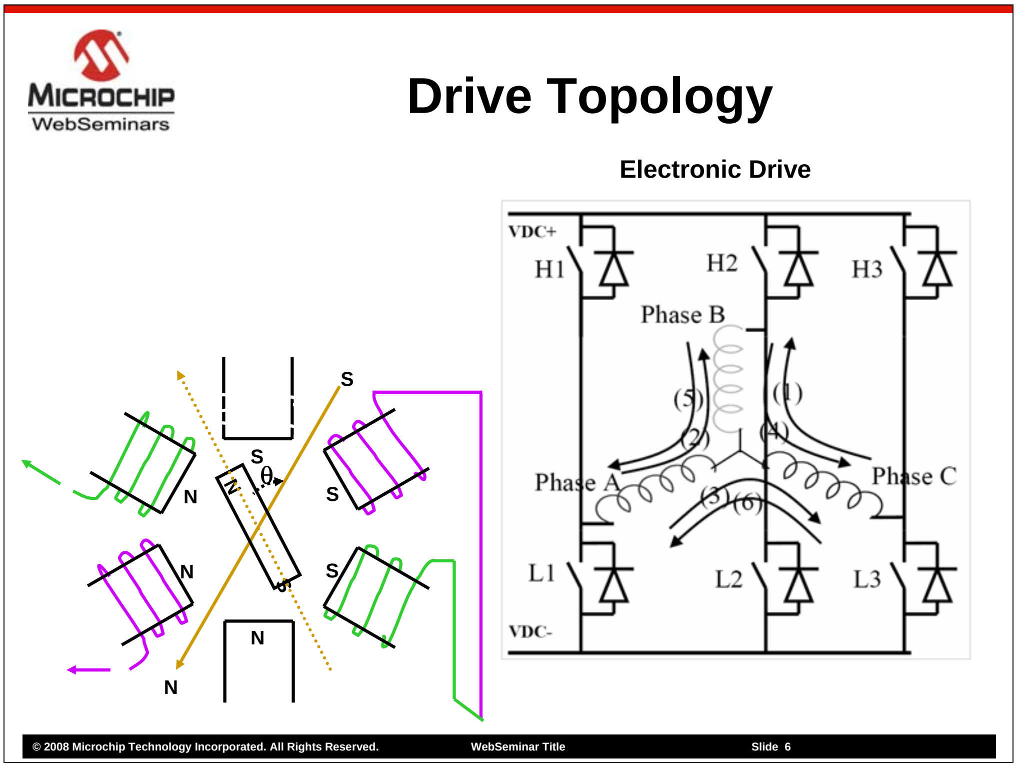


Drive Topology

Rotor Field

Stator Field

BLDC motors are electronically commutated based on the rotor position with respect to the stator winding.



Drive Topology

Electronic Drive

WebSeminar Title Slide 6

This means, to run a BLDC motor an electronic drive is required.

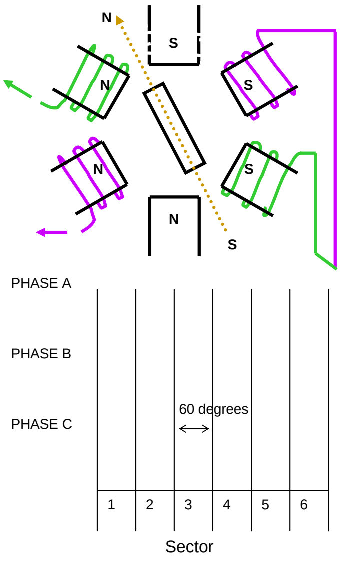
The BLDC motor is usually operated with one or more rotor position sensors since the electrical excitation must be synchronous to the rotor position.

For reasons of cost, reliability, mechanical packaging and especially if the rotor runs immersed in fluid, it is desirable to run the motor without position sensors, which is commonly known as sensorless operation.

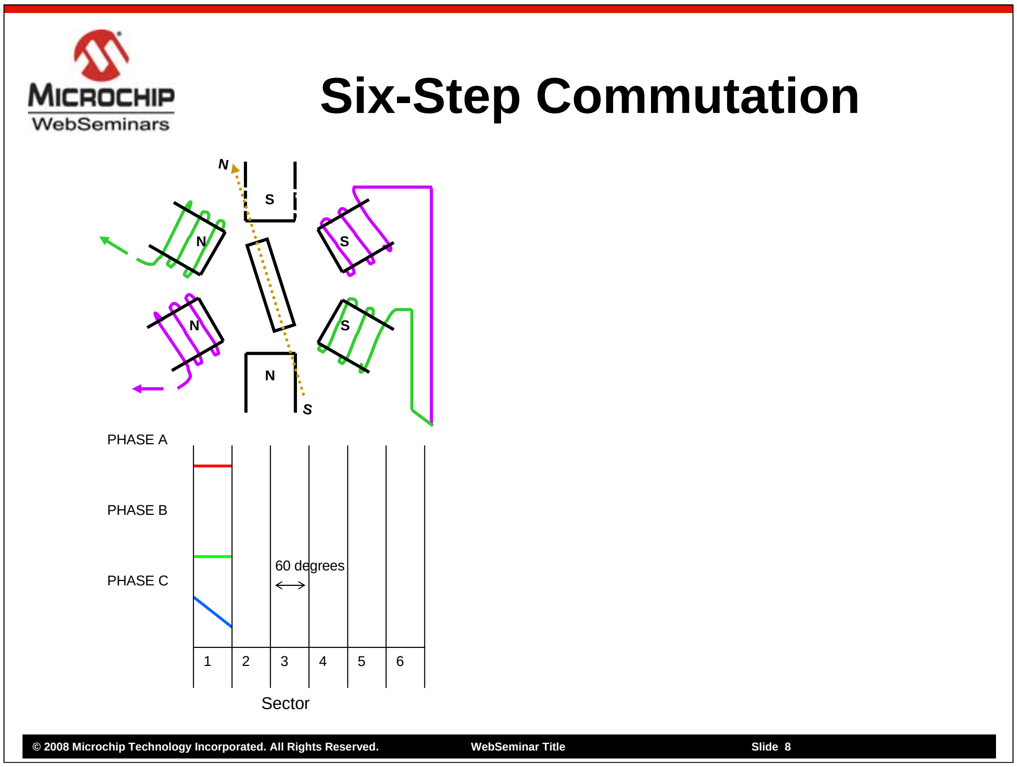
It is possible to determine when to commutate the motor drive voltages by sensing the back-EMF voltage on an undriven motor terminal during one of the drive phases. The obvious cost advantage of sensorless control is the elimination of the Hall position sensors.

A typical control circuit with 3 phase winding connection is shown in the figure H1,H2, H3 and L1, L2, L3 make 3 phase voltage source inverter connected across the power supply indicated by VDC+ and VDC-. Stator windings A, B and C are connected in star to the inverter.

Six-Step Commutation



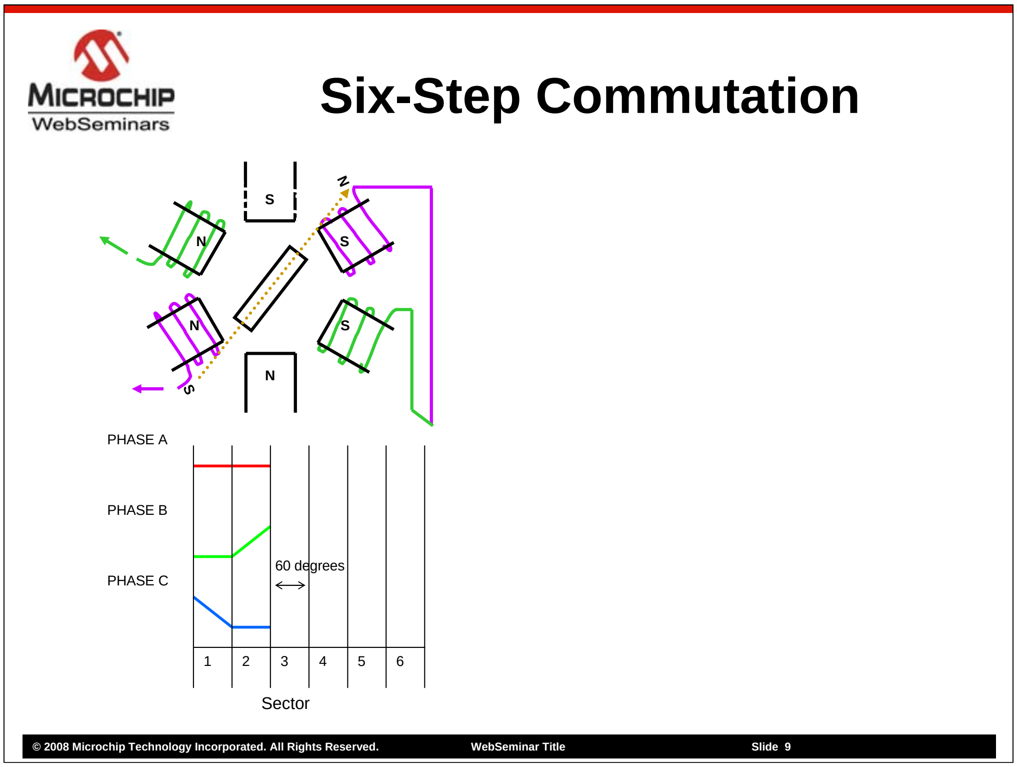
The method for energizing the motor windings in this sensorless motor control algorithm is the six-step trapezoidal or 120° commutation.



Six-Step Commutation

WebSeminar Title Slide 8

The Figure shows how the six-step commutation works. Each step, or sector, is equivalent to 60 electrical degrees.



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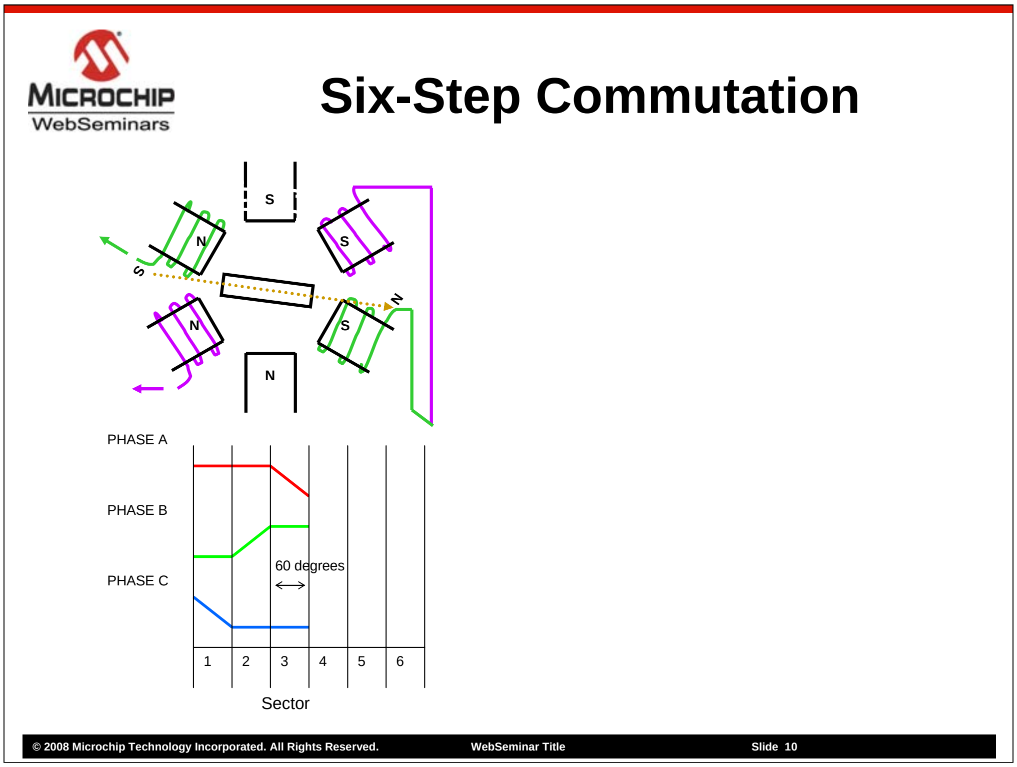
Six-Step Commutation

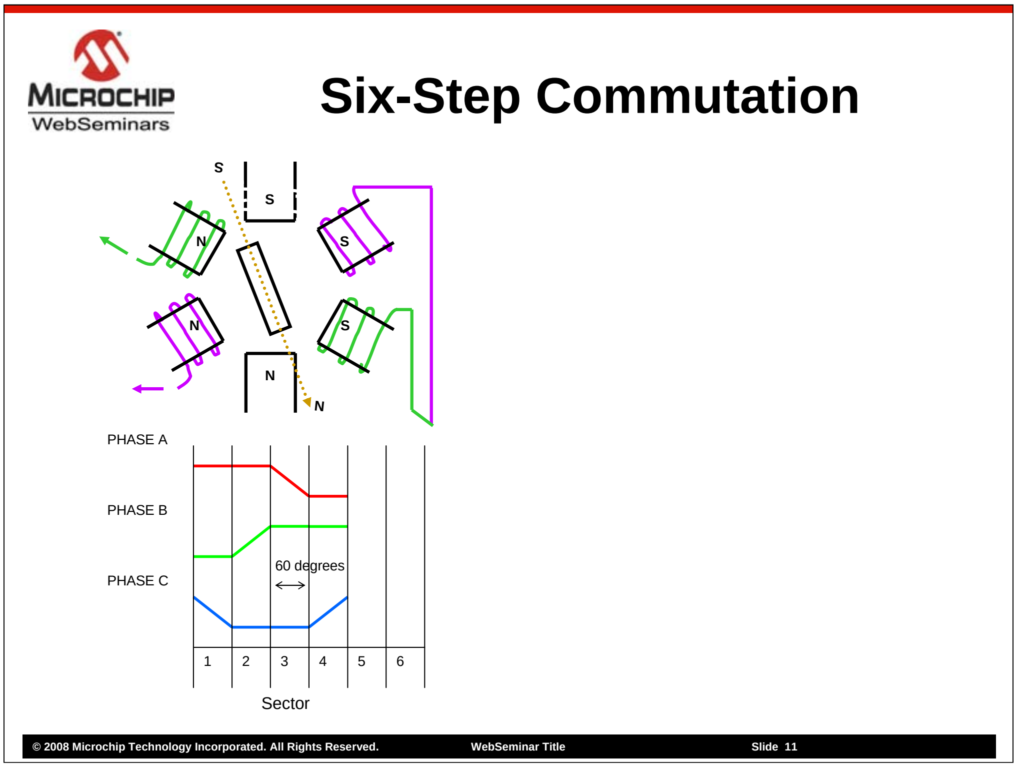
WebSeminar Title Slide 9

The Figure shows how the six-step commutation works. Each step, or sector, is equivalent to 60 electrical degrees.



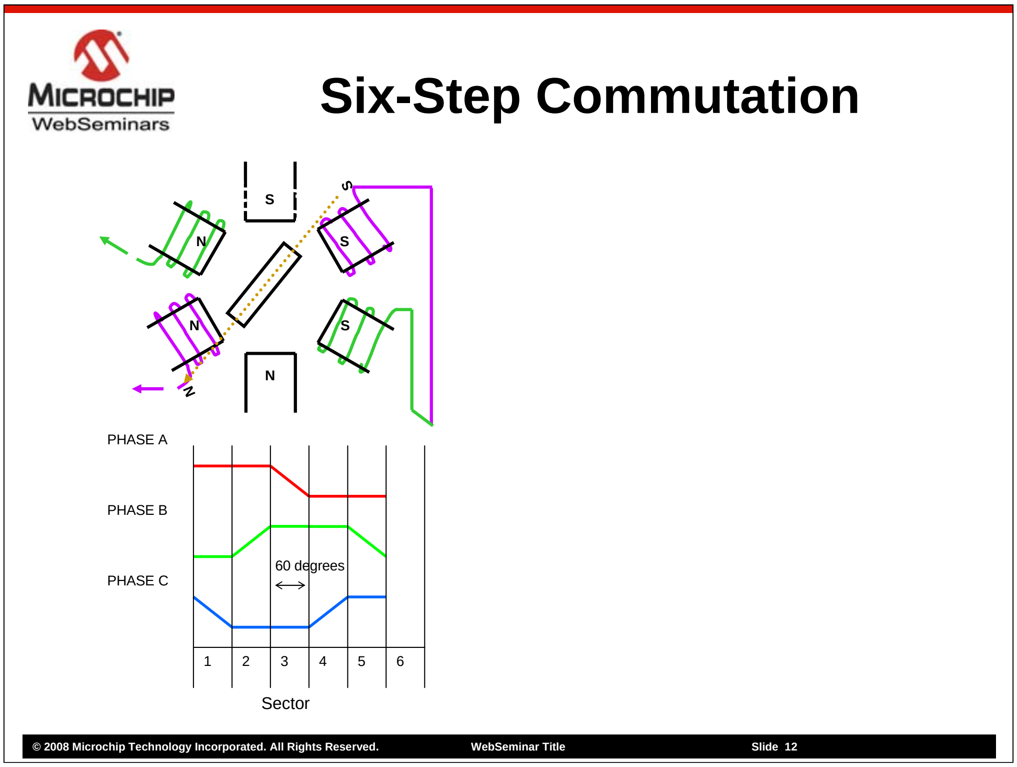
Six-Step Commutation

The Figure shows how the six-step commutation works. Each step, or sector, is equivalent to 60 electrical degrees.



Six-Step Commutation

The Figure shows how the six-step commutation works. Each step, or sector, is equivalent to 60 electrical degrees.



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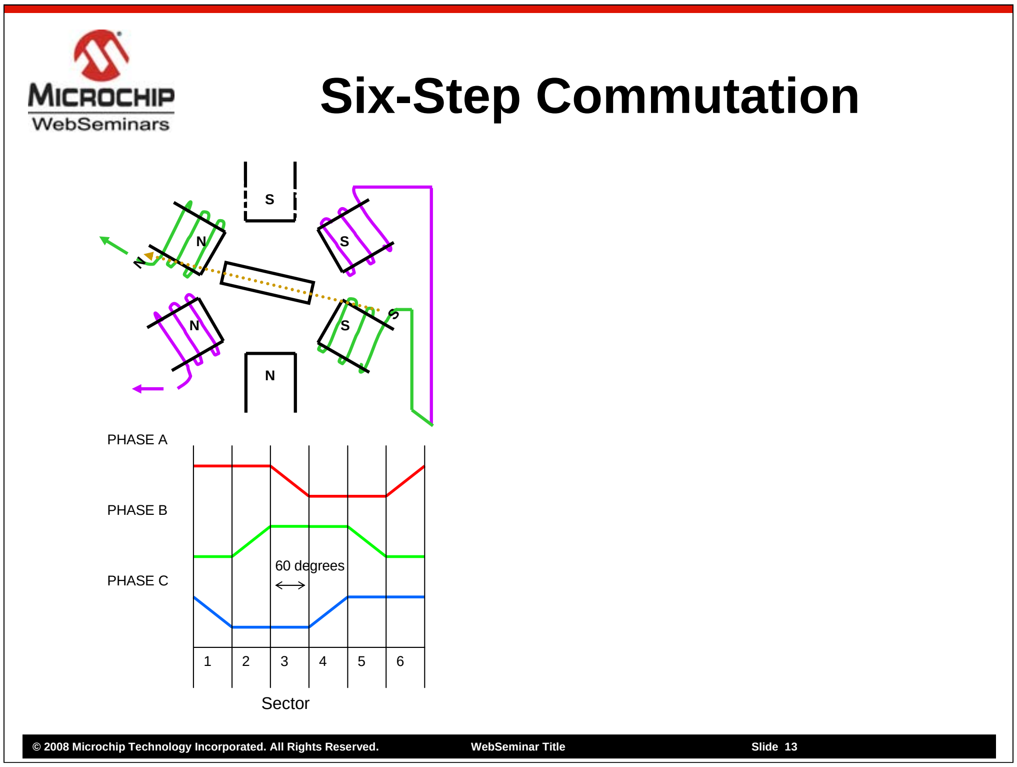
Six-Step Commutation

WebSeminar Title Slide 12

The Figure shows how the six-step commutation works. Each step, or sector, is equivalent to 60 electrical degrees.



Six-Step Commutation

WebSeminar Title Slide 13

The method for energizing the motor windings in this sensorless motor control algorithm is the six-step trapezoidal or 120° commutation.

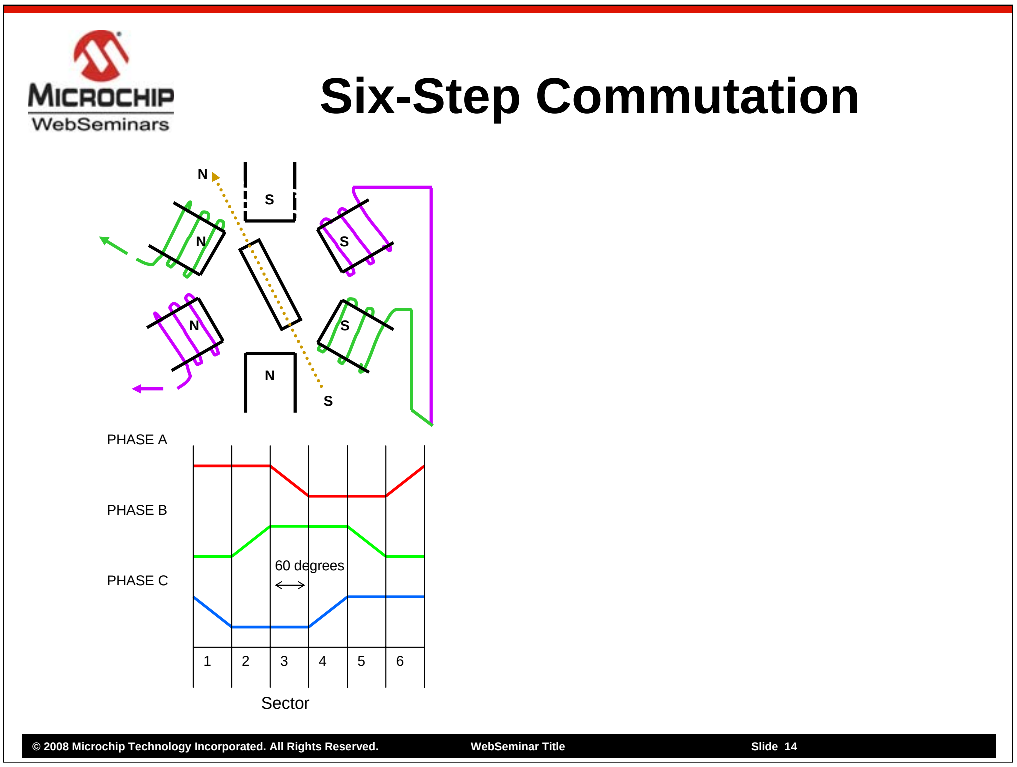
The Figure shows how the six-step commutation works. Each step, or sector, is equivalent to 60 electrical degrees.

Six sectors make up 360 electrical degrees, or one electrical revolution. It is easier to discuss motor speed in these terms rather than mechanical RPM because when talking about electrical RPM, the number of motor poles need not be factored in. The relationship between mechanical and electrical RPM is shown in the equation

For every sector, two windings are energized and one winding is not energized. The fact that one of the windings is not energized during each sector is an important characteristic of the six-step control that allows for the use of a sensorless control algorithm.

When a brushless DC motor rotates, each winding generates a back-Electromotive Force which opposes the main voltage supplied to the windings according to the Lenz's law. The polarity of this BEMF is in the opposite direction of the energizing voltage. BEMF is mainly dependent on three motor parameters:

- Number of turns in the stator windings
- Rotor's Angular Velocity
- Magnetic field generated by rotor magnets

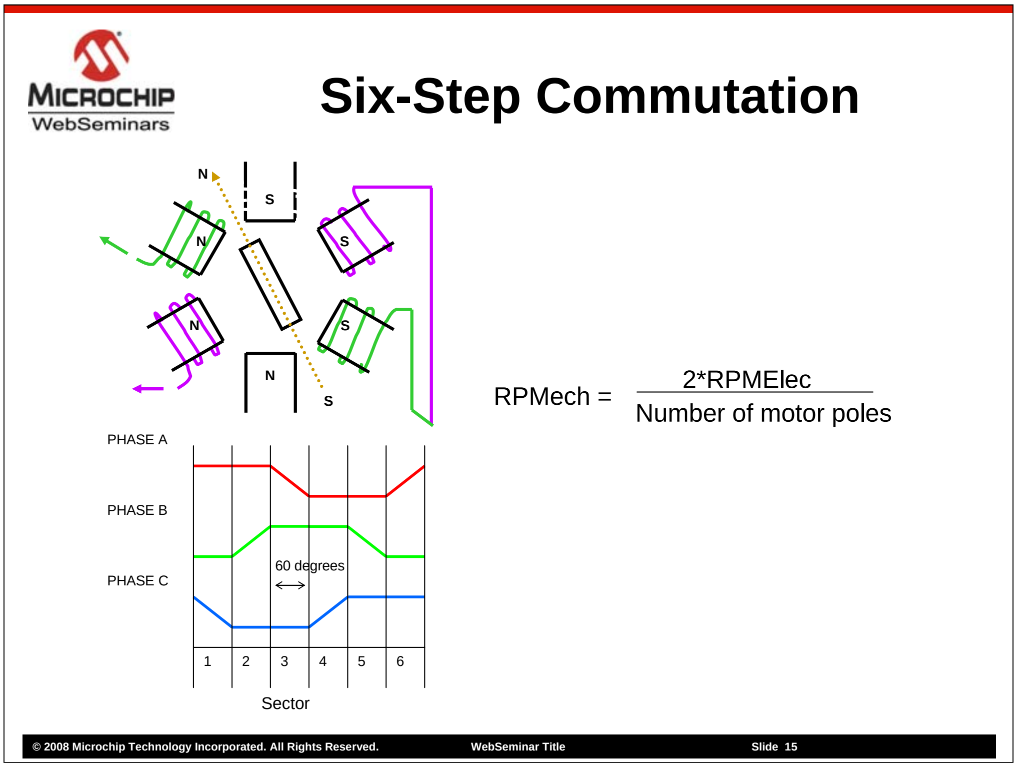


Six-Step Commutation

WebSeminar Title

Slide 14

The Figure shows how the six-step commutation works. Each step, or sector, is equivalent to 60 electrical degrees.



Six-Step Commutation

$$\text{RPMech} = \frac{2*\text{RPMElec}}{\text{Number of motor poles}}$$

WebSeminar Title Slide 15

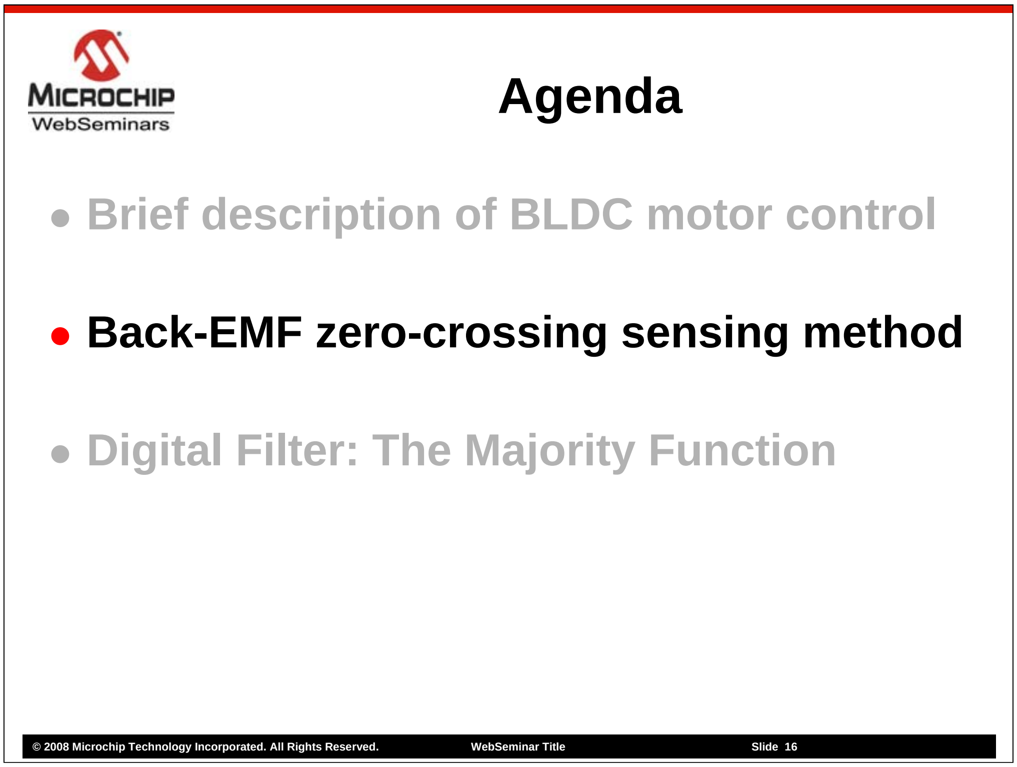
The relationship between mechanical and electrical RPM is shown in the equation

For every sector, two windings are energized and one winding is not energized. The fact that one of the windings is not energized during each sector is an important characteristic of the six-step control that allows for the use of a sensorless control algorithm.

When a brushless DC motor rotates, each winding generates a back-Electromotive Force which opposes the main voltage supplied to the windings according to the Lenz’s law. The polarity of this BEMF is in the opposite direction of the energizing voltage. BEMF is mainly dependent on three motor parameters:

- Number of turns in the stator windings
- Rotor’s Angular Velocity
- Magnetic field generated by rotor magnets

The BEMF waveform of the motor varies as both a function of the rotor’s position and speed. Detection of position using the BEMF at zero and very low speeds is, therefore, not possible.



MICROCHIP WebSeminars

Agenda

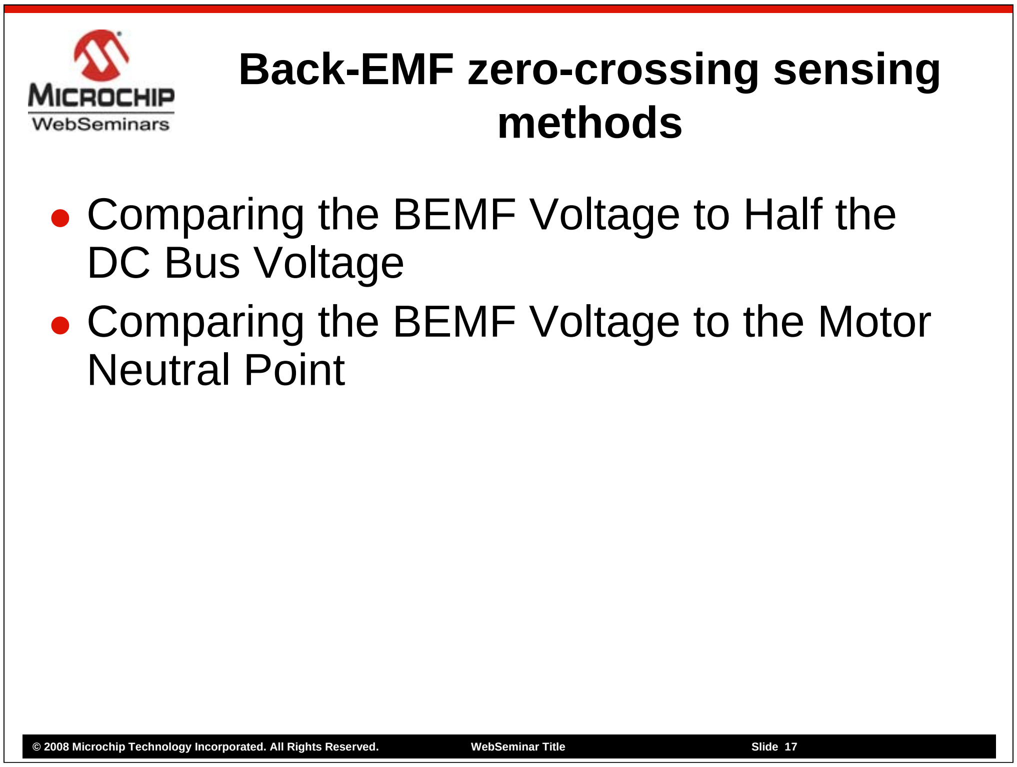
- Brief description of BLDC motor control
- **Back-EMF zero-crossing sensing method**
- Digital Filter: The Majority Function

In this section we will discuss the different methods used to sense the back-EMF signals

The algorithm described in this web seminar is based on the Mid-Point voltage reconstruction, and it is also based on detecting the instances when the back-EMF signal of an inactive phase is zero. Therefore, it is important to mention that the back-EMF sensing method described in this application note can only be implemented using trapezoidal back-EMF signals in order to have zero crossing events.

This method is suitable for use on a wide range of motors.

- It can be used on both Y- and delta-connected 3-phase motors in theory. Certain classes of connected motors may not work.
- It requires no detailed knowledge of motor properties.
- It is relatively insensitive to motor manufacturing tolerance variations.
- It will work for either voltage or current control.
- The zero-crossing technique is suitable for a wide range of applications where closed-loop operation near zero speed is not required.



Back-EMF zero-crossing sensing methods

- Comparing the BEMF Voltage to Half the DC Bus Voltage
- Comparing the BEMF Voltage to the Motor Neutral Point

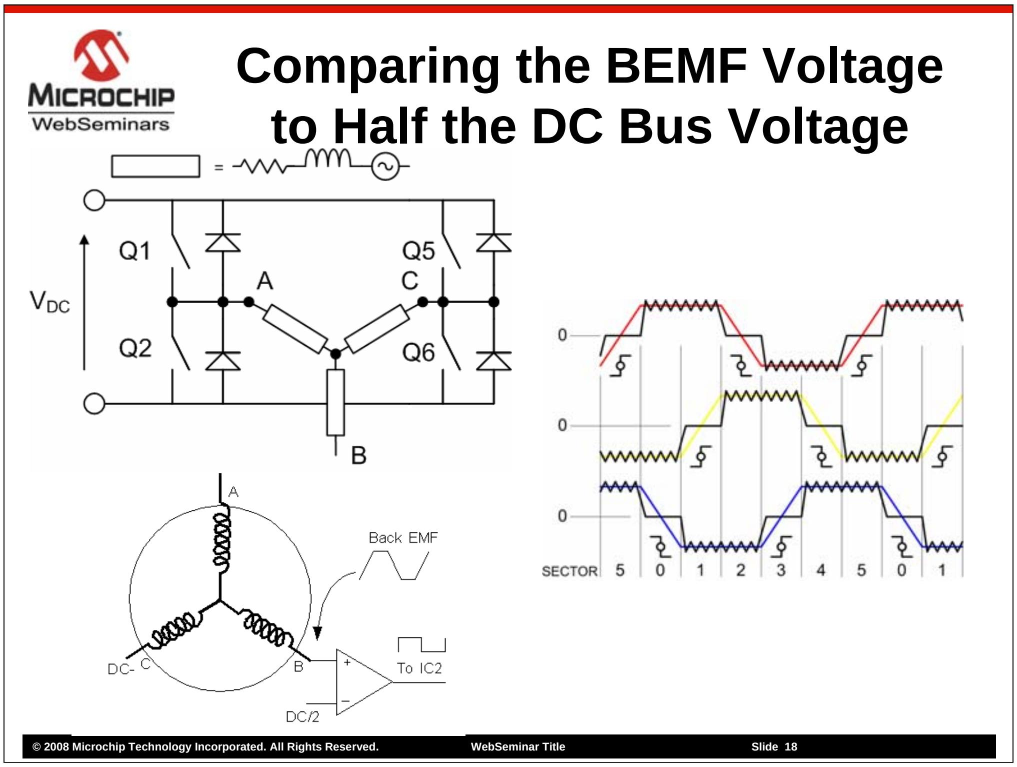
WebSeminar Title Slide 17

BEMF voltage zero-crossing signals can be detected by different methods. The most common sensing methods are:

Comparing the BEMF Voltage to Half the DC Bus Voltage

Comparing the BEMF Voltage to the Motor Neutral Point

Both methods have advantages and as well as drawbacks, which will be discussed in the next slides. Both methods are based on the fact that most of the times the motor neutral point is not available, due to the fact that either it was not wired or the motor windings were built in a delta mode.



Comparing the BEMF Voltage to Half the DC Bus Voltage

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This method consists of comparing the BEMF voltage to half the DC bus voltage by using comparators assuming that the zero crossing events occur when the Back-EMF is equal to VDC/2. Figure shows the circuitry used to implement this method.

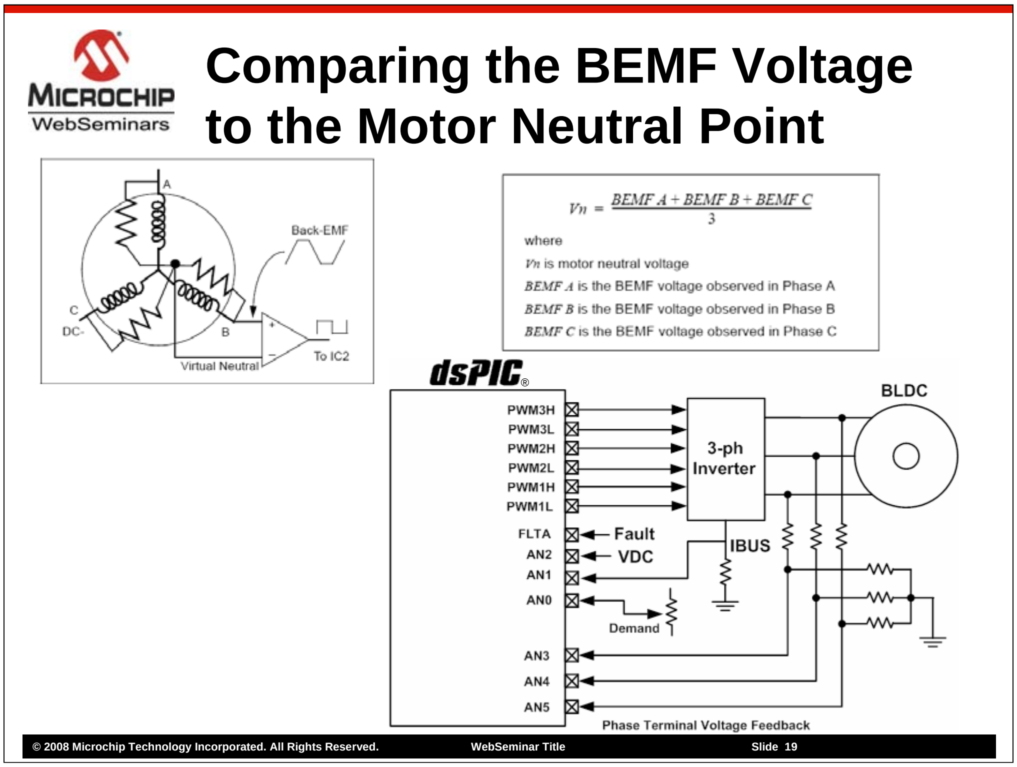
Let’s assume that the motor is in the commutation Step 1, in which Phase A is connected to +VBUS through the electronic switch Q1 and Phase C is connected to -VBUS through the electronic switch Q6 and Phase B is open. The BEMF signal observed on Phase B has a negative slope and its maximum value is almost equal to +VDC just before the commutation Step 2 occurs. The Phase B reaches the +VDC value when the commutation Step 2 occurs.

At that moment, Phase B is now connected to +VDC through an electronic switch, Phase A is now open and Phase C remains connected to -VDC. The BEMF signal observed on Phase A has a positive slope and its minimum value is almost equal to -VDC just before the commutation Step 3 occurs. Both slopes observed on Phase B and Phase A are compared to VDC/2 in order to determine the zero crossing event.

This circuitry is easy to implement with three operational amplifiers configured as comparators.

The drawbacks of this method are:

- This method assumes that the motor windings parameters are identical.
- The sensed BEMF signals have positive and negative phase shifts.
- Motor-rated voltage is less than the VDC voltage most of the time; therefore, the zero crossing event not always occurs at VDC/2.



Comparing the BEMF Voltage to the Motor Neutral Point

$$Vn = \frac{BEMF\ A + BEMF\ B + BEMF\ C}{3}$$

where

Vn is motor neutral voltage

$BEMF\ A$ is the BEMF voltage observed in Phase A

$BEMF\ B$ is the BEMF voltage observed in Phase B

$BEMF\ C$ is the BEMF voltage observed in Phase C

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The zero-crossing sensing method described before can be improved by having a variable threshold voltage point used to detect the zero crossing events. This variable voltage is in fact the motor neutral point.

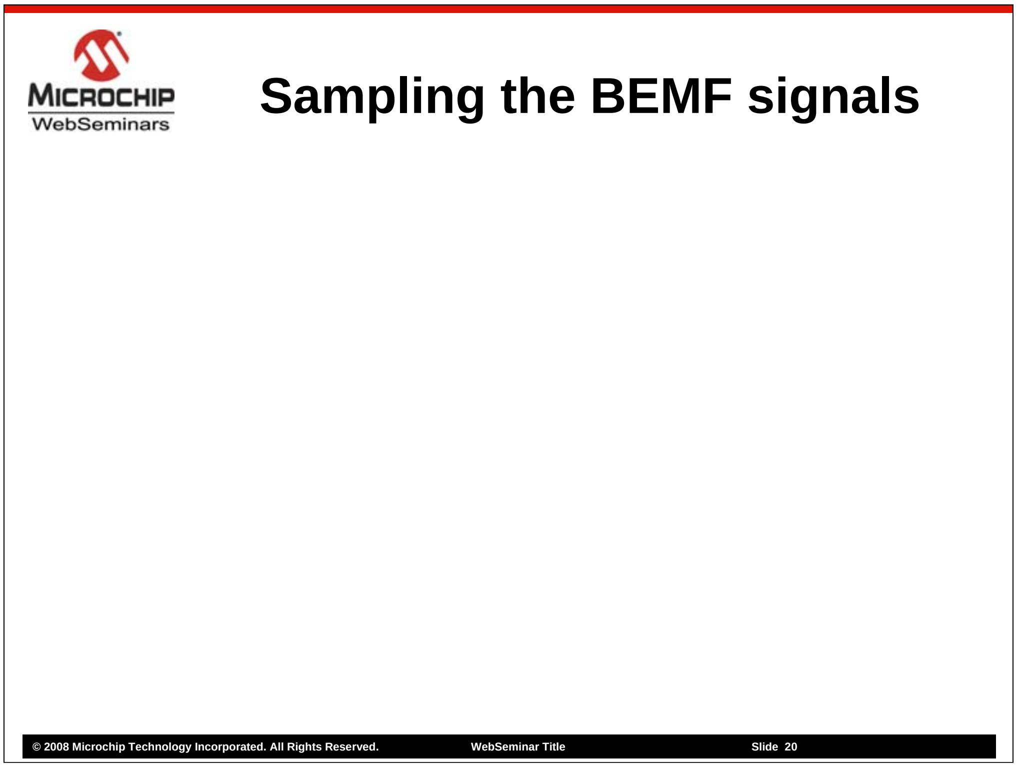
Often, the motor manufacturers do not wire the motor neutral point. However, it can be generated by using a resistor network. Three networks are connected in parallel with the motor windings and connected together to generate a virtual neutral point.

The method used in this application note is based on the same principle. However, the neutral point signal is reconstructed by software. The neutral voltage is equal to the average of the BEMF signals.

Then the reconstructed motor neutral voltage is compared to each back-EMF signal to determine the zero crossing events. A zero crossing event occurs when the BEMF signals are equal to the motor neutral point.

The challenge of this method consist of determining the correct time where the back-EMF signals should be sampled since the samples acquired by the ADC may be affected by the resonant transition voltages caused by the PWM switching frequency.

These samples may be also affected by the kickback currents produced by the windings de-energization.



Sampling the BEMF signals

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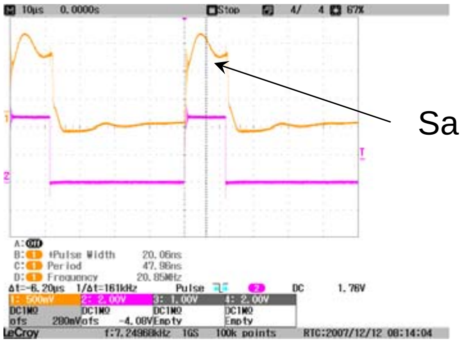
To avoid these noises the dsPIC® ADC is configured in such a way that it simultaneously samples the back-EMF signals at a sampling rate equal to the PWM reload frequency.

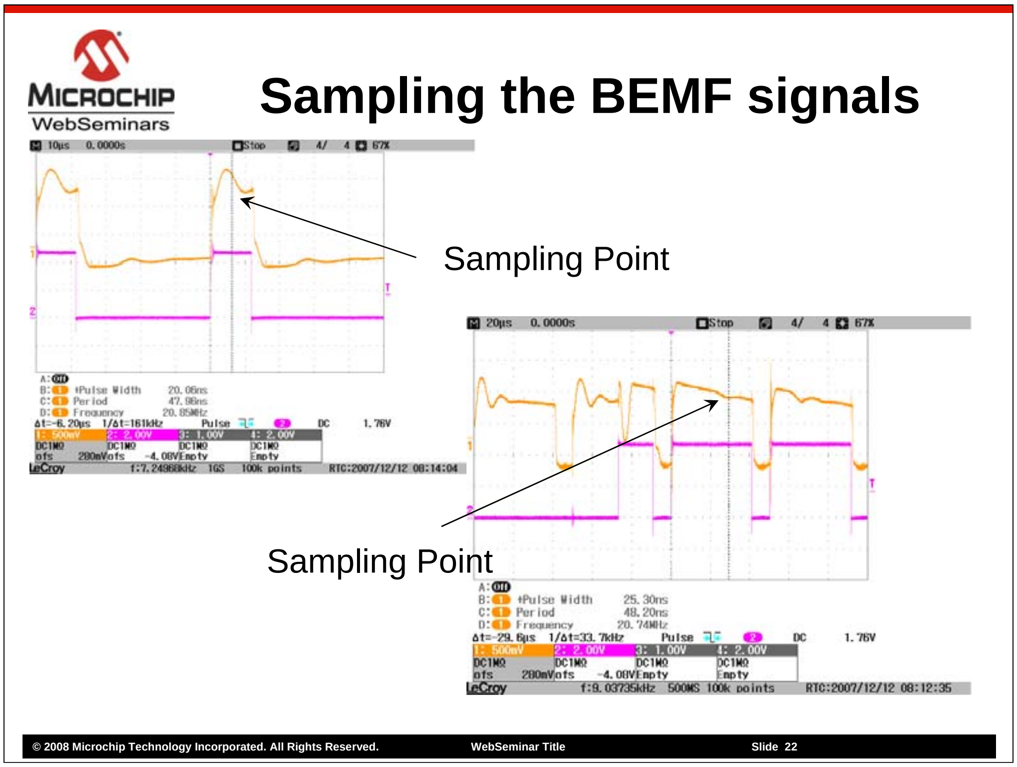
The dsPIC® ADC is also configured to take samples at the PWM ON time with the purpose of avoiding the ringing noise produced by the electronic switches and other noises such as the high voltage spikes produced by the winding de-energization event. These noises could create false zero-crossing events.

Sampling the BEMF signals


10µs 0.0000s
Stop 4/ 4 67%
1
2
T
A: Off
B: 1 +Pulse Width 20.06ns
C: 1 Period 47.96ns
D: 1 Frequency 20.85MHz
Δt=-6.20µs 1/Δt=161kHz Pulse 2 DC 1.76V
1: 500mV 2: 2.00V 3: 1.00V 4: 2.00V
DC1MΩ DC1MΩ DC1MΩ DC1MΩ
ofs 280mV ofs -4.08V Empty Empty
LeCroy 1:7.24968kHz 1GS 100k points RTC:2007/12/12 08:14:04

Sampling Point

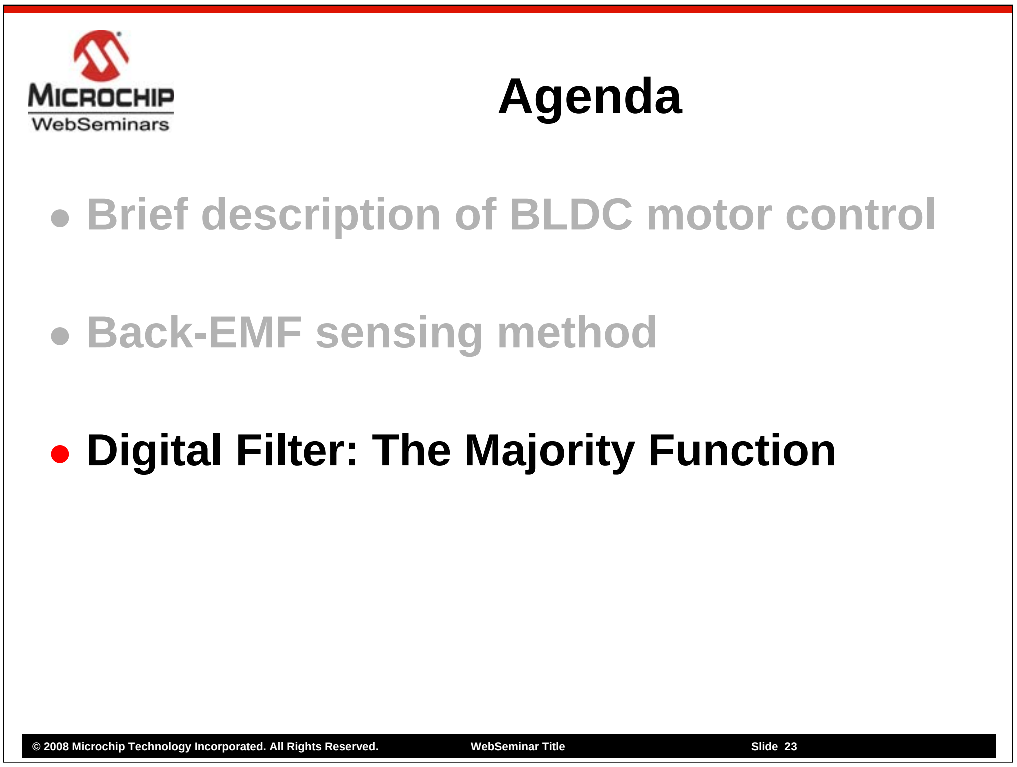
The point in which the signals are sampled is variable across the PWM ON time depending on the motor speed. At low speeds, the dsPIC® DSC device samples the BEMF signals at 50% of the PWM ON time.



Sampling the BEMF signals

WebSeminar Title Slide 22

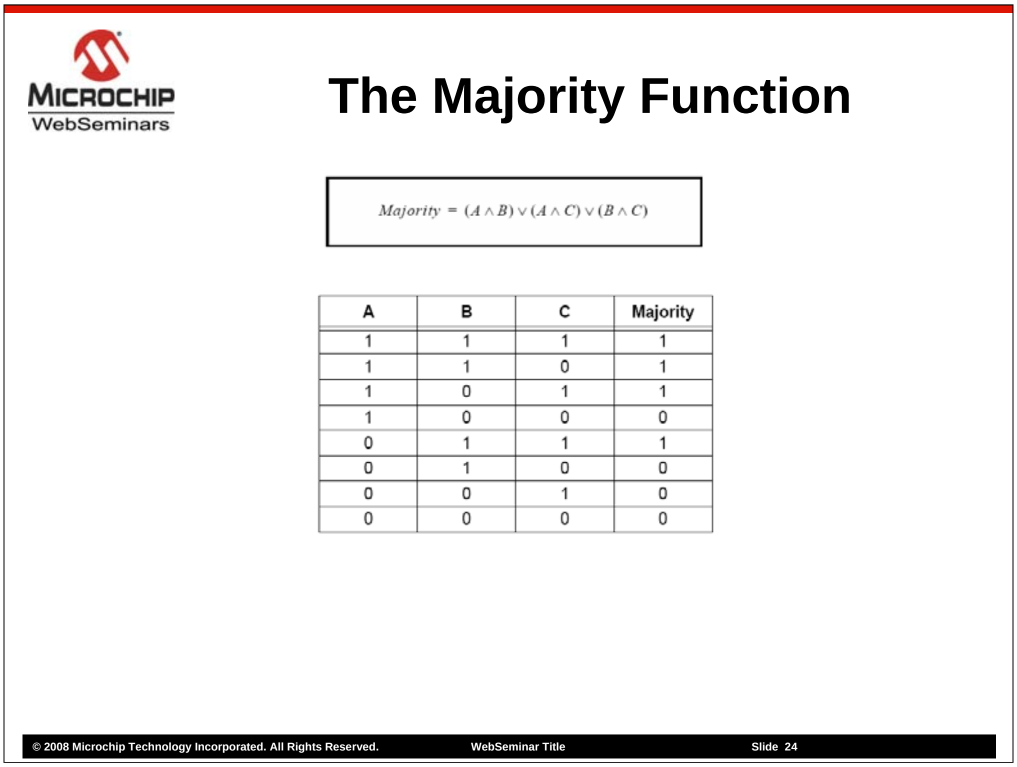
However, the sampling point moves forward according to the PWM duty cycle to reach the maximum point of 75% of the PWM ON time when the PWM duty cycle is equal to 100%.



Agenda

- Brief description of BLDC motor control
- Back-EMF sensing method
- Digital Filter: The Majority Function

In this section we will discuss the principles of the digital filter, the majority detection function.



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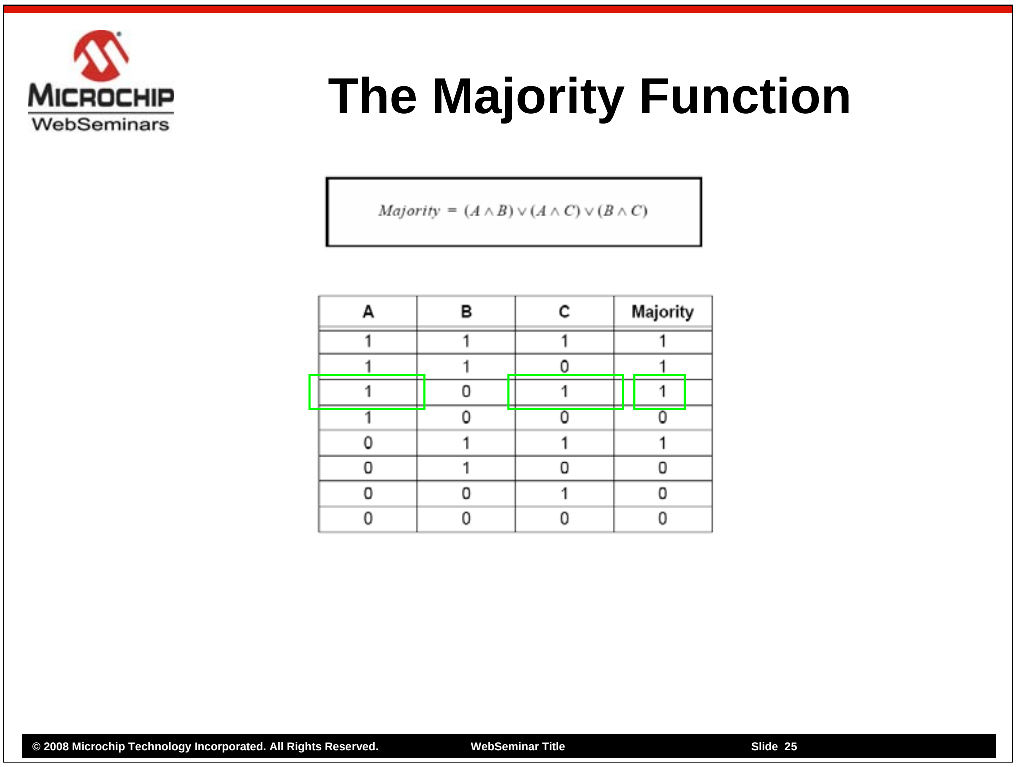
The Majority Function

$$\boxed{Majority = (A \wedge B) \vee (A \wedge C) \vee (B \wedge C)}$$

A	B	C	Majority
1	1	1	1
1	1	0	1
1	0	1	1
1	0	0	0
0	1	1	1
0	1	0	0
0	0	1	0
0	0	0	0

WebSeminar Title Slide 24

This back-EMF sensing method is based on a nonlinear digital filter called ‘majority function’. In certain situations it is also known as ‘median operator’. The majority function is a Boolean function, which takes a number *n* of binary inputs and returns the value which is most common among them.



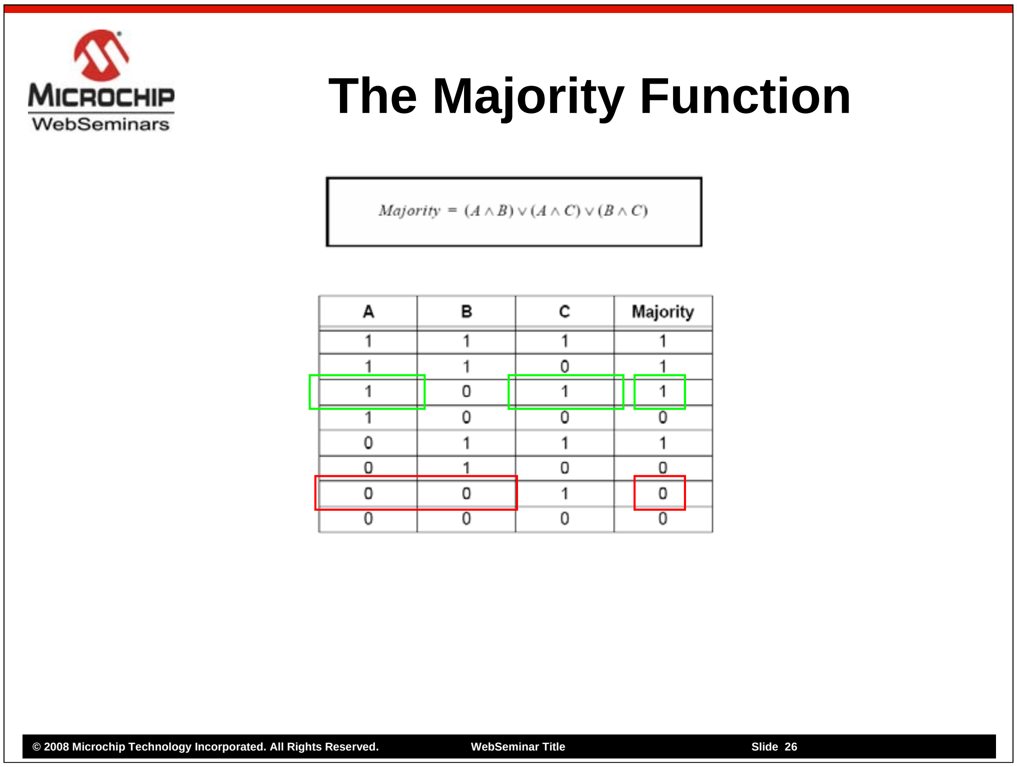
MICROCHIP WebSeminars

The Majority Function

$$Majority = (A \wedge B) \vee (A \wedge C) \vee (B \wedge C)$$

A	B	C	Majority
1	1	1	1
1	1	0	1
1	0	1	1
1	0	0	0
0	1	1	1
0	1	0	0
0	0	1	0
0	0	0	0

Let’s consider a system with three inputs. The majority function of this three inputs will return whichever value (true or false) occurs at least twice. In this case, two equal values represents 66% of the numbers. The majority function always returns the value of the majority (> 50%) of the numbers.



The Majority Function

$$Majority = (A \wedge B) \vee (A \wedge C) \vee (B \wedge C)$$

A	B	C	Majority
1	1	1	1
1	1	0	1
1	0	1	1
1	0	0	0
0	1	1	1
0	1	0	0
0	0	1	0
0	0	0	0

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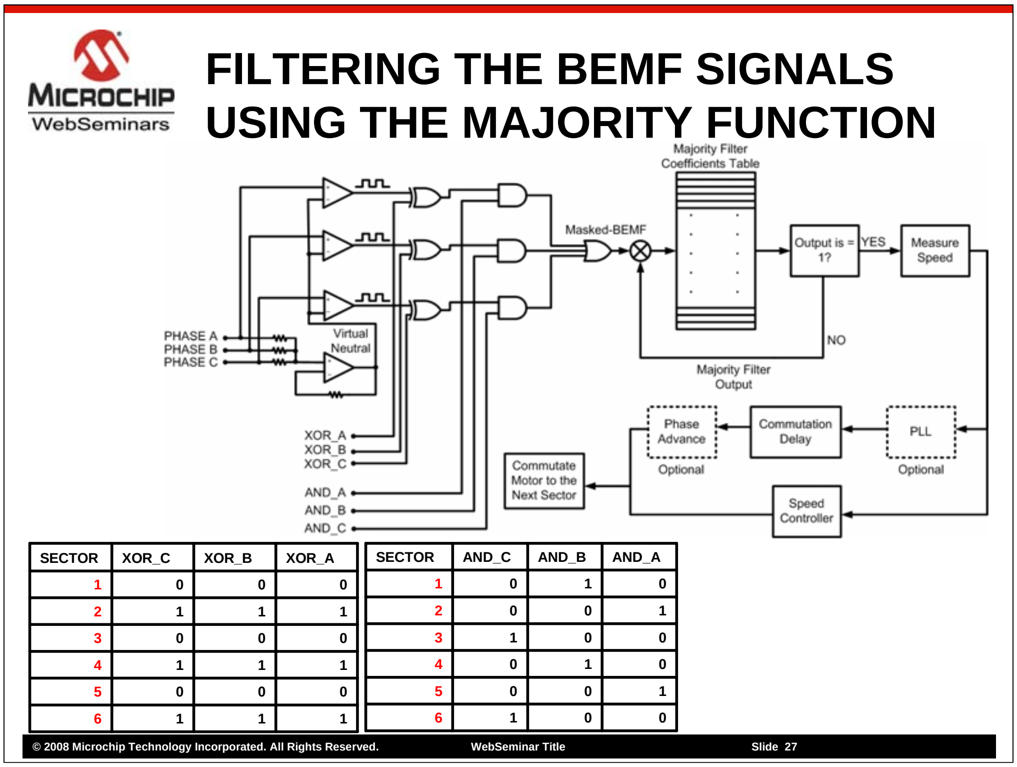
The majority of the values can be expressed using two logic operators, AND and OR operators. As shown in the equation, It is the result of the ORed value of the AND operation between A and B, A and C and finally B and C.

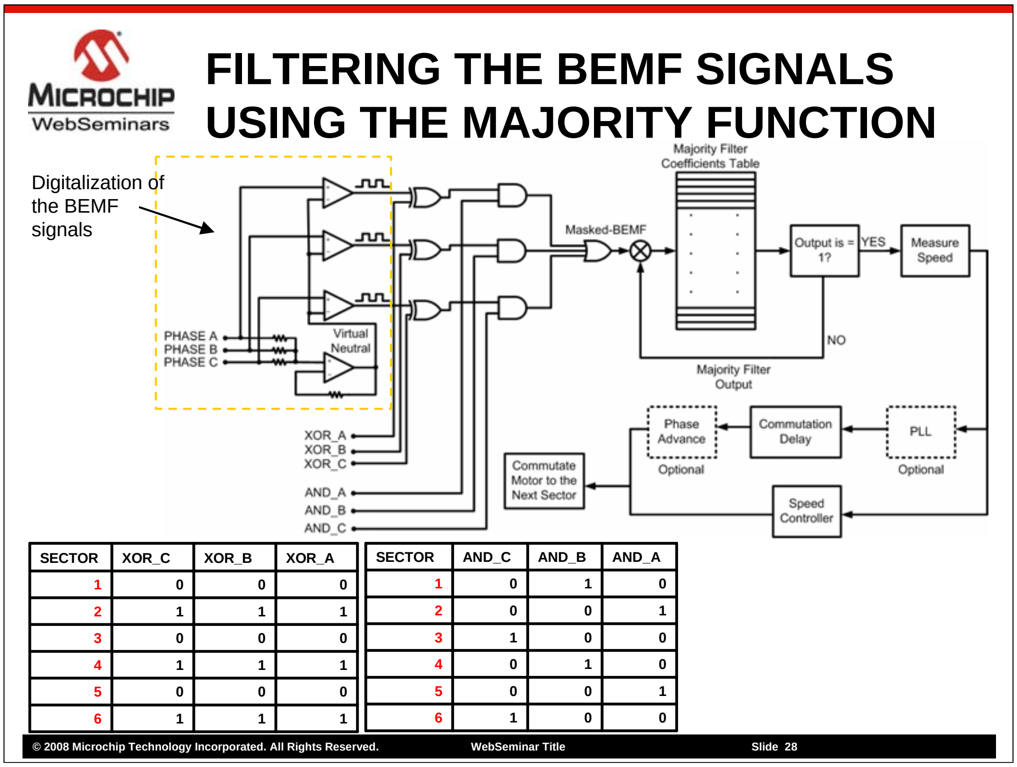


FILTERING THE BEMF SIGNALS USING THE MAJORITY FUNCTION

SECTOR	XOR_C	XOR_B	XOR_A
1	0	0	0
2	1	1	1
3	0	0	0
4	1	1	1
5	0	0	0
6	1	1	1

SECTOR	AND_C	AND_B	AND_A
1	0	1	0
2	0	0	1
3	1	0	0
4	0	1	0
5	0	0	1
6	1	0	0

The implementation of this nonlinear filter is based on a 6-samples window in which at least 51% of the three most significant samples should be equal to “1” and the three least significant samples should be equal to “0” for the purpose of identifying the occurrence of a zero-crossing event in the digitalized back-EMF signals.



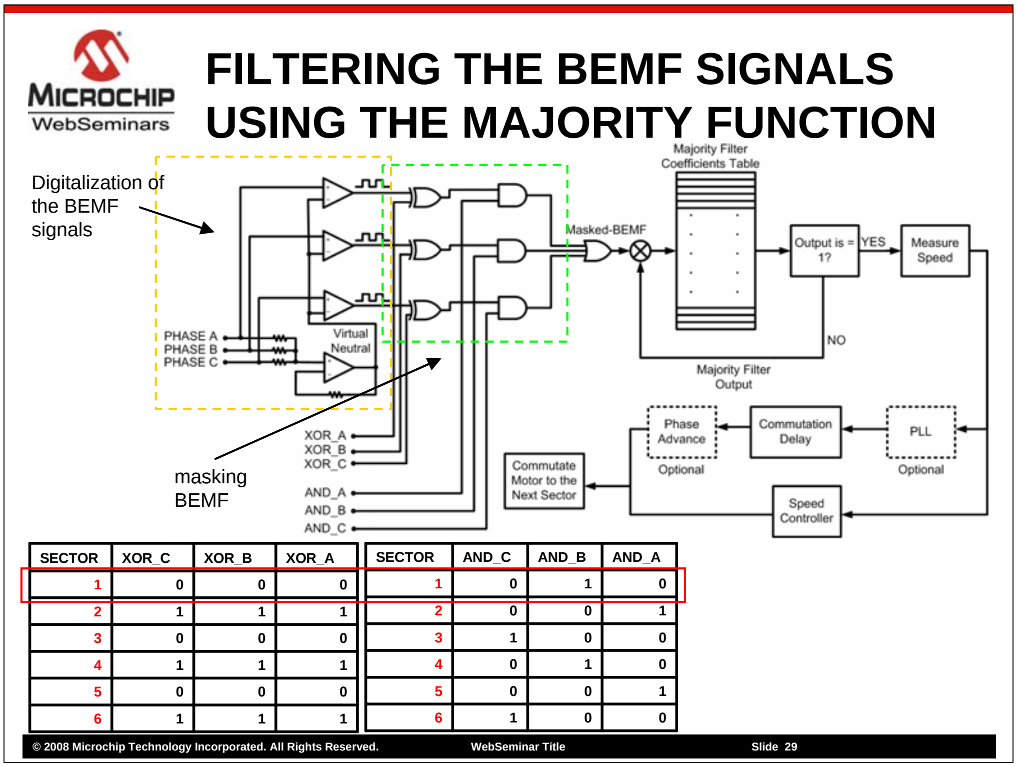
FILTERING THE BEMF SIGNALS USING THE MAJORITY FUNCTION

Digitalization of the BEMF signals

SECTOR	XOR_C	XOR_B	XOR_A
1	0	0	0
2	1	1	1
3	0	0	0
4	1	1	1
5	0	0	0
6	1	1	1

SECTOR	AND_C	AND_B	AND_A
1	0	1	0
2	0	0	1
3	1	0	0
4	0	1	0
5	0	0	1
6	1	0	0

The first stage of the majority function filter is implemented using two logic operators, an AND operator for detecting the active BEMF signal correspondingly to the existing commutation state, and an Exclusive-OR (XOR) operator is used to detect the falling or rising edges on the active BEMF signal.



FILTERING THE BEMF SIGNALS USING THE MAJORITY FUNCTION

SECTOR	XOR_C	XOR_B	XOR_A
1	0	0	0
2	1	1	1
3	0	0	0
4	1	1	1
5	0	0	0
6	1	1	1

SECTOR	AND_C	AND_B	AND_A
1	0	1	0
2	0	0	1
3	1	0	0
4	0	1	0
5	0	0	1
6	1	0	0

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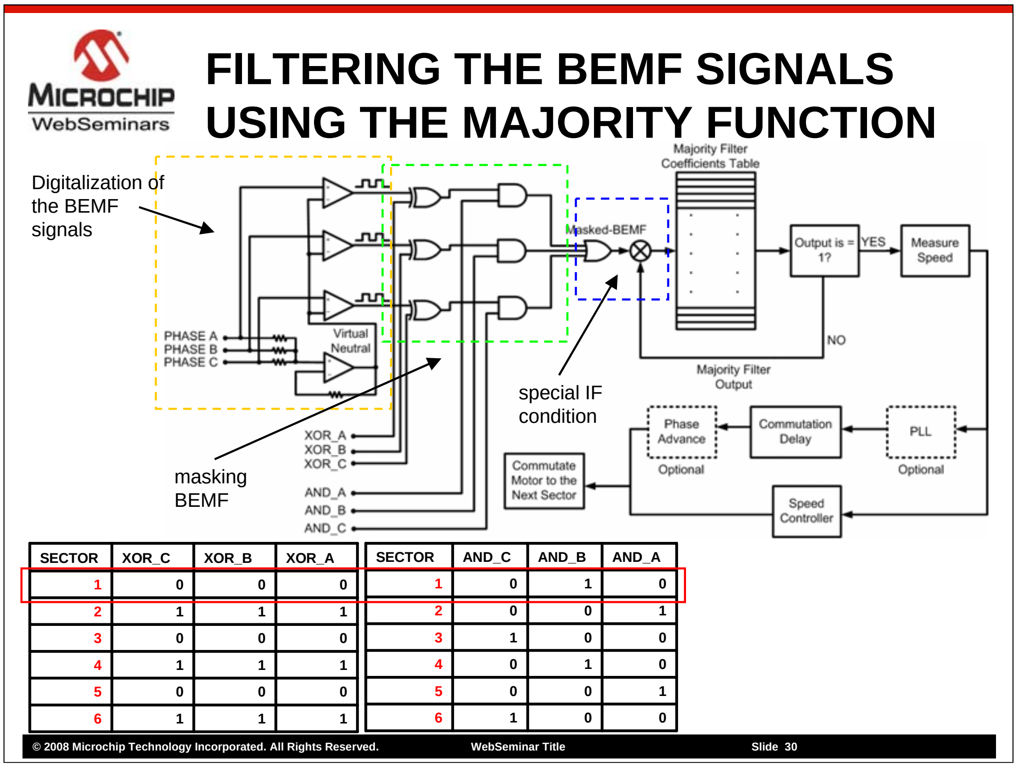
The values of the XOR and AND mask depend on the number of the six-step commutation sector as shown in the tables.



MICROCHIP WebSeminars

FILTERING THE BEMF SIGNALS USING THE MAJORITY FUNCTION

SECTOR	XOR_C	XOR_B	XOR_A
1	0	0	0
2	1	1	1
3	0	0	0
4	1	1	1
5	0	0	0
6	1	1	1

SECTOR	AND_C	AND_B	AND_A
1	0	1	0
2	0	0	1
3	1	0	0
4	0	1	0
5	0	0	1
6	1	0	0

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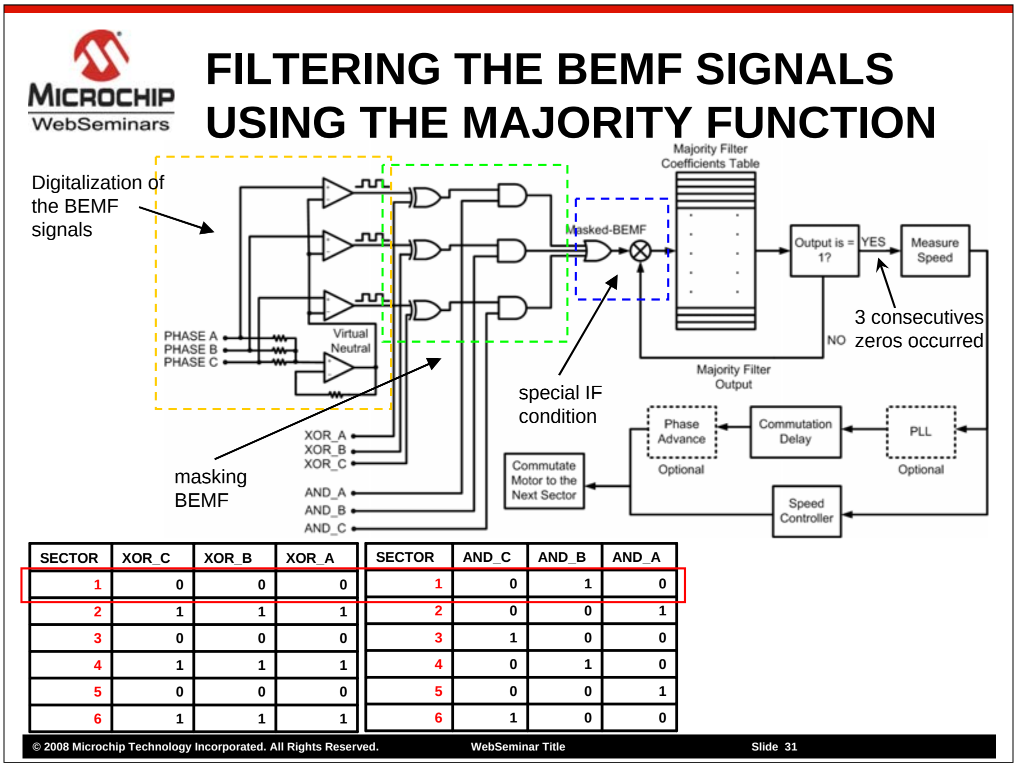
The active-masked BEMF signal is then filtered using the majority detection filter. This filter is implemented with an array compounded by 64 values and a special logic test condition that is used to modify the pointer of the next data array. This logic test condition also identifies both the falling and rising edges of the active-masked BEMF signals; both edges are represented as a true-to-false event at the output of the logical test condition.

The output of this condition is also used as an input to the majority detection filter. The 64 values represent the 26 possible combinations that the 6-sample window could have for the active masked BEMF signal; each value on the look-up table is a pointer to the next signal state over time. The filter is always looking for a true-to-false change at the output of the logic test condition, if this true-to-false condition is detected,



FILTERING THE BEMF SIGNALS USING THE MAJORITY FUNCTION

SECTOR	XOR_C	XOR_B	XOR_A
1	0	0	0
2	1	1	1
3	0	0	0
4	1	1	1
5	0	0	0
6	1	1	1

SECTOR	AND_C	AND_B	AND_A
1	0	1	0
2	0	0	1
3	1	0	0
4	0	1	0
5	0	0	1
6	1	0	0

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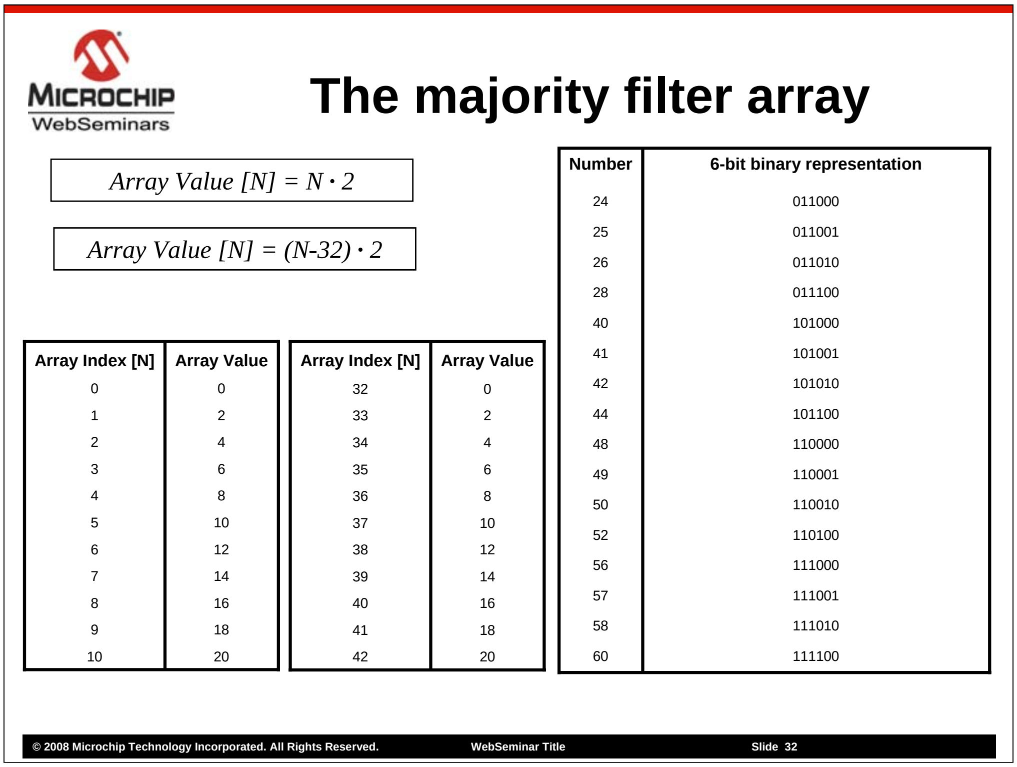
the filter looks for three consecutive false states to validate that a zero-crossing event occurred. A true-to-false condition at the output of the logic test represents a zero-crossing event and therefore a commutation on the motor, which occurs after a delay.



The majority filter array

$$\text{Array Value}\,[N] = N \cdot 2$$

$$\text{Array Value}\,[N] = (N-32) \cdot 2$$

Array Index [N]	Array Value
0	0
1	2
2	4
3	6
4	8
5	10
6	12
7	14
8	16
9	18
10	20

Array Index [N]	Array Value
32	0
33	2
34	4
35	6
36	8
37	10
38	12
39	14
40	16
41	18
42	20

Number	6-bit binary representation
24	011000
25	011001
26	011010
28	011100
40	101000
41	101001
42	101010
44	101100
48	110000
49	110001
50	110010
52	110100
56	111000
57	111001
58	111010
60	111100

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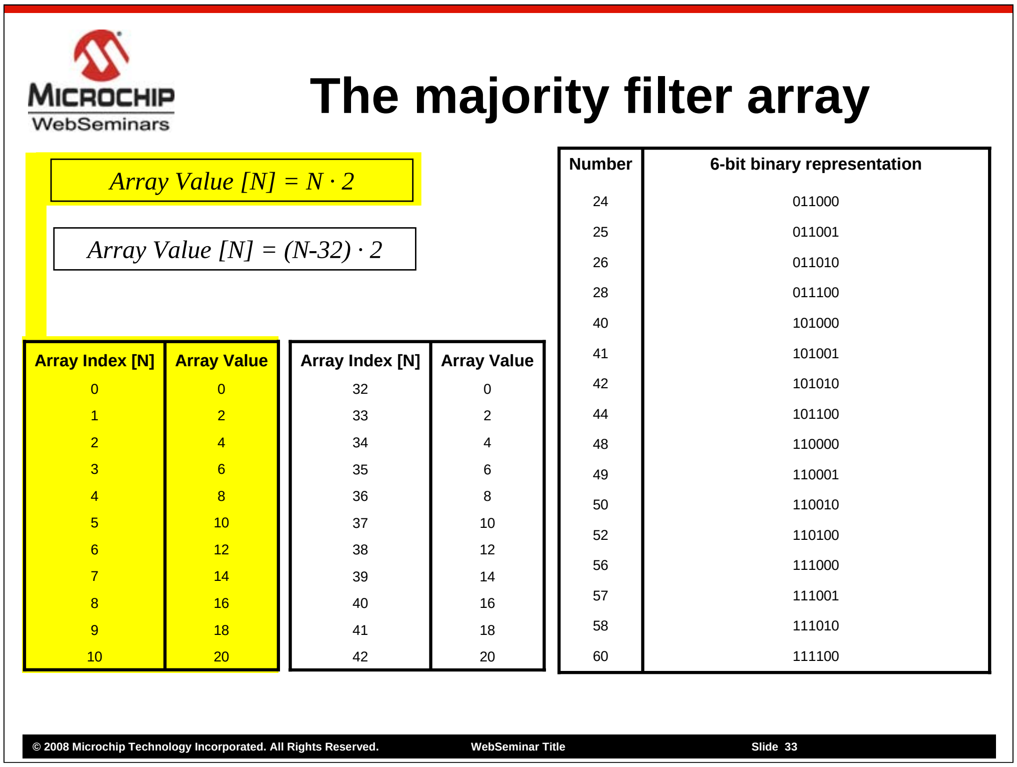
The 64 array values are determined as follows:



The majority filter array

Array Value [N] = N · 2

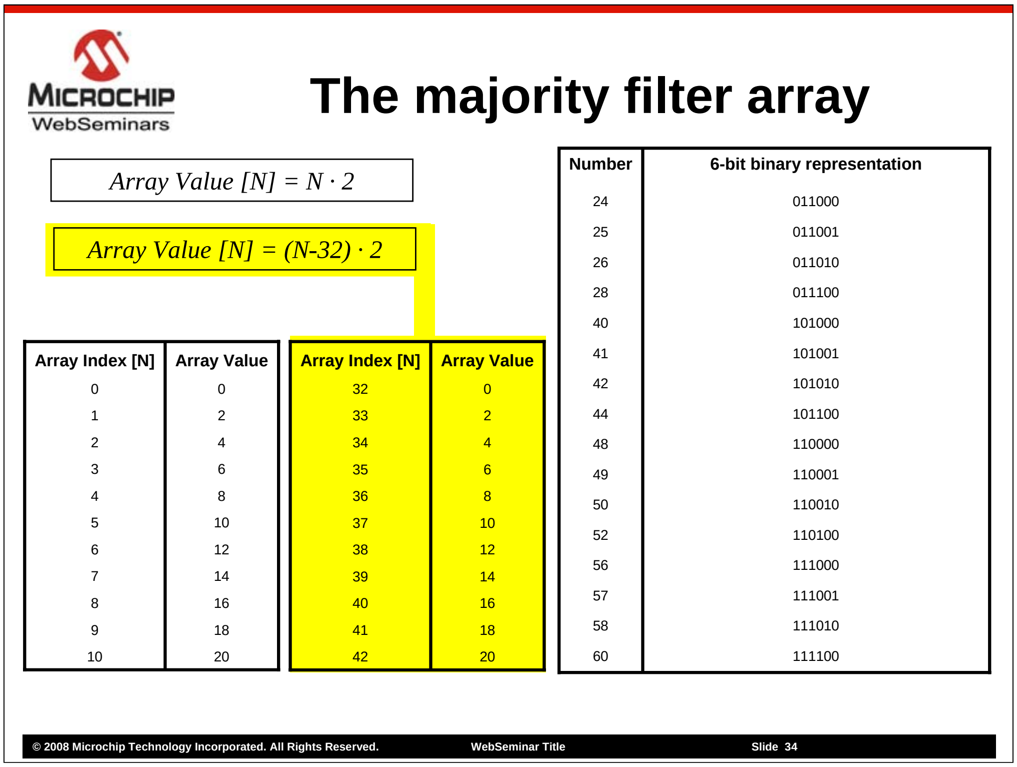
Array Value [N] = (N-32) · 2

Array Index [N]	Array Value
0	0
1	2
2	4
3	6
4	8
5	10
6	12
7	14
8	16
9	18
10	20

Array Index [N]	Array Value
32	0
33	2
34	4
35	6
36	8
37	10
38	12
39	14
40	16
41	18
42	20

Number	6-bit binary representation
24	011000
25	011001
26	011010
28	011100
40	101000
41	101001
42	101010
44	101100
48	110000
49	110001
50	110010
52	110100
56	111000
57	111001
58	111010
60	111100

The first 32 numbers are the index number multiplied by two



The majority filter array

$$\text{Array Value }[N] = N \cdot 2$$

$$\text{Array Value }[N] = (N-32) \cdot 2$$

Array Index [N]	Array Value
0	0
1	2
2	4
3	6
4	8
5	10
6	12
7	14
8	16
9	18
10	20

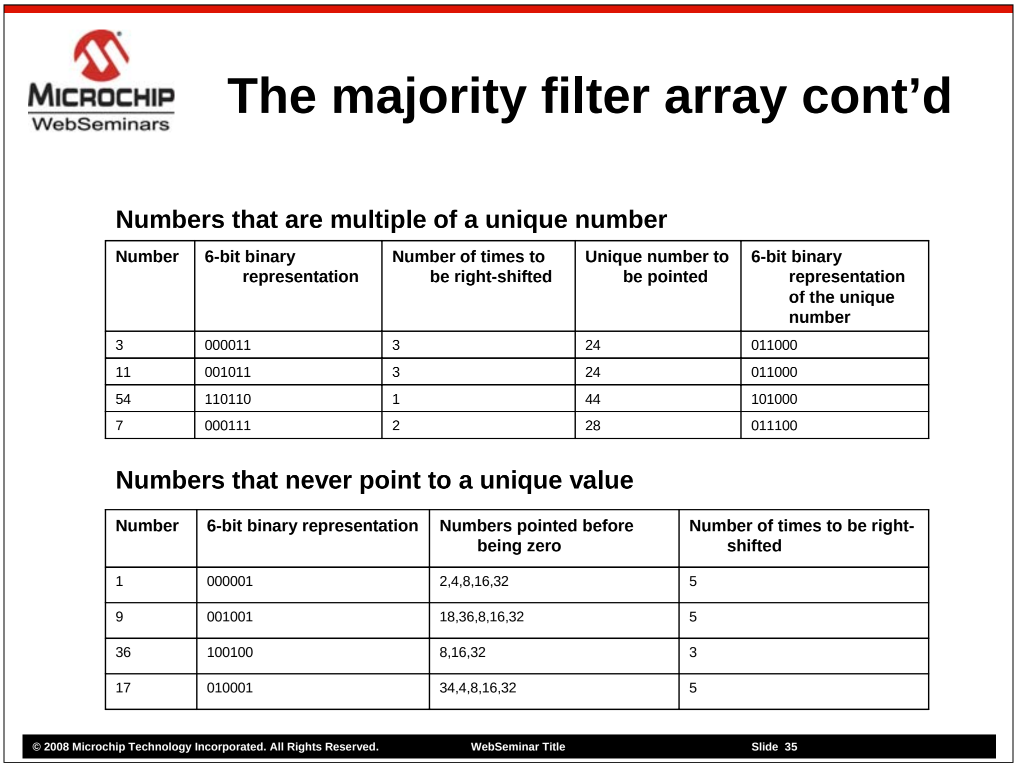
Array Index [N]	Array Value
32	0
33	2
34	4
35	6
36	8
37	10
38	12
39	14
40	16
41	18
42	20

Number	6-bit binary representation
24	011000
25	011001
26	011010
28	011100
40	101000
41	101001
42	101010
44	101100
48	110000
49	110001
50	110010
52	110100
56	111000
57	111001
58	111010
60	111100

The last 32 values are filled out subtracting 32 to the Index value and multiplying the result by 2

There are 16 unique array index numbers that represent the true-to-false condition. These values are listed in order of appearance 24, 25, 26, 28, 40, 41, 42, 44, 48, 49, 50, 52, 56, 57, 58 and 60. The values pointed by these unique indexes are replaced by “1” to indicate that a true-to-false condition occurred.

The 16 unique index values are selected using the following majority function criteria. An array index number is a unique value when its binary representation contains a majority of “1” (> 50%) in the three most significant bits followed by a majority of “0” (> 50%) in the three least significant bits.



The majority filter array cont’d

Numbers that are multiple of a unique number

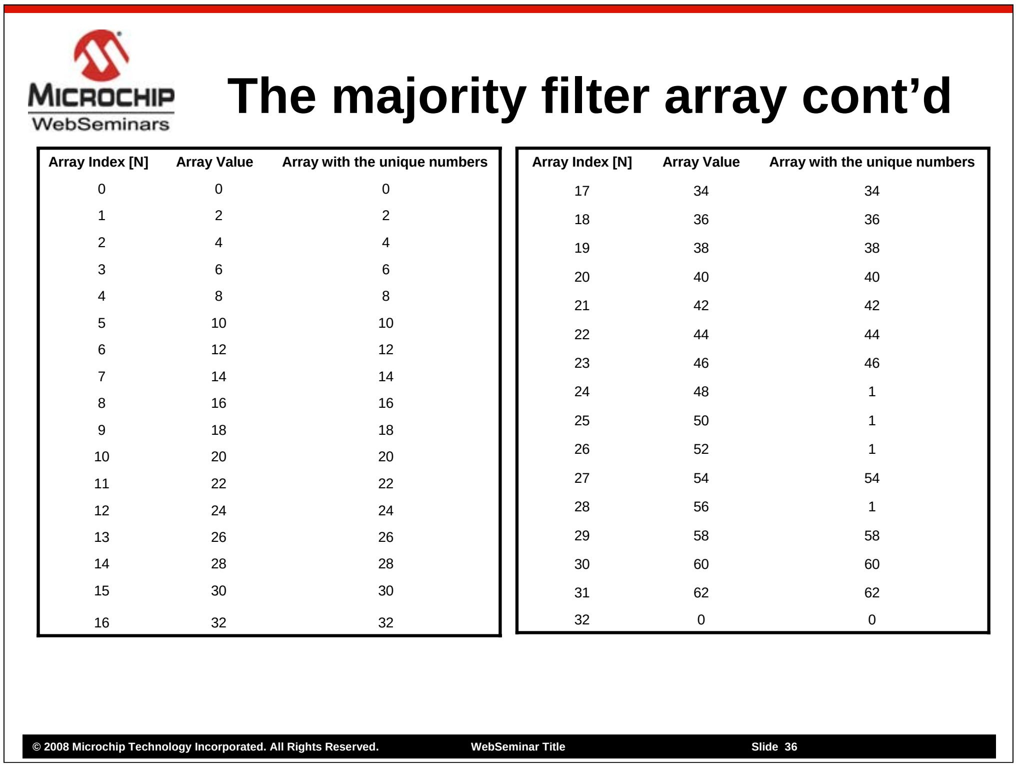
Number	6-bit binary representation	Number of times to be right-shifted	Unique number to be pointed	6-bit binary representation of the unique number
3	000011	3	24	011000
11	001011	3	24	011000
54	110110	1	44	101000
7	000111	2	28	011100

Numbers that never point to a unique value

Number	6-bit binary representation	Numbers pointed before being zero	Number of times to be right-shifted
1	000001	2,4,8,16,32	5
9	001001	18,36,8,16,32	5
36	100100	8,16,32	3
17	010001	34,4,8,16,32	5

The 48 remaining array numbers are pointers to the unique values in case a true-to-false condition occurs. There are some values that never point to any of the unique values because they are not multiple of any of the 16 unique numbers.

Those numbers that never point to a 16 unique number are then pointed to its multiple and they are trapped into a loop in such a way that the filter is waiting for a new value, which points to a unique number.



The majority filter array cont'd

Array Index [N]	Array Value	Array with the unique numbers
0	0	0
1	2	2
2	4	4
3	6	6
4	8	8
5	10	10
6	12	12
7	14	14
8	16	16
9	18	18
10	20	20
11	22	22
12	24	24
13	26	26
14	28	28
15	30	30
16	32	32
17	34	34
18	36	36
19	38	38
20	40	40
21	42	42
22	44	44
23	46	46
24	48	1
25	50	1
26	52	1
27	54	54
28	56	1
29	58	58
30	60	60
31	62	62
32	0	0

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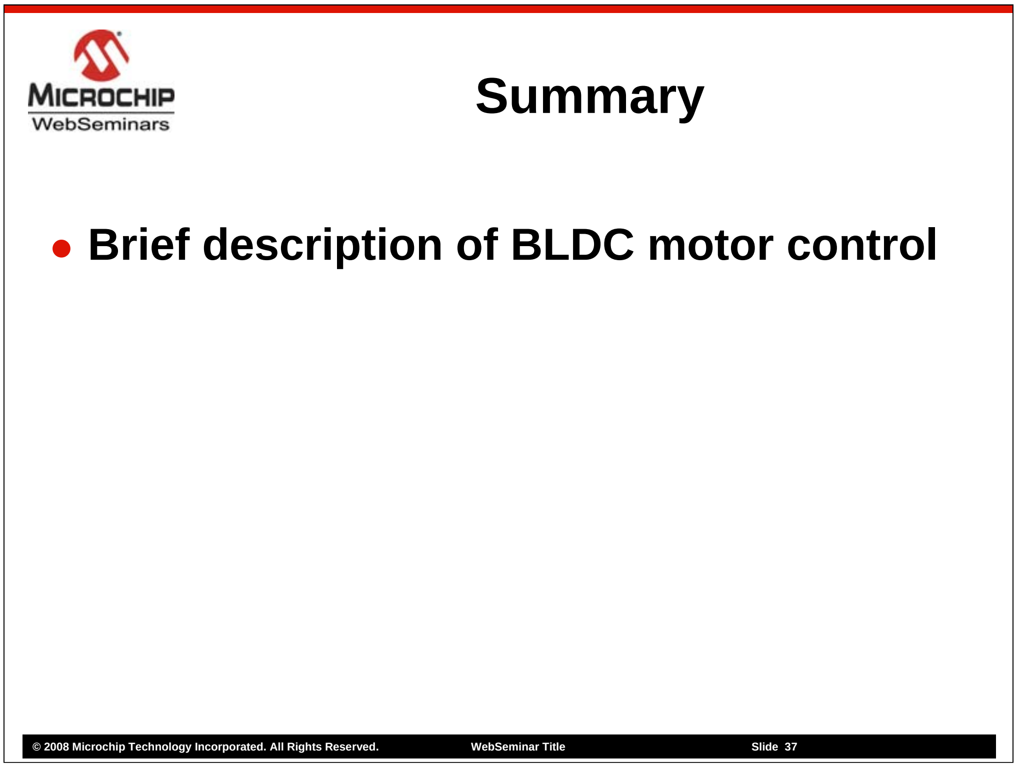
The complete filter coefficients are shown in the following table.

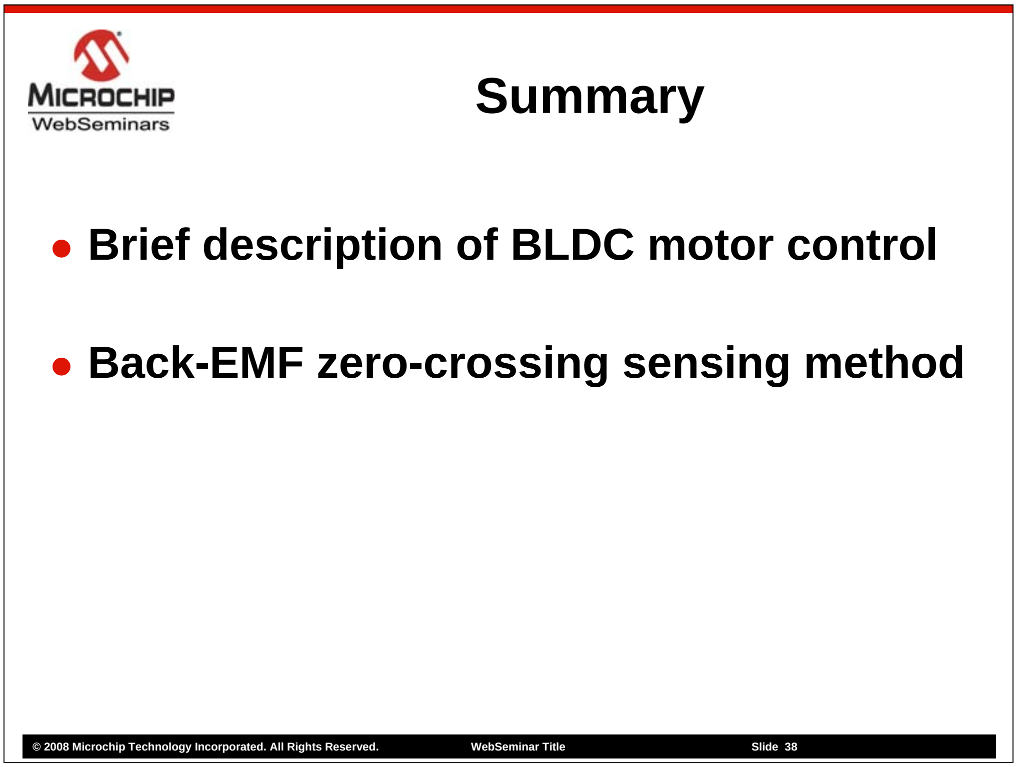
Here is the first half of the 64 coefficients. The first column shows the index value, the second column shows the calculated array value and finally the third column shows how the sixteen unique values are replaced by 1



Summary

- Brief description of BLDC motor control

In summary, we have discussed the six-step commutation technique used to control a brushless DC motor.



Microchip WebSeminars

Summary

- Brief description of BLDC motor control
- Back-EMF zero-crossing sensing method

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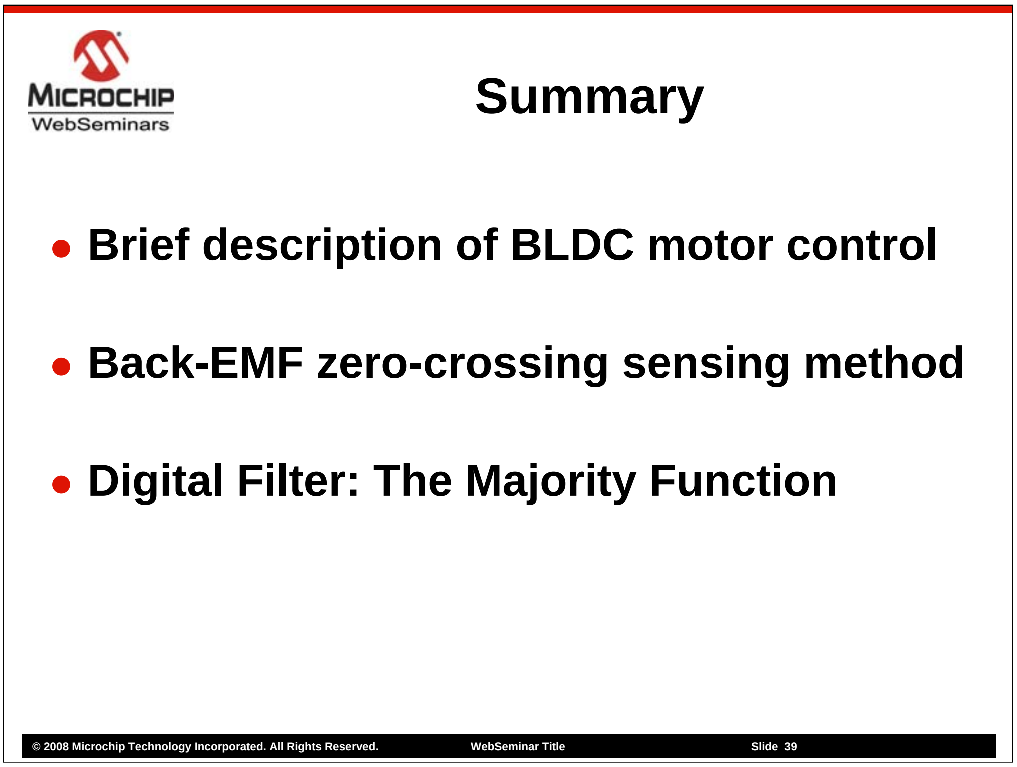
We have discussed a sensorless method to control the commutation based on the back-EMF signals.



Summary

- Brief description of BLDC motor control
- Back-EMF zero-crossing sensing method
- Digital Filter: The Majority Function

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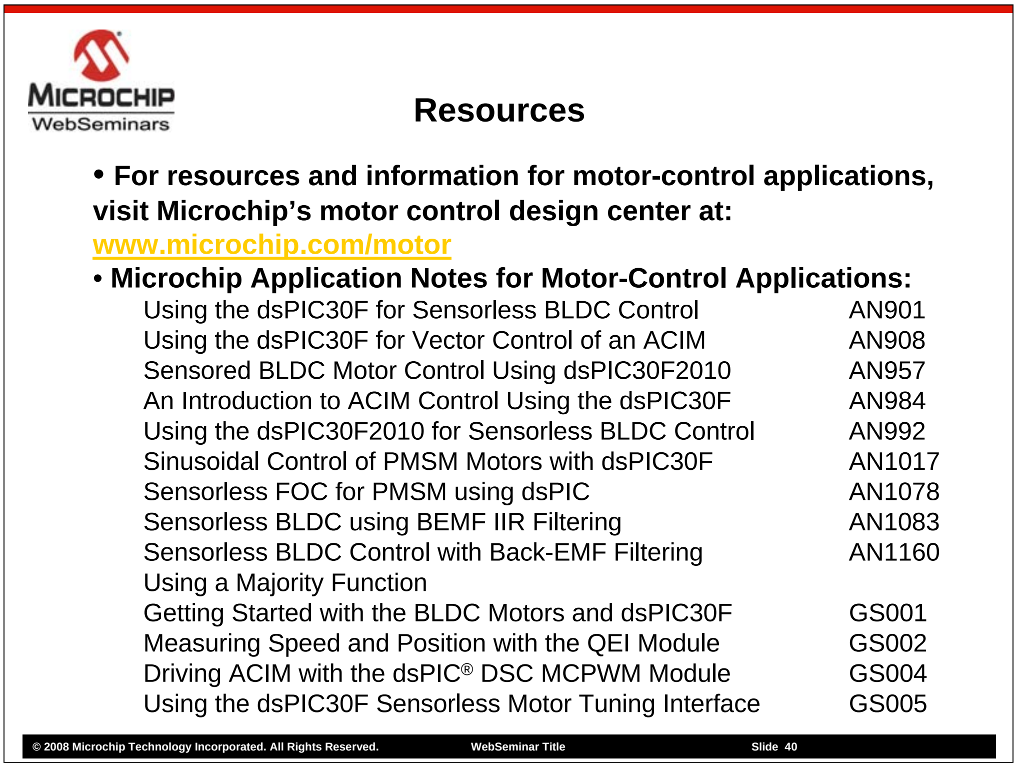
In order to precisely determine the commutation time, these signals are filtered using a digital filter based on a simple majority function.



Resources

- **For resources and information for motor-control applications, visit Microchip's motor control design center at: www.microchip.com/motor**
- **Microchip Application Notes for Motor-Control Applications:**

Using the dsPIC30F for Sensorless BLDC Control	AN901
Using the dsPIC30F for Vector Control of an ACIM	AN908
Sensored BLDC Motor Control Using dsPIC30F2010	AN957
An Introduction to ACIM Control Using the dsPIC30F	AN984
Using the dsPIC30F2010 for Sensorless BLDC Control	AN992
Sinusoidal Control of PMSM Motors with dsPIC30F	AN1017
Sensorless FOC for PMSM using dsPIC	AN1078
Sensorless BLDC using BEMF IIR Filtering	AN1083
Sensorless BLDC Control with Back-EMF Filtering Using a Majority Function	AN1160
Getting Started with the BLDC Motors and dsPIC30F	GS001
Measuring Speed and Position with the QEI Module	GS002
Driving ACIM with the dsPIC® DSC MCPWM Module	GS004
Using the dsPIC30F Sensorless Motor Tuning Interface	GS005

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We have application notes on motor control. These documents can be obtained from Microchip's web site, by clicking on the "dsPIC® Digital Signal Controllers" or "Technical Documentation" link. We also have a motor control design center at www.microchip.com/motor.

This wraps up the seminar on Sensorless Field Oriented Control of AC Induction Motors. Thank you for your interest in the dsPIC Digital Signal Controllers.