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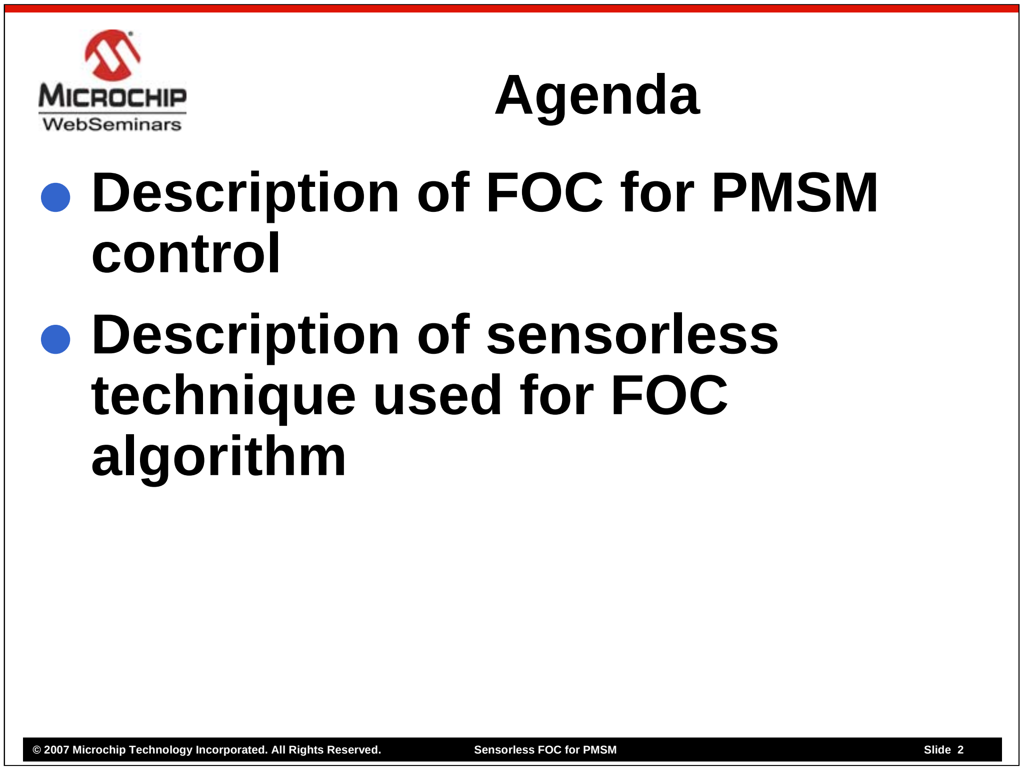
WebSeminars

Sensorless Field Oriented Control (FOC) for Permanent Magnet Synchronous Motors (PMSM)

 Sensorless FOC for PMSM Slide 1

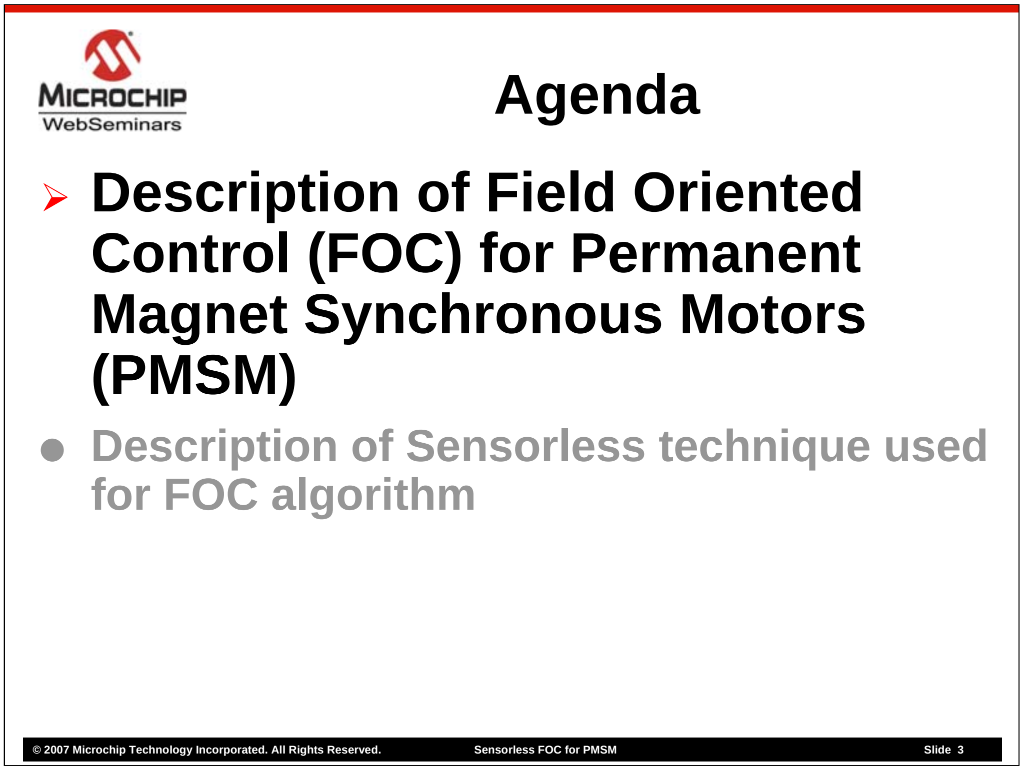
Welcome to the Sensorless Field Oriented Control for Permanent Magnet Synchronous Motors web seminar.



Here is the Agenda for today's seminar.

We will talk about Field Oriented Control (FOC) specifically targeting Permanent Magnet Synchronous Motors (PMSM). We will cover the main block for Field Oriented Control.

Secondly, we will cover a position estimator to allow FOC control in a PMSM Motor.



We will start with an introduction to Permanent Magnet Synchronous Motors. We will talk about internal electrical diagram of a PMSM motor, and how it operates. We will also explain how Field Oriented Control works, and how it enables a high performance motor control application.

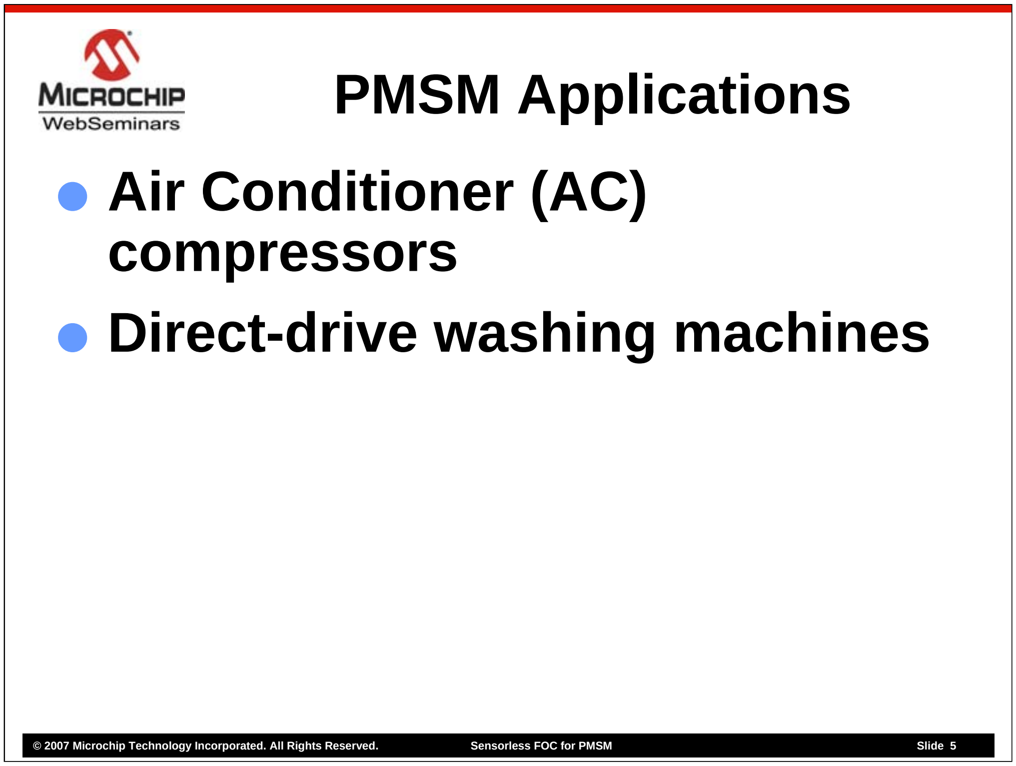
PMSM Applications

- **Air Conditioner (AC) compressors**

 Sensorless FOC for PMSM Slide 4

These are some applications where PMSM motors are used.

1. In order to boost the efficiency of air conditioning compressors, PMSM motors are used. Also, physical conditions of a compressor, where the motor is flooded in oil, position sensors are not allowed. Sensorless algorithms are required for compressors in general.
2. PMSM motors are also becoming popular in Direct Drive washing machine due to their torque available at very low speeds. FOC enables better dynamic response in a washing machine without increasing the overall system cost.
3. Refrigerator compressors also require better efficiency and torque performance at low speeds. These requirements are covered by PMSM motors as well.
4. Pumps and Air Conditioner compressors in the automotive applications are also transitioning to PMSM motors due to they efficiency gains, increased life time compared to DC motors, and high torque at low speeds.



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PMSM Applications

- Air Conditioner (AC) compressors
- Direct-drive washing machines
- Refrigerator compressors

 Sensorless FOC for PMSM Slide 6

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PMSM Applications

- Air Conditioner (AC) compressors
- Direct-drive washing machines
- Refrigerator compressors
- Automotive AC compressors

 Sensorless FOC for PMSM Slide 7

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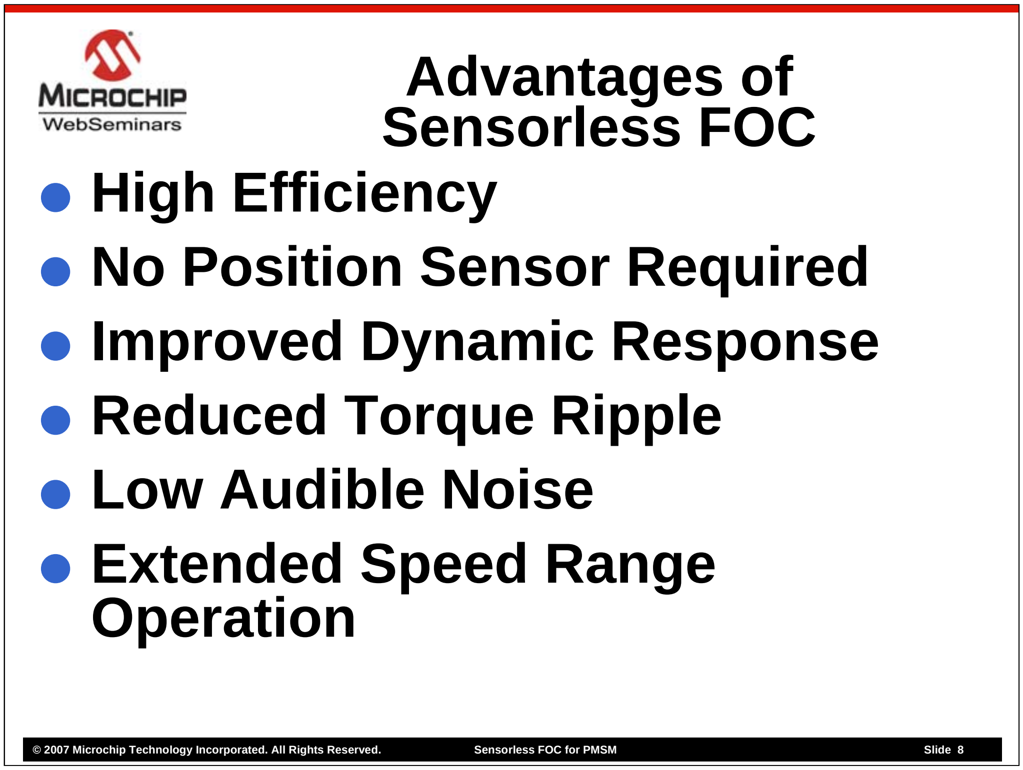


These are some advantages of Sensorless FOC for PMSM motors.

High efficiency is one of the top advantages of Field Oriented Control by aligning rotor and stator flux in order to generate the most optimal torque production of the motor.

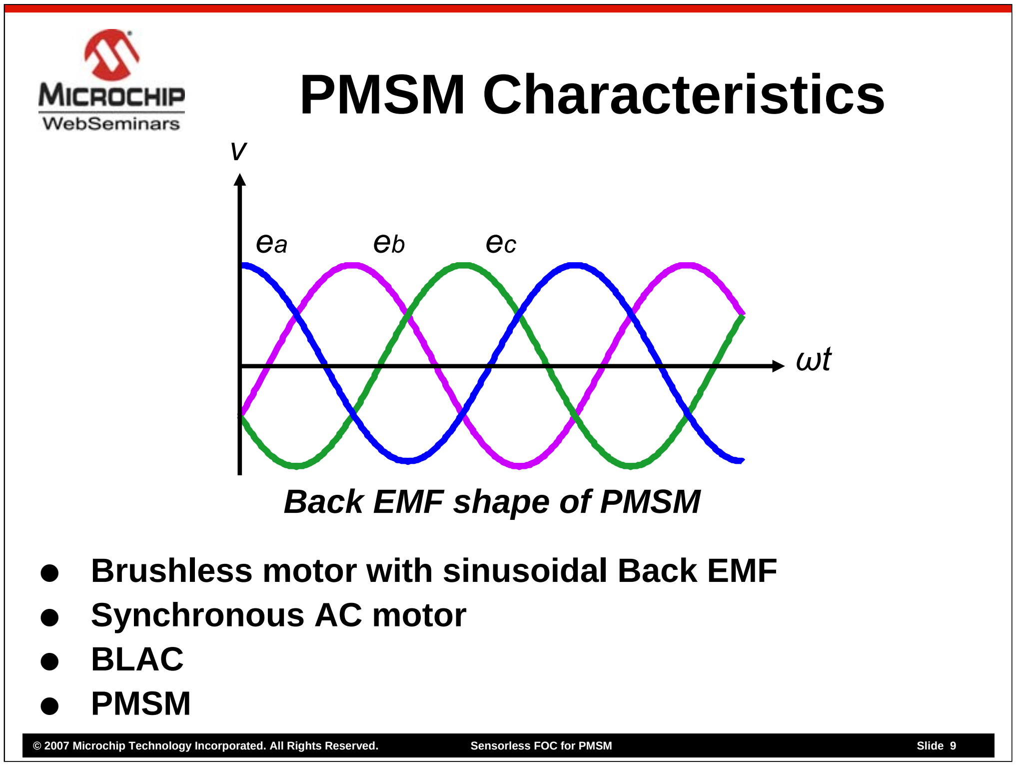
No positions sensors are required in this algorithm since position and speed of the motor are estimated based on currents and voltages. The implemented estimator will be discuss in this web seminar.

Field oriented control improves dynamic response by adjusting both amplitude and phase of the control signals fed back to the motor. Applications such direct drive washing machines benefit with this advantage.

In Field oriented control, stator field is continuously updated based on the position of the rotor field. By continuously pulling the rotor to a new position, the rotor is always magnetized with a new vector, thus reducing torque ripple. Applications where low speeds are required take advantage of this property of FOC.

Sinusoidal commutation accomplished with FOC, also reduces audible noise produced by other types of control such as 6 step control.

Another advantage of FOC is enabling speeds above motor’s rated speed. This is accomplished by energizing the stator windings at an angle where the rotor’s magnetic field is weakened, and the resulting magnetic field vector composed by stator’s field and rotor’s field is increased. Speed range can be increased considerably by using field weakening or phase advance control.



Let us get started with a description of a PMSM Motor.

What is a PMSM motor?

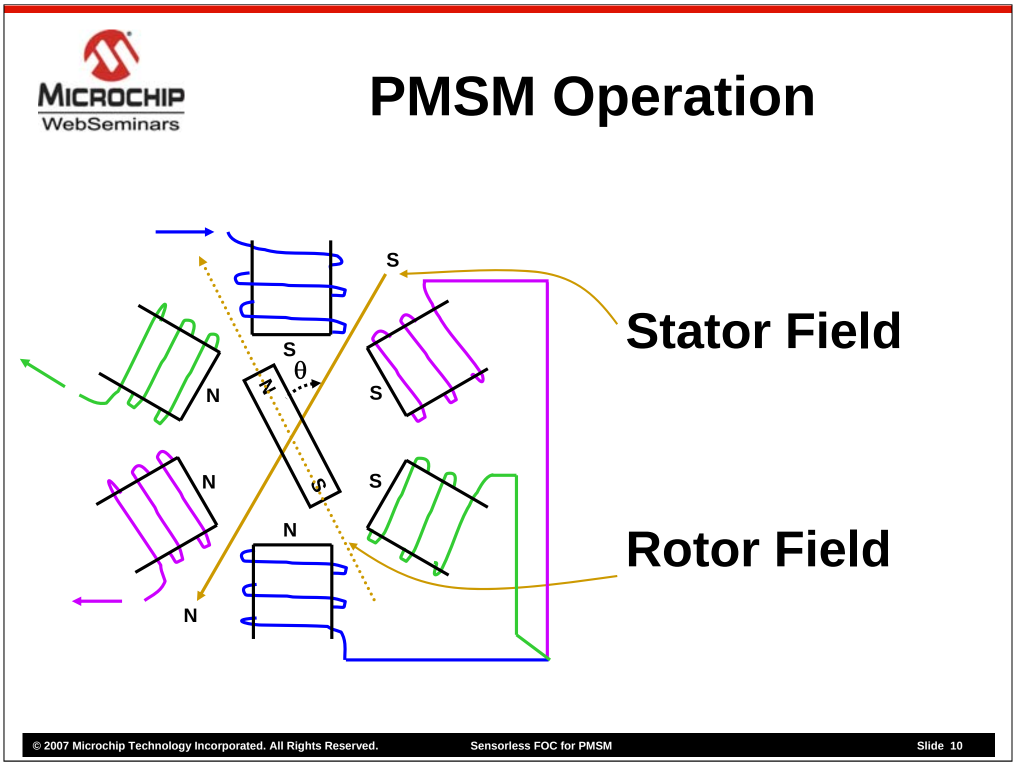
If we take a PMSM motor, and spin it as a generator, that is, if we spin it with another motor, or even with our hands, these are the measurements we will get from the motor windings. These voltages are sinusoidal in a PMSM motor, whereas in a BLDC motor they are trapezoidal.

Here are some alternate names we find for Permanent Magnet Synchronous motors:

1. Brushless Motors with Sinusoidal Back EMF
2. Synchronous AC Motors
3. BLAC, or Brushless AC Motors
4. and PMSM, Permanent Magnet Synchronous Motors.

A synchronous motor differs from an asynchronous motor in the relationship between the mechanical speed and the electrical speed. In a synchronous motor, the supplied voltages have the same frequency as the mechanical motor speed. In an asynchronous motor, the end mechanical speed is different from the input frequency, and the relationship between input frequency and mechanical speed varies depending on mechanical load applied to the motor.

The distribution of the windings in a Synchronous AC motor (or PMSM) is

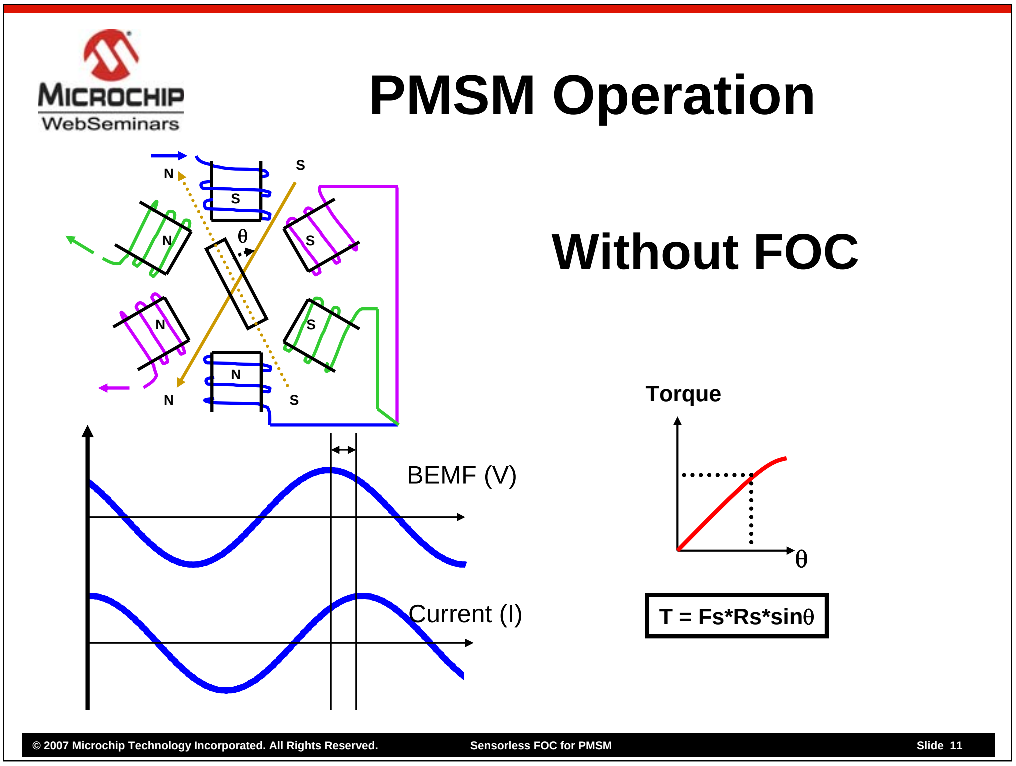


There are two main components in a PMSM motor: Permanent magnet and stator windings.

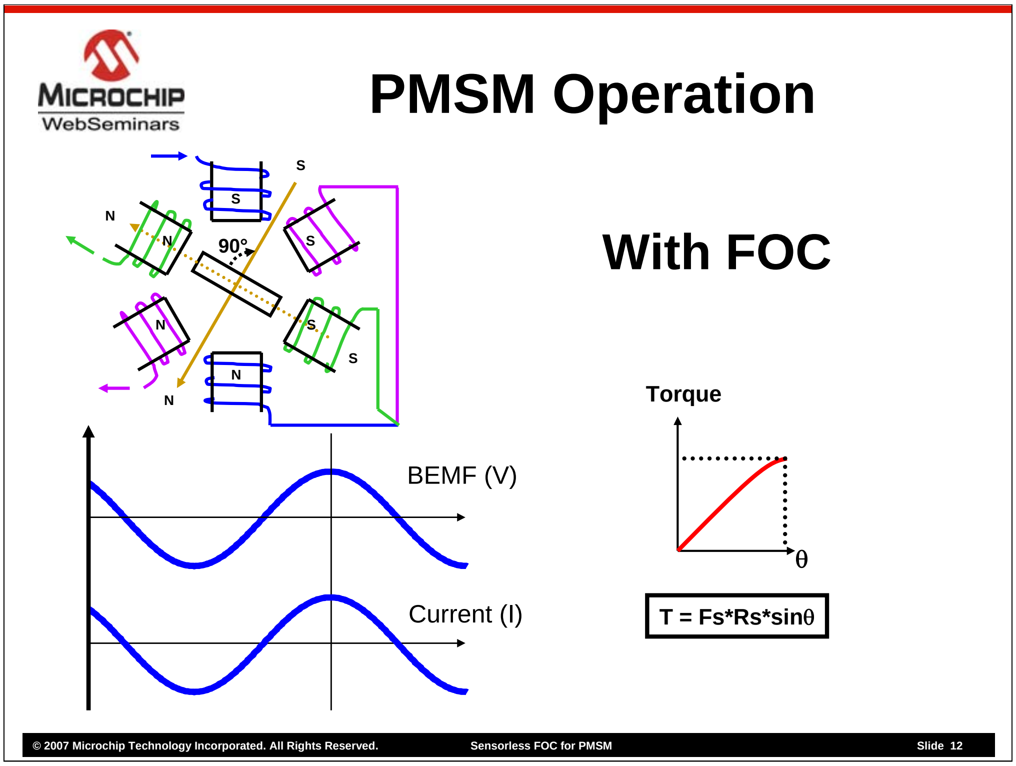
This is how the motor operates:

Stator windings generate a rotating magnetic field. Since the permanent magnet rotor has its own magnetic field, it will try to align with the stator's magnetic field. The electronics will generate a rotating magnetic field in the stator that is always ahead of the rotor, thus keeping the rotor spinning. The angle between rotor and stator magnetic fields plays an important role on the torque generation of the motor.

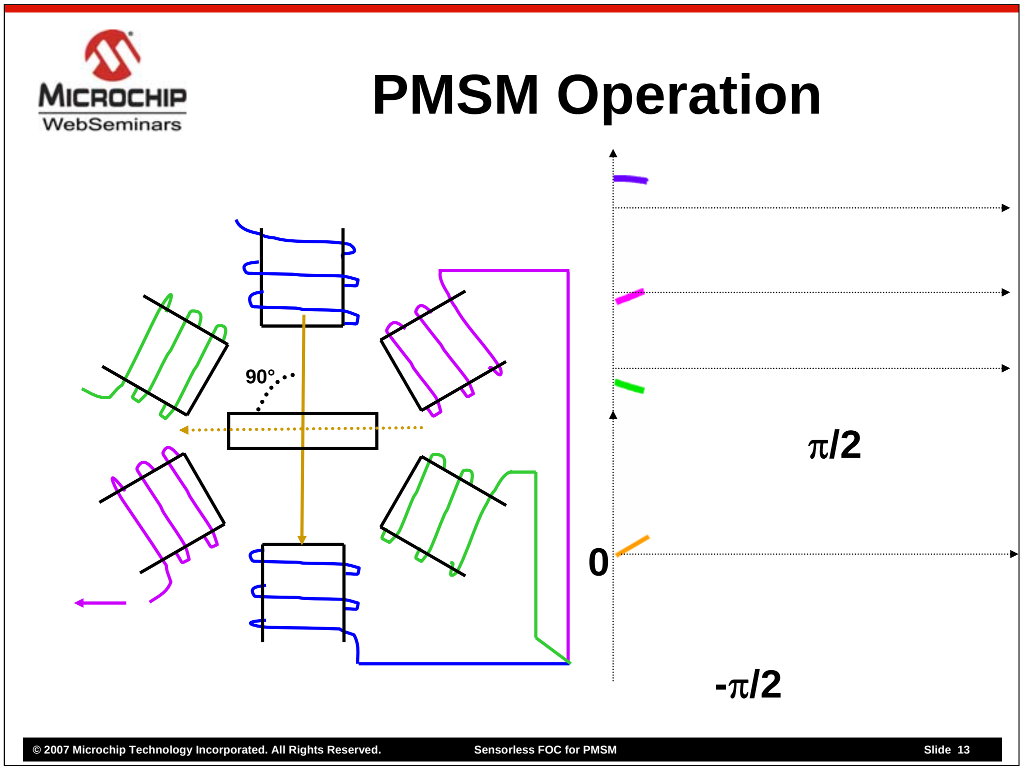
For simplicity a single pole pair motor is shown, which means that for every revolution of the magnetic field there is one revolution on the motor shaft. In reality most of the motors have multiple pole pairs, where the mechanical speed is the product of input frequency and number of pole pairs. For example, if the motor has five pole pairs, for every revolution on the motor shaft, there will be five revolutions on the magnetic field.



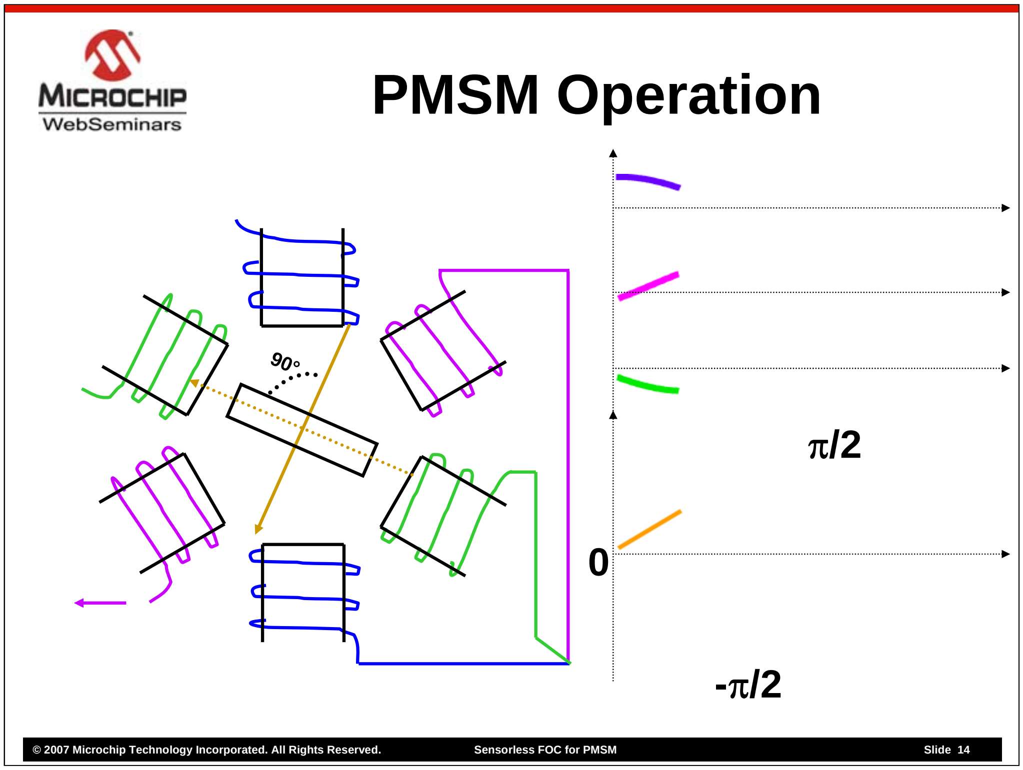
As the motor spins, there is an angle between rotor magnetic field and stator magnetic field. If these two magnetic fields are not ninety degrees from each other, there will be an offset angle between Back EMF and Current. With this phase offset the torque production at a given input power will not be the maximum. This can be seen in the torque Vs angle plot, where torque generation is proportional to sine of theta. If the control logic does not adjust commutation angle to be ninety degrees, torque production will not be the maximum.



If we have a way to detect the rotor magnetic field angle, we can generate a rotating magnetic field that meets the ninety degrees. With this commutation angle of ninety degrees, torque production is maximized.



With this animation we can see how the commutation angle is always ninety degrees ahead of the rotor. On the left we see how the motor spins with Field Oriented Control. On the voltage diagrams we show how the output voltages have a sinusoidal shape. On the lower right we see the rotor angle changing from minus pi (minus one eighty degrees) to plus pi (plus one eighty degrees).



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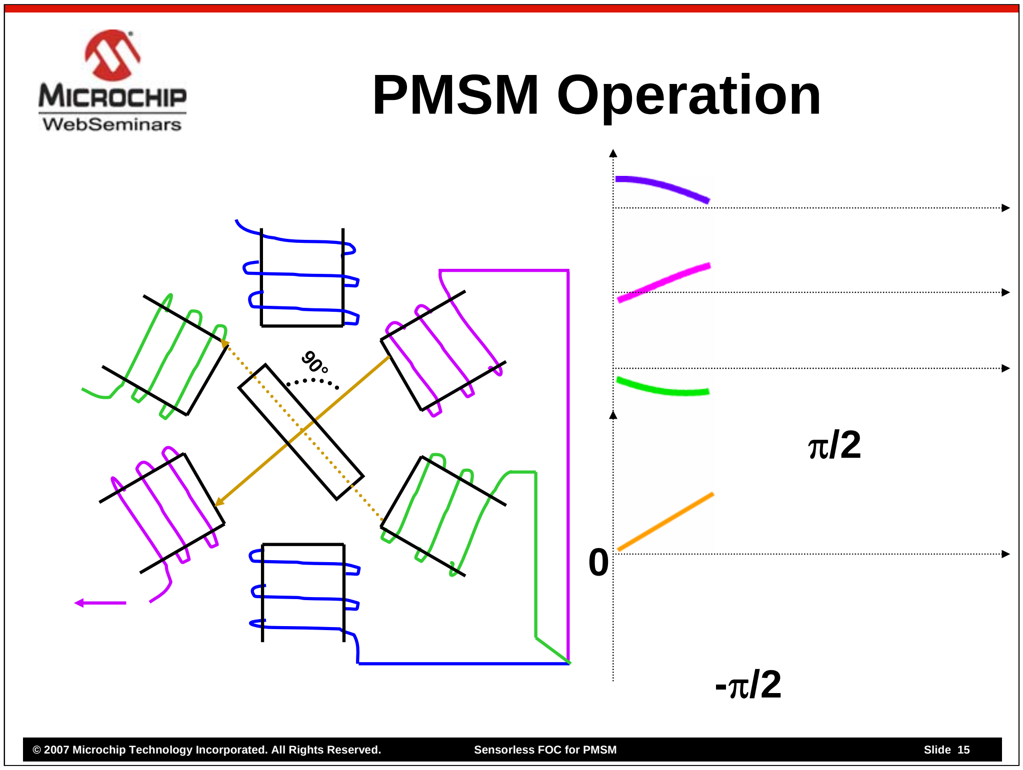

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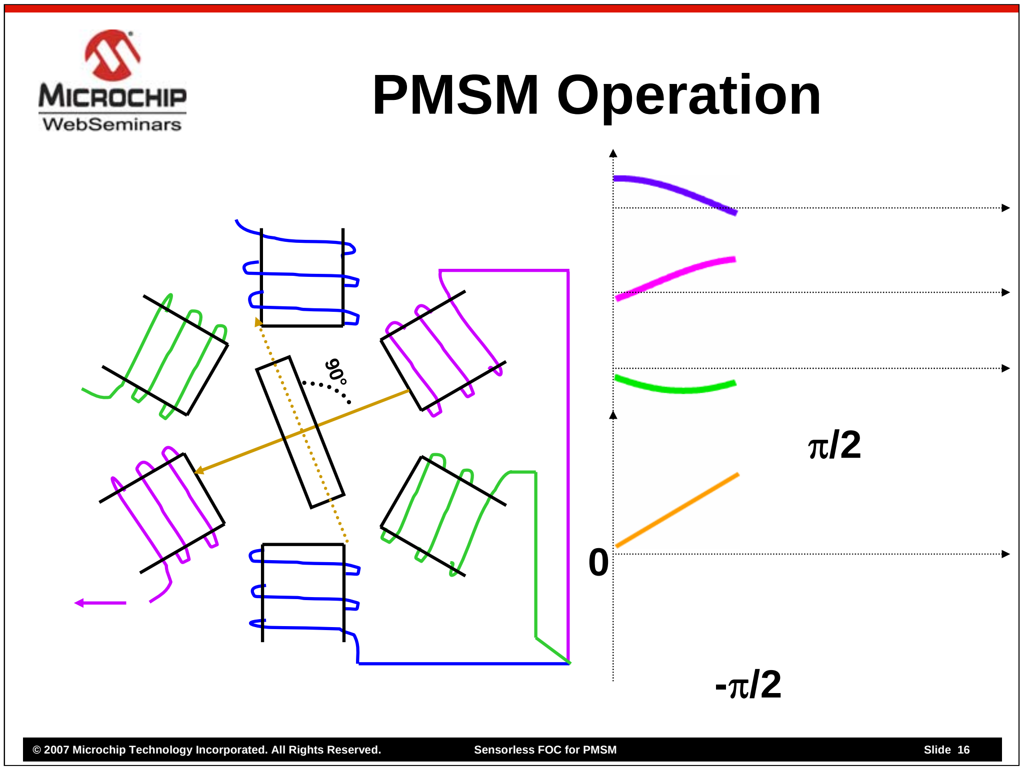

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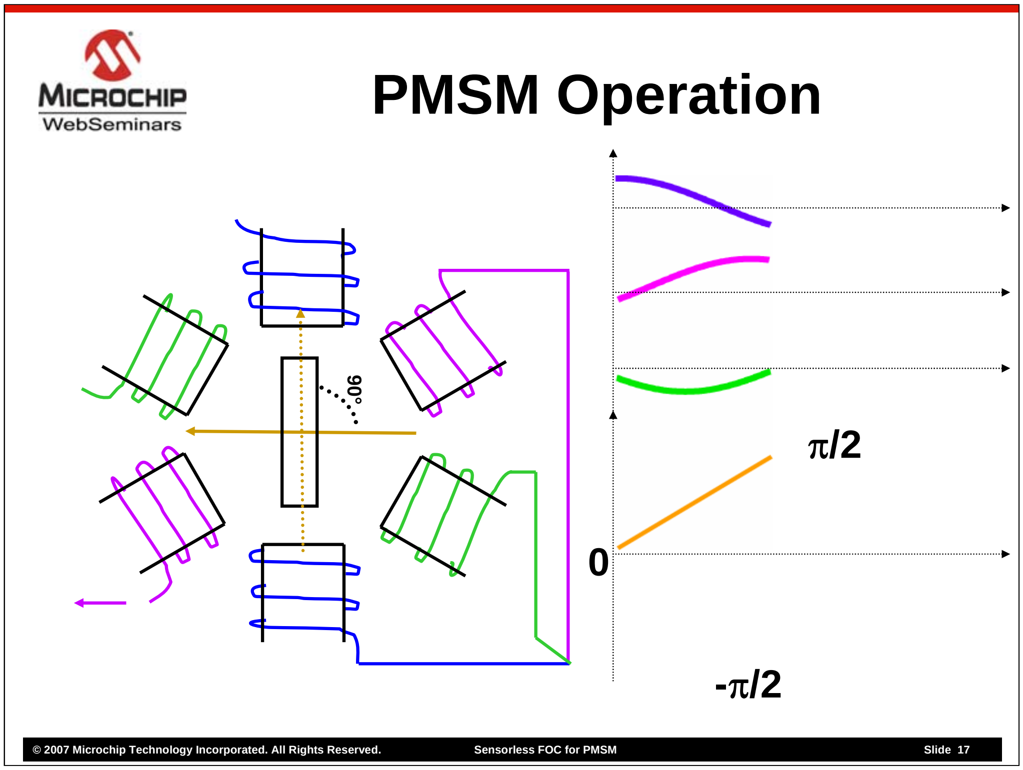

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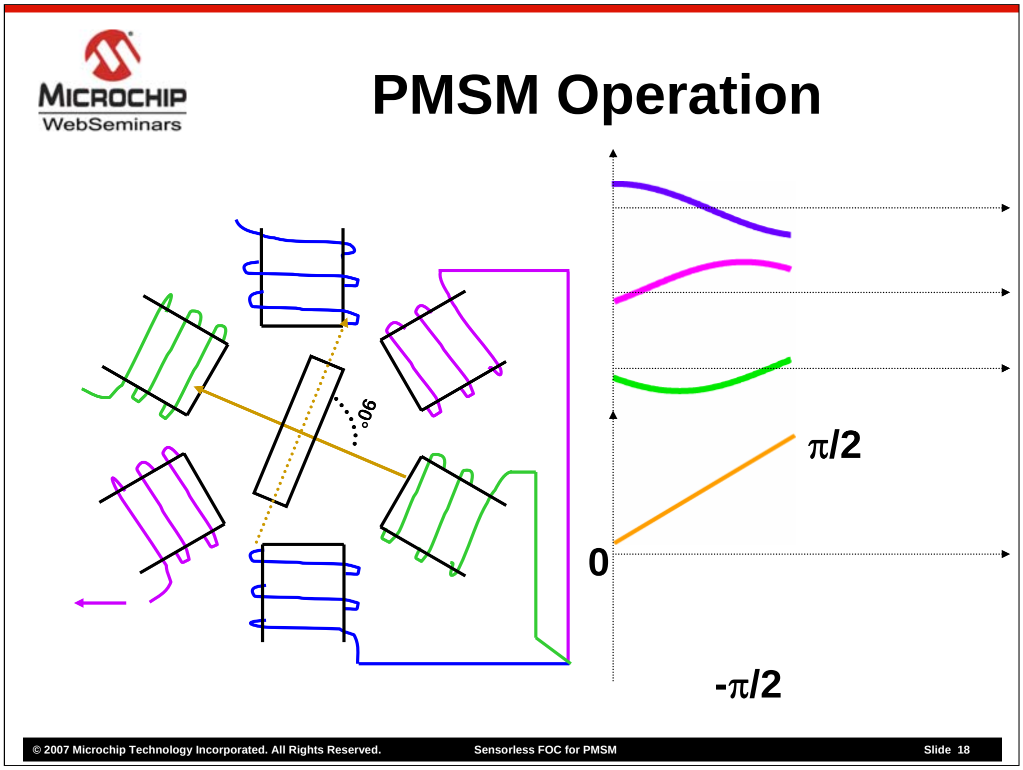

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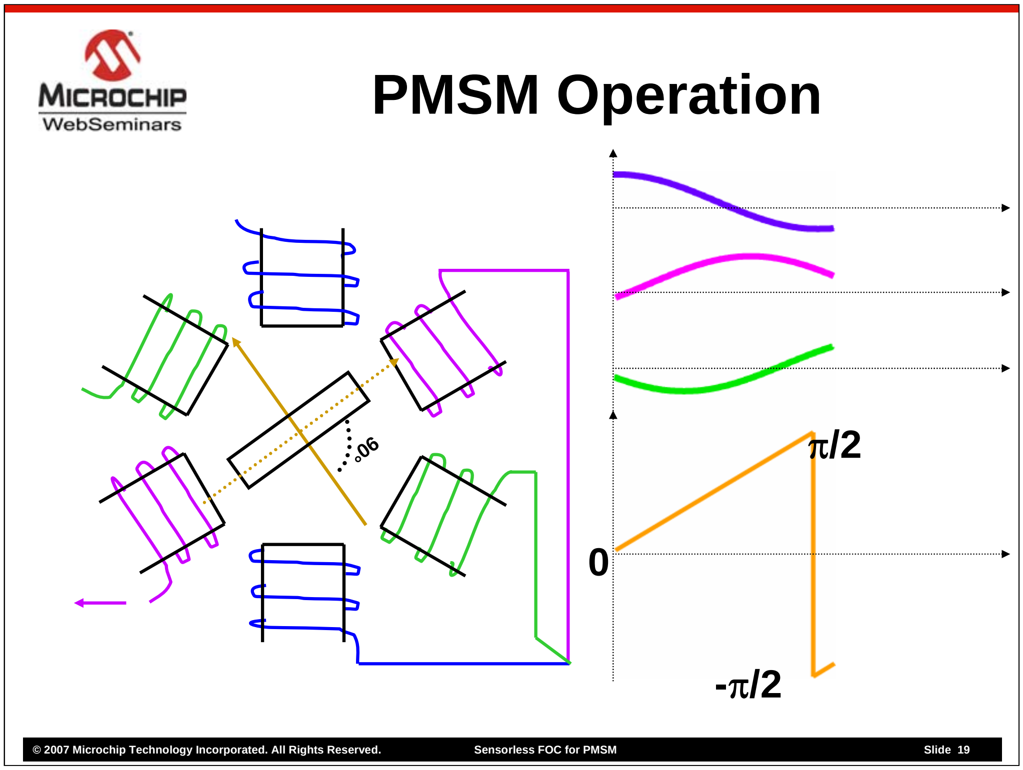

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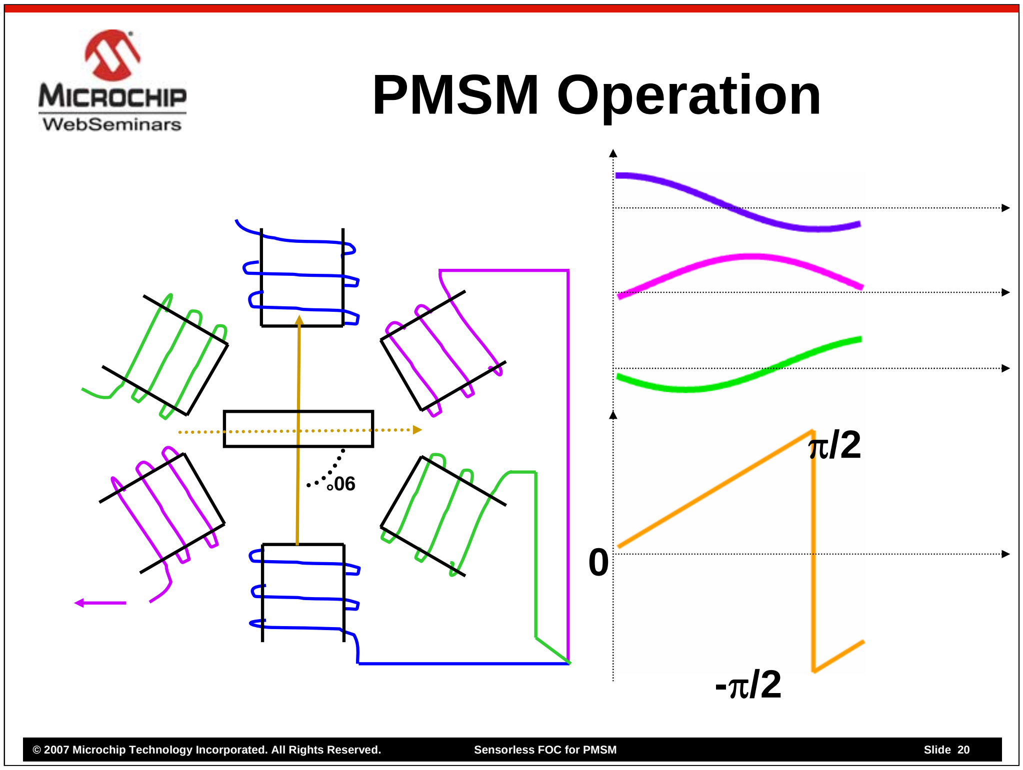

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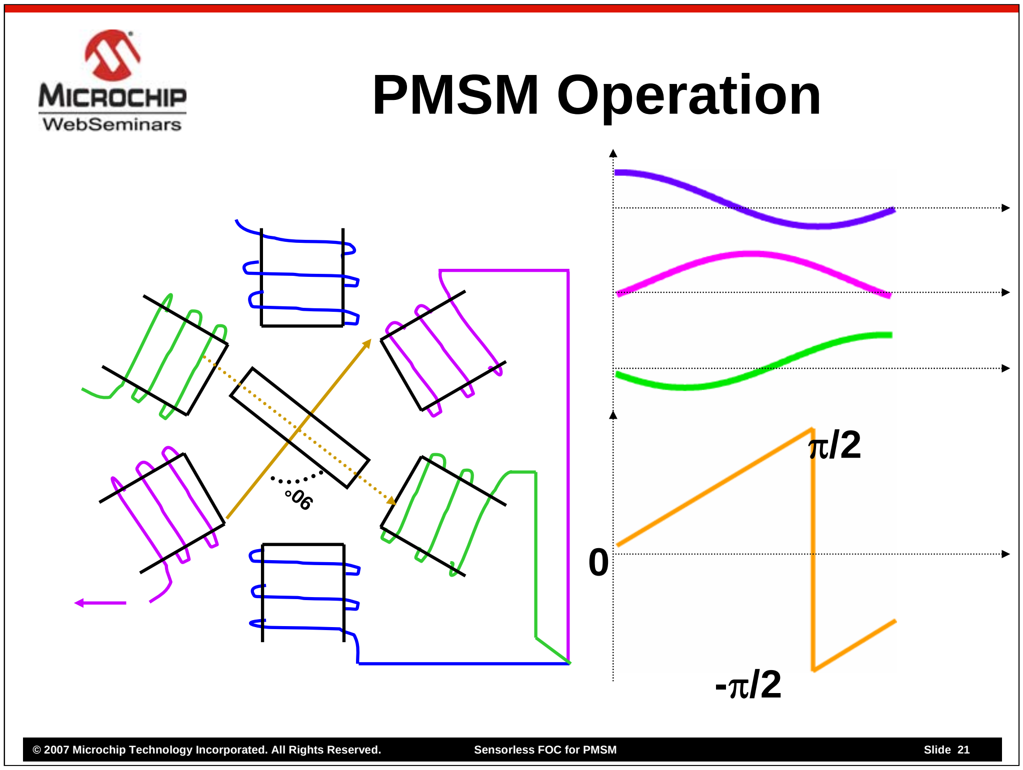

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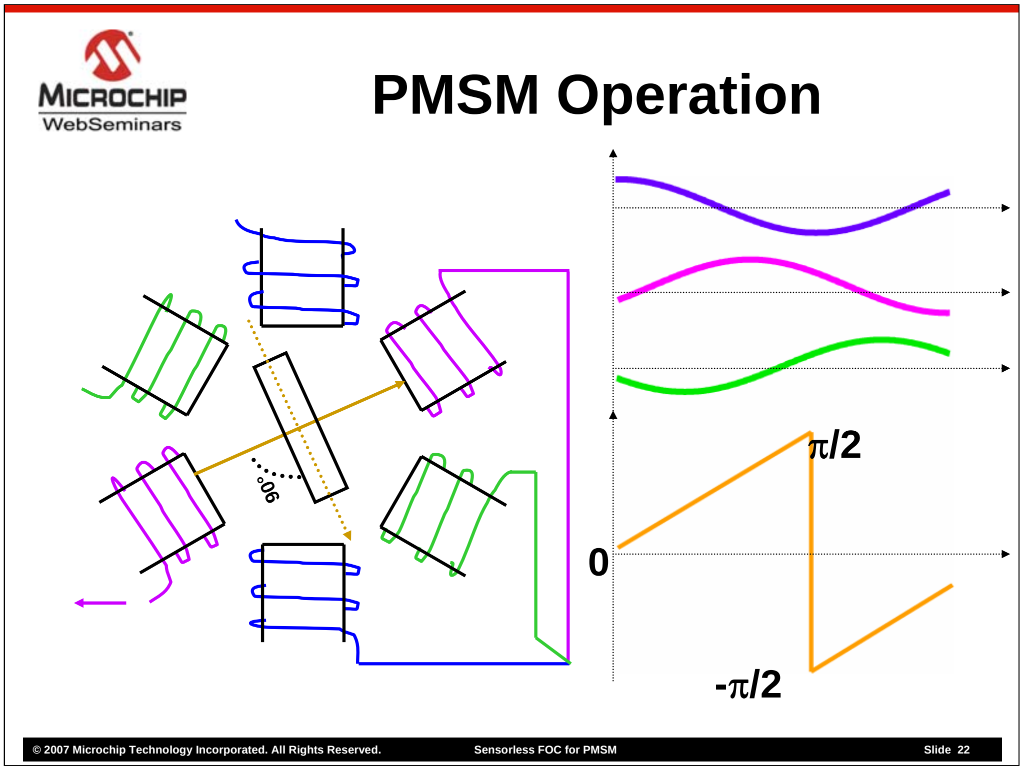

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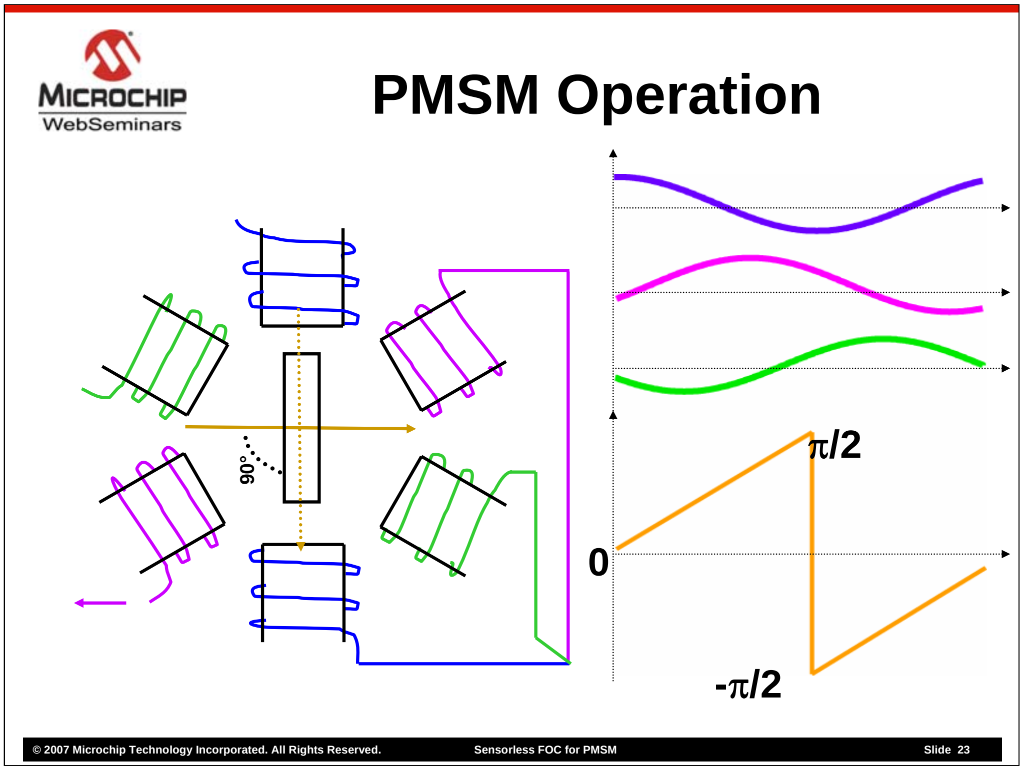

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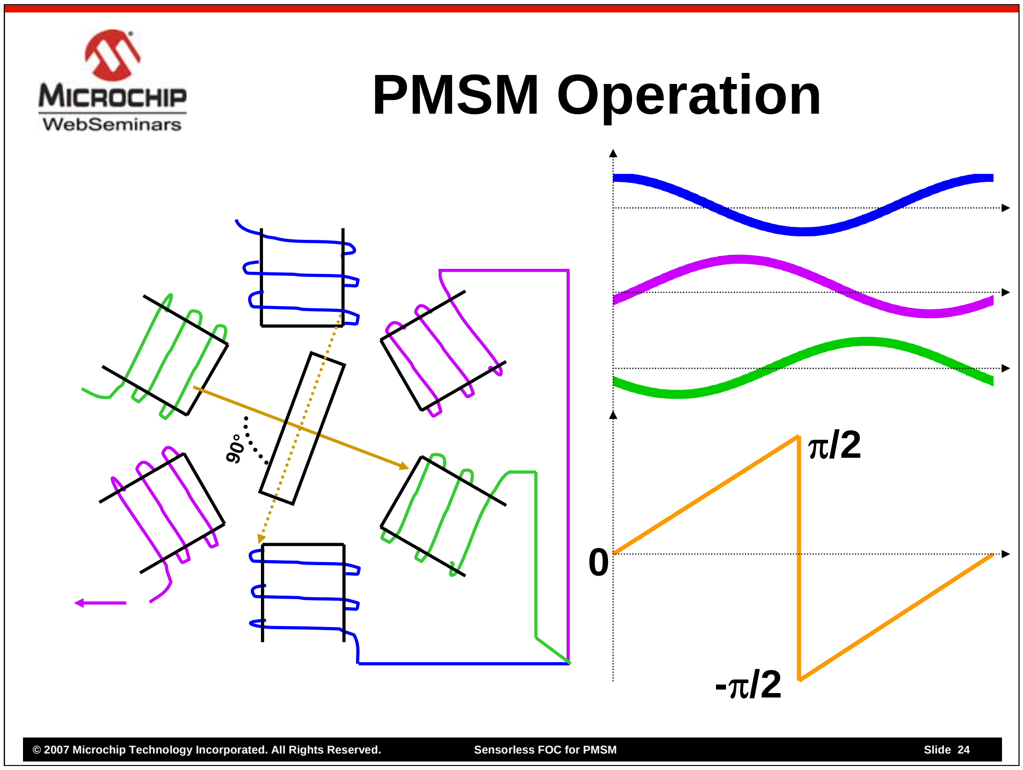

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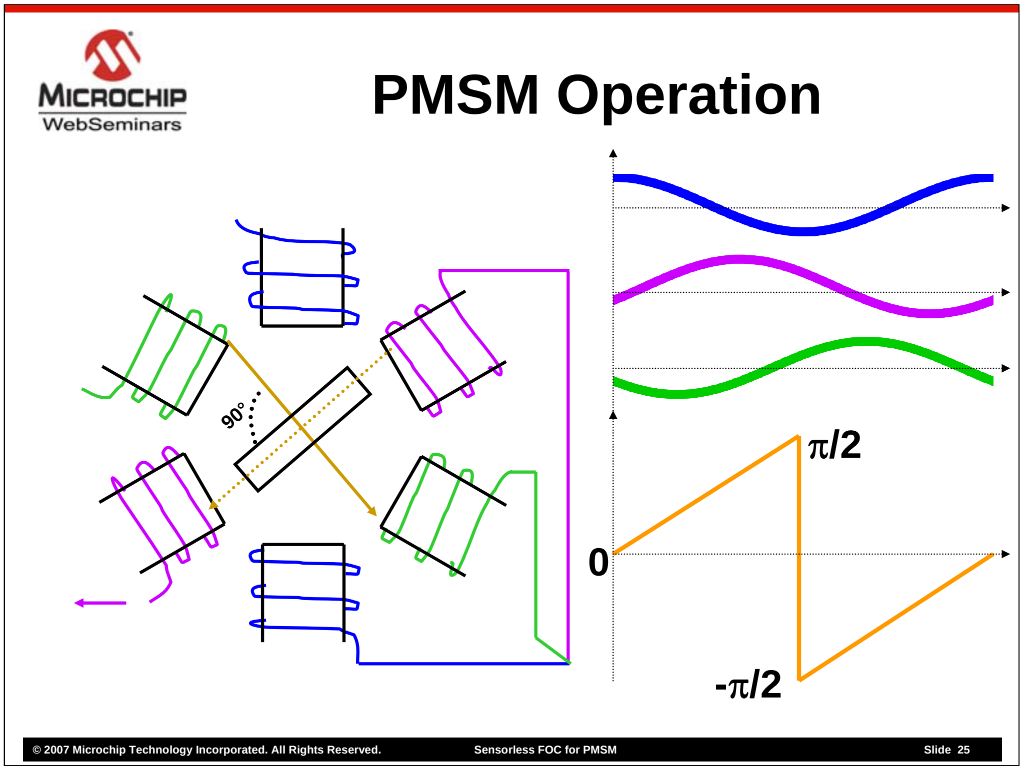

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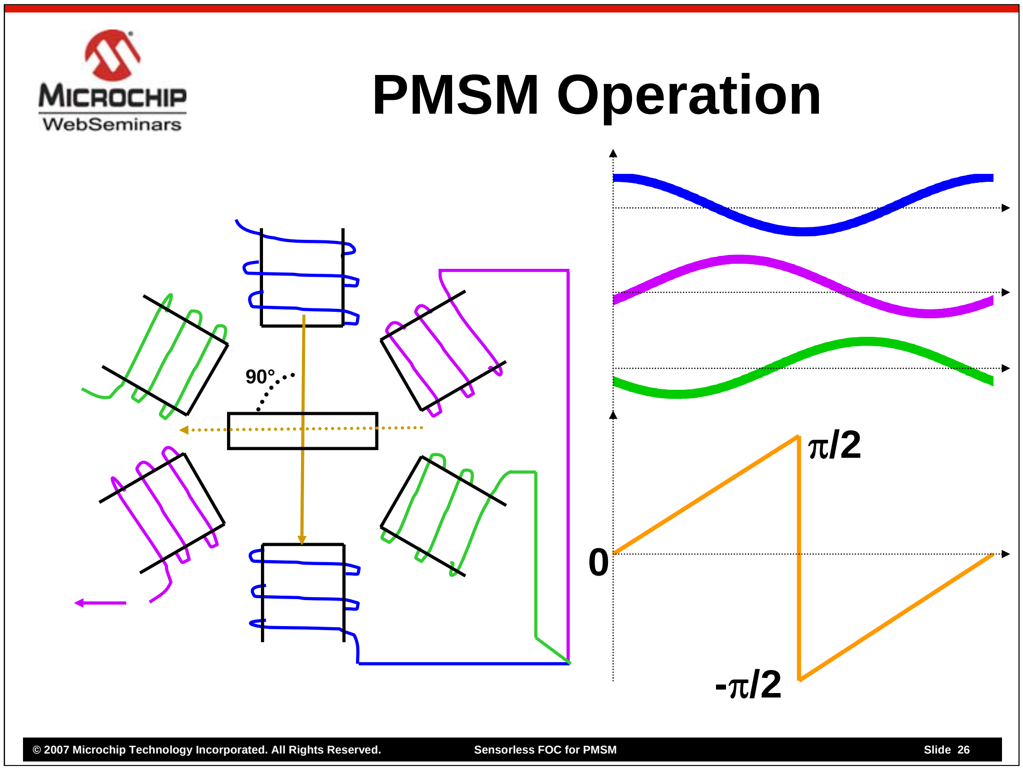

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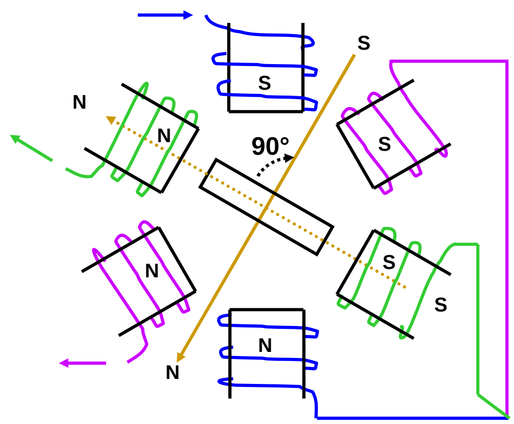
PMSM with FOC

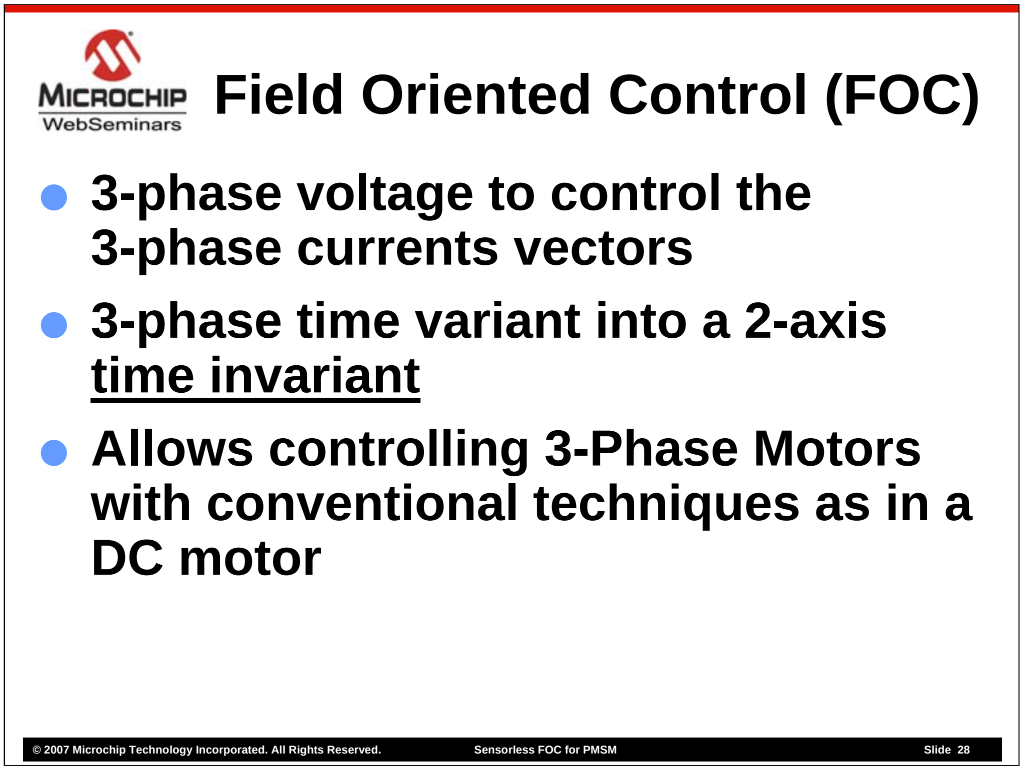
- Keep load 90° ahead of rotor position
- Knowledge of rotor position required at all times
- Better torque production
- No torque ripple



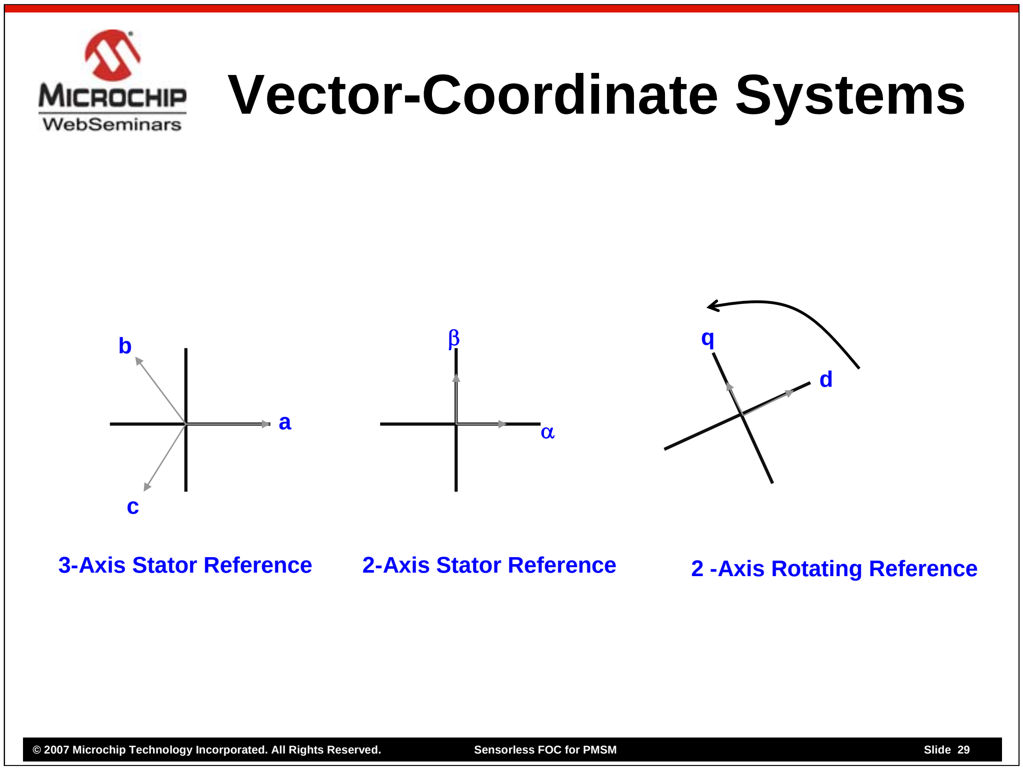
 Sensorless FOC for PMSM Slide 27

In order to accomplish FOC, stator magnetic field is always kept ninety degrees ahead of the rotor. This requires rotor position information at all times. In a scenario where hall sensors are used to detect rotor position, we get new position information every sixty degrees. In Field Oriented control a different algorithm to detect or estimate rotor position is needed.

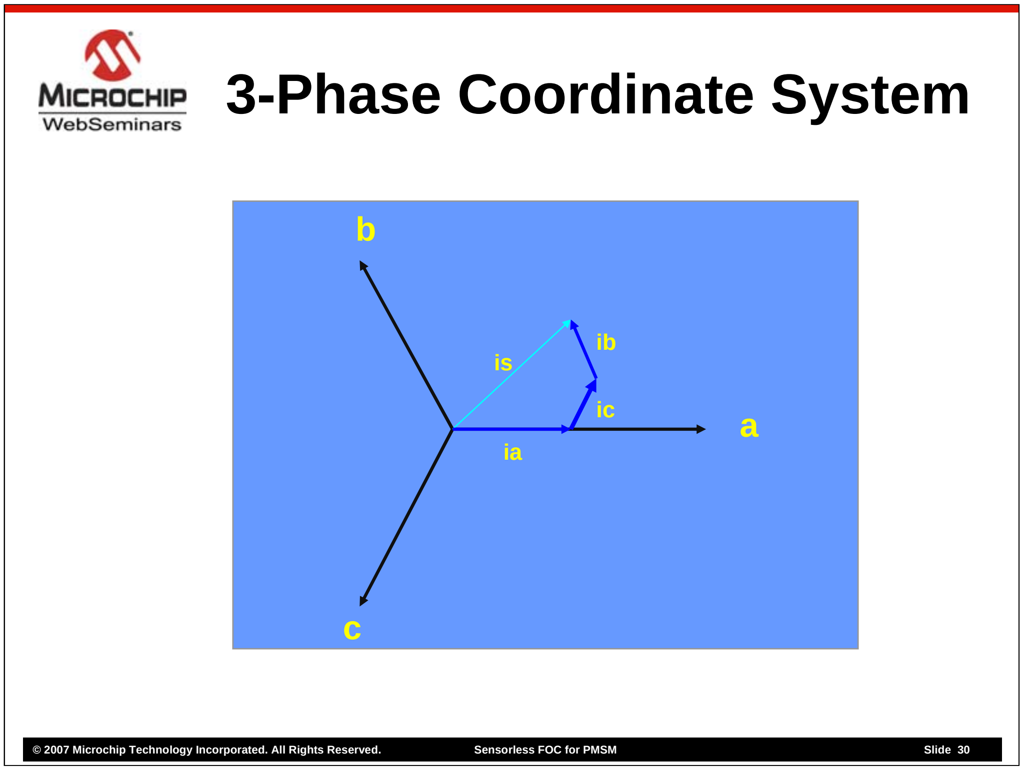
The outcome of field oriented control is a better torque production and less torque ripple generated by the motor.



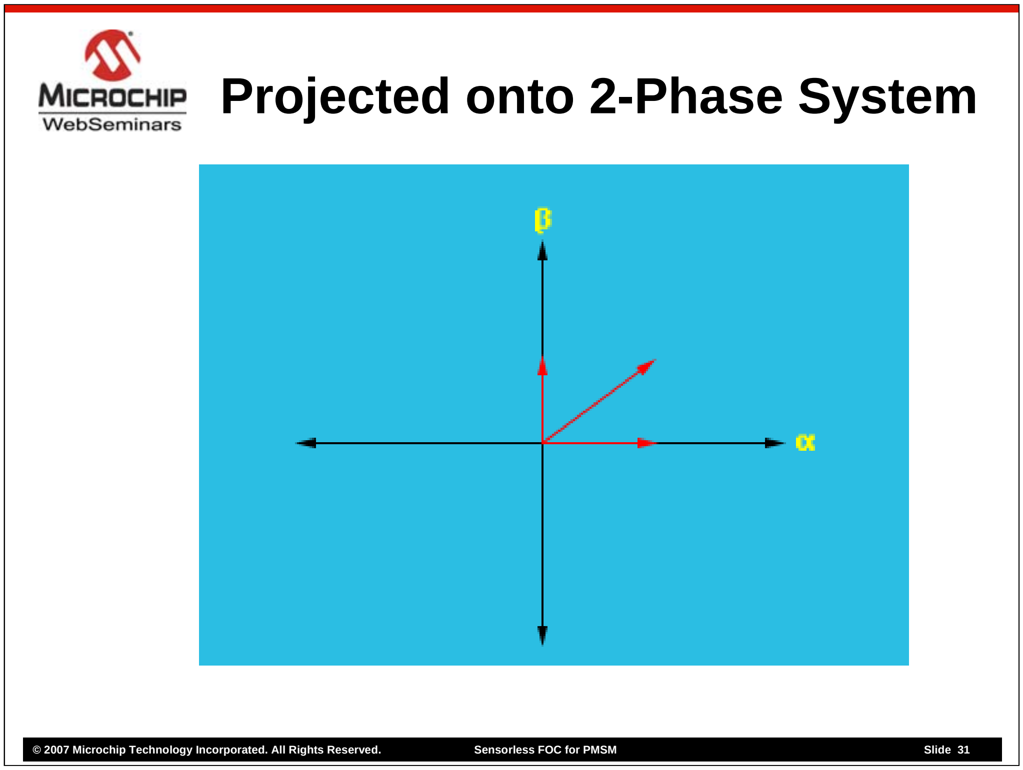
The FOC algorithm generates a 3-phase voltage as a vector to control the 3-phase stator current. By transforming the physical current into rotational vector using transforms, the torque and flux components become time-invariant—allowing control with conventional techniques such as Proportional & Integral (PI) controllers, as with a DC motor. In brushed DC motors, by construction, the stator flux and rotor flux are kept at 90 degrees to each other, thus generating maximum possible torque from the motor. Using the FOC technique, the motor currents are transformed to 2-axis vectors, as seen in a DC motor. The process starts out by measuring the three phase motor currents. In practice, since the instantaneous sum of the three current values will be zero, by measuring only two of the three currents, the value of the third can be determined. Further, there is a reduction in the hardware cost because only two current sensors are required.



The first transform moves a 3-axis, 2-dimensional coordinate system referenced to the stator onto a 2-axis system keeping the same reference. At this point, the stator current phasor can be represented on a 2-axis orthogonal system with the axis called α-β. The next step is to transform into another 2-axis system called the d-q axis that is rotating with the rotor flux.

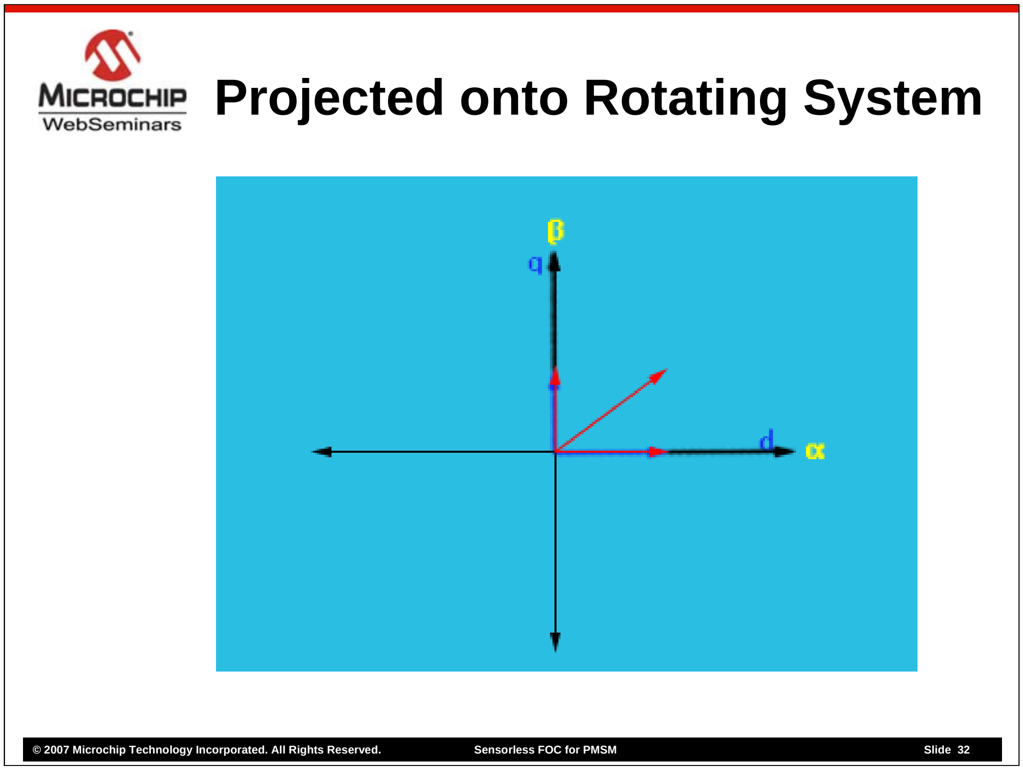


The following animation will help us understand the transformations needed in Field Oriented Control. We start at a three phase system, where Ia, Ib and Ic are the components of vector Is.

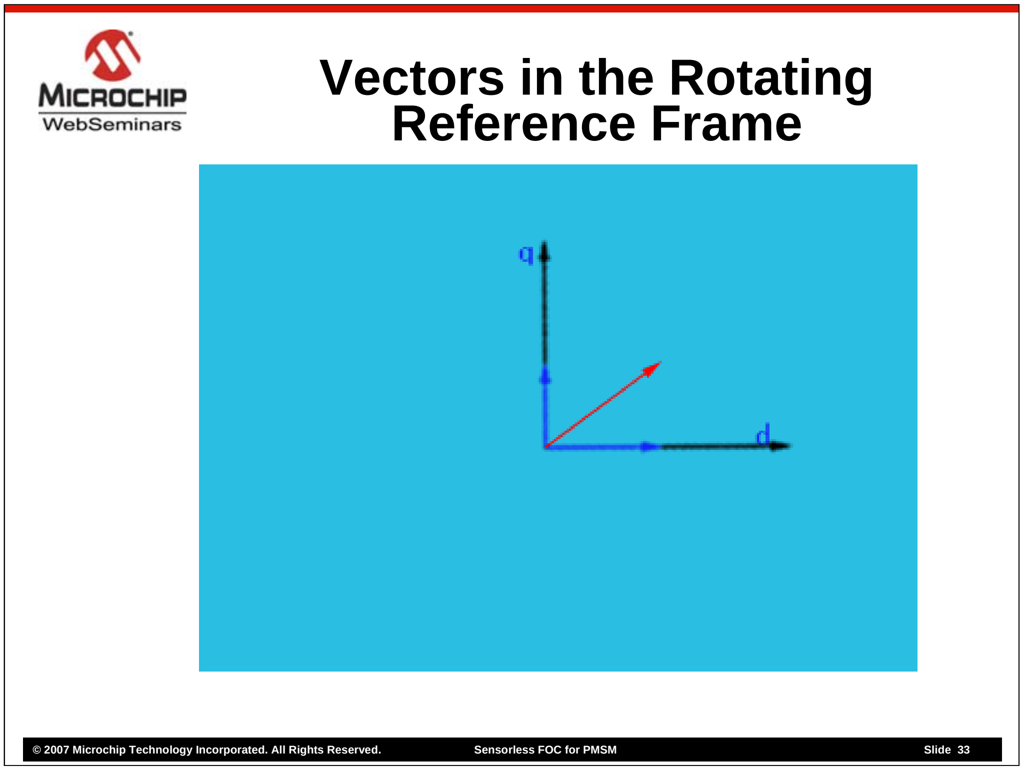


When we project the three phase system to a two phase system, we see how the components of vector Is vary with time. I alpha and I beta change their value from maximum to minimum in a sinusoidal fashion. However, the resulting vector does not change as the motor turns.

If we were to control alpha and beta variables, we would need to modify our PI control loops, so that the reference and measured values vary with time as well, which makes it more complicated than traditional control loops.



When we add the commutation angle to vector component calculation, they become stationary.



After jumping into the rotor perspective, individual component of vector Is do not change as the motor spins, and traditional PI control loops can be applied to control them.

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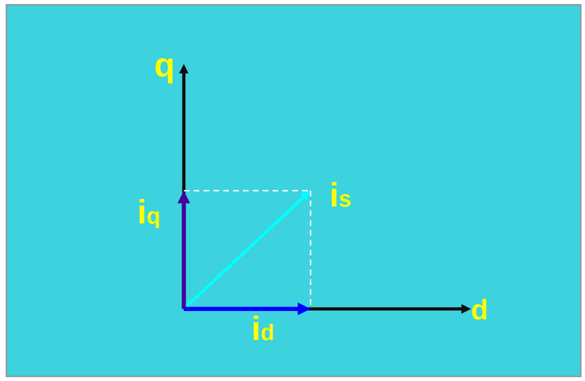
Vectors in the Rotating Reference Frame

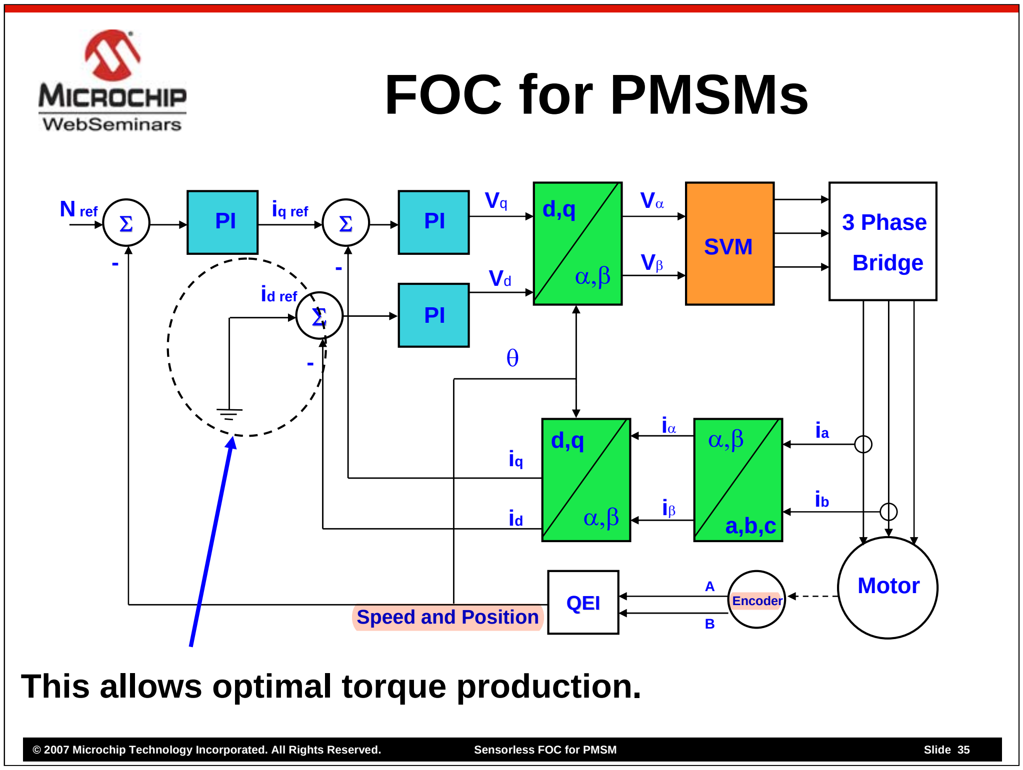


Torque ∝ iq **Flux ∝ id**

They are time-invariant and can be treated as DC parameters, which allows them to be controlled independently.

 Sensorless FOC for PMSM Slide 34

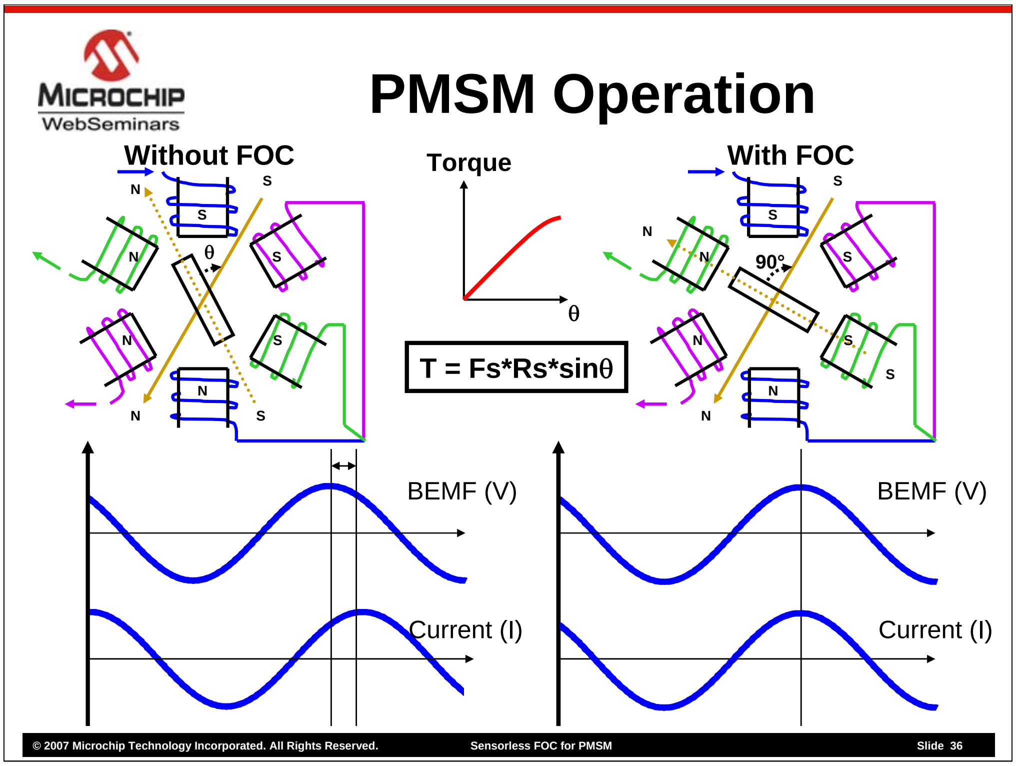
These two components of the current vector are responsible for torque and flux generation of the motor. Now we are able to have independent control of torque and flux generation by directly compensating the responsible component.



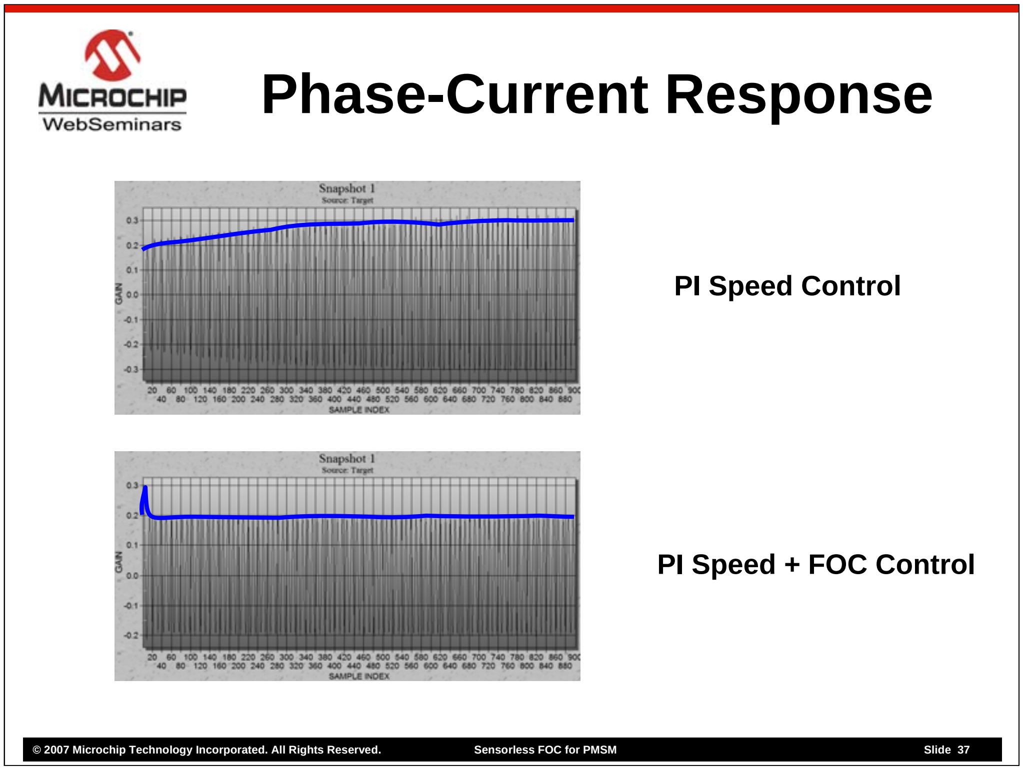
The entire process is illustrated in this block diagram, including coordinate transformations, PI iteration, transforming back and generating PWM. This block diagram also describes the functions required for FOC control. Error signals are formed using Id, Iq and reference values for each. The Id reference controls rotor-magnetizing flux. The flux vector must be kept in alignment with the rotor magnetic poles at all times, so that the motor can produce the maximum torque. This is accomplished by a flux reference of zero. Keep in mind that Id and Iq (representing torque and flux) are only time-invariant under steady-state load conditions. The Iq reference controls the torque output of the motor. The outputs of the PI controllers provide Vd and Vq, which is a voltage vector that is sent to the motor. A new coordinate transformation angle is calculated based on the motor speed, rotor electrical time constant, Id and Iq.

The FOC algorithm uses the new angle to place the next voltage vector, in order to produce an amount of torque needed to keep the rotor spinning. The Vd and Vq output values from the PI controllers are rotated back to the stationary reference frame, using the new angle. This calculation provides quadrature voltage values $v\alpha$ and $v\beta$. Next, the $v\alpha$ and $v\beta$ values are transformed back to 3-phase values va, vb and vc. The 3-phase voltage values are used to calculate new PWM duty-cycle values that generate the desired voltage vector.

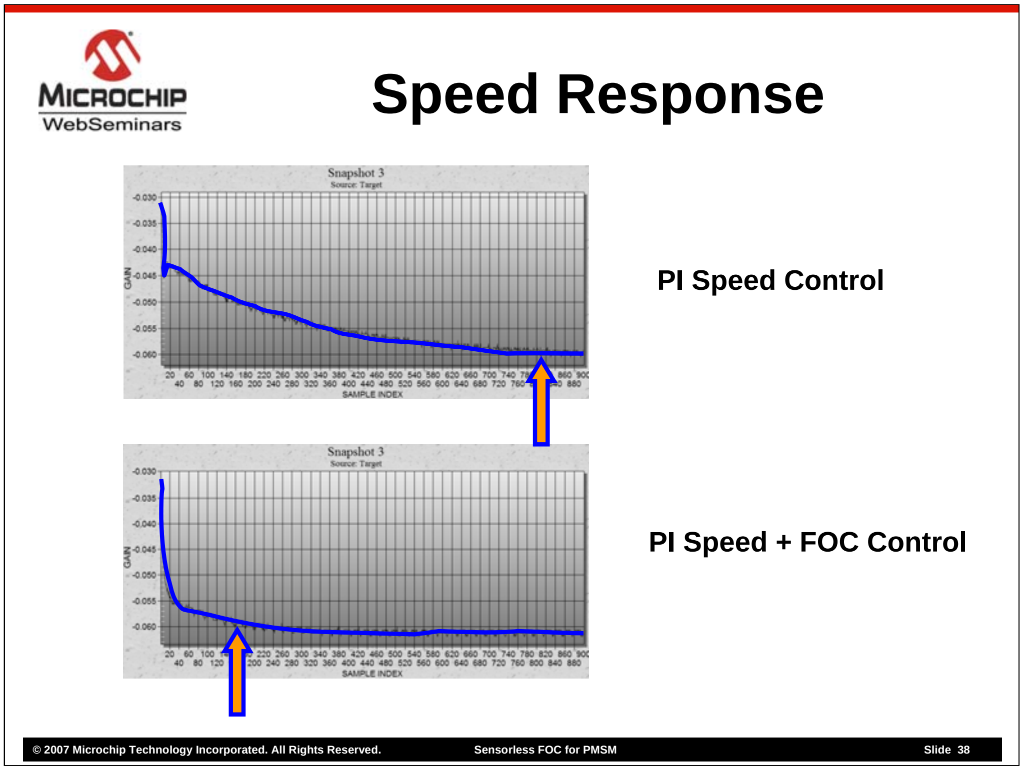
The transformation angle, theta, and motor speed are coming from an optical encoder mounted on the shaft of the motor. Later on in the presentation we will see how to estimate this angle so no position sensor is used for field oriented control.



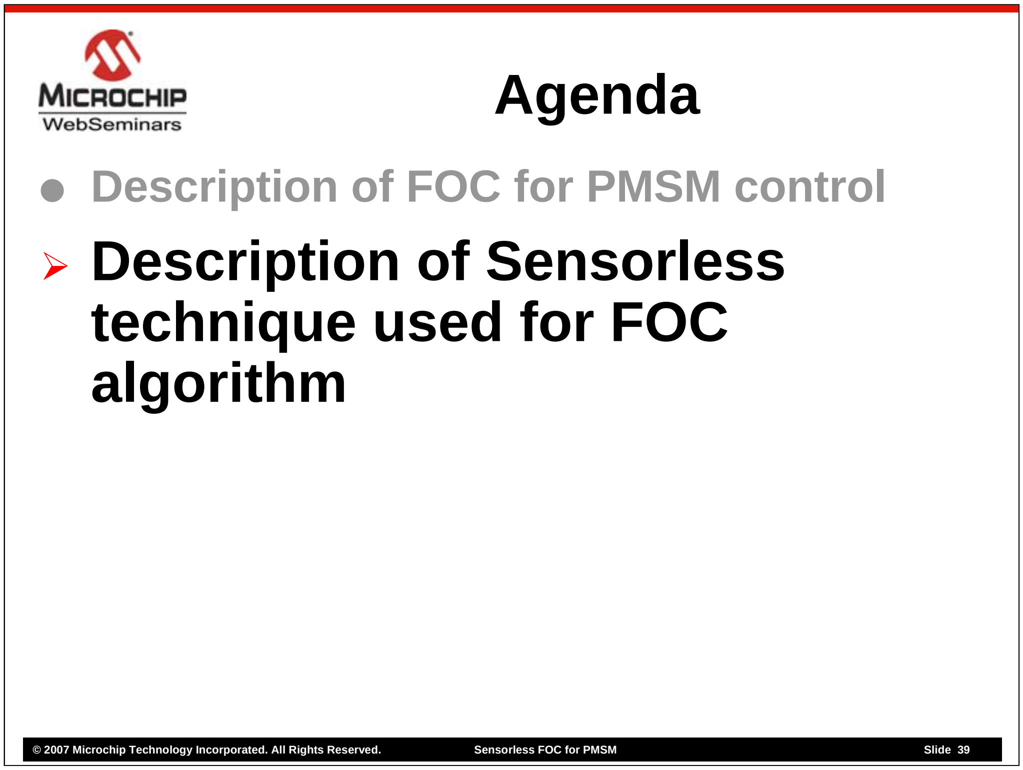
This is a side to side comparison between Field Oriented Control and conventional speed control. Main difference is in the commutation angle between rotor and stator of the motor.



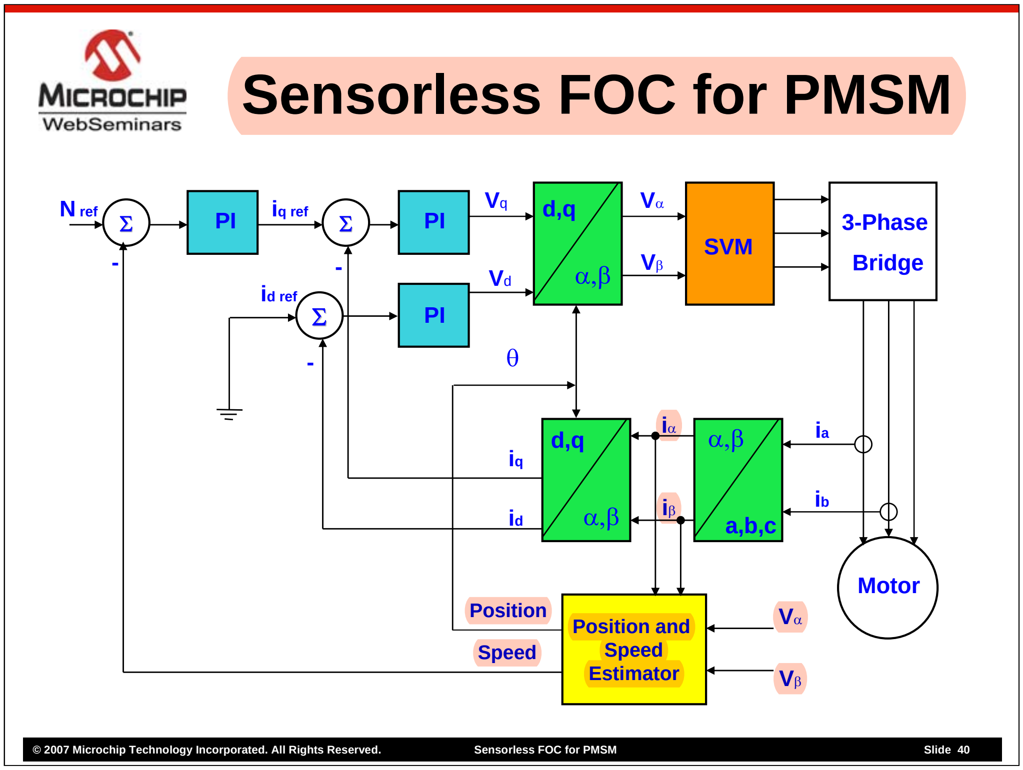
Let's look at some actual results. As an input we have a step in the speed reference of the motor. On the upper plot, we see the current consumption using conventional PI control loop. We can see how current consumption goes up to 0.3 Amps. On the other hand, we see how PI Controller with FOC improves current consumption. We only get a transient response, and then current consumption goes back to 0.2 Amps. It is important to note that PI controller coefficient are the same in both scenarios, but by adding FOC current consumption is now regulated.



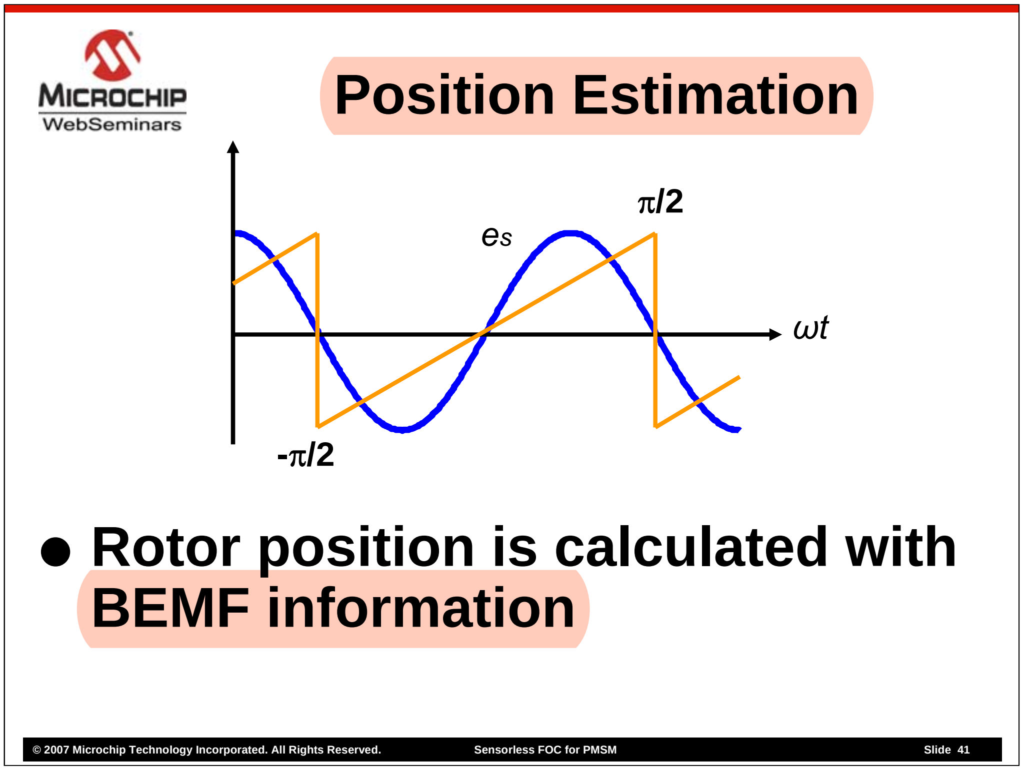
With the same step input on the speed reference, we have a comparison between the two control topologies. There is a noticeable difference on the dynamic response. PI control plus FOC improves dynamic response significantly compared to conventional PI control loop.



In this section of the web seminar, we will discuss a special technique used to calculate the position and speed of the motor without using any position sensor. This algorithm will allow us to implement sensorless field oriented control.



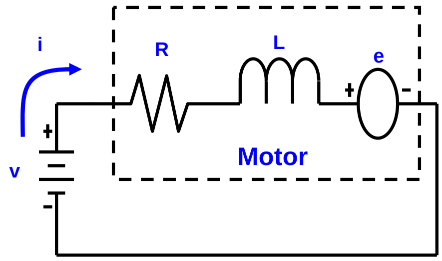
As we can see from this block diagram, field oriented control block diagrams did not change, we still jump from stator to rotor perspective in order to control the motor. We added a new block to calculate position and speed of the motor. As we can see from the yellow block, there is no position or speed sensor as input. Current sensors and software voltages are used to estimate position and speed of the motor. I alpha and I beta are derived by current measurements from motor windings. V alpha and V beta are variables that we calculate during FOC. Those four variables are inputs to the position and speed estimator. But how do we calculate position and speed from those four variables?



First of all, let's take a look at a characteristic of PMSM motors. We have plotted back EMF of the motor and position of the rotor together in this plot. There is a perfect phase relationship between these two signals in a PMSM motor. Since we are trying to measure position of the motor, we need to find a way to detect or measure the back EMF voltage. There are some algorithms where the back EMF zero crossings are detected by measuring phase voltages, but in FOC, the phases are being driven during the complete cycle, so these methods are not feasible in FOC control.

Position Estimation

PMSM Electric Model



$$v_s = Ri_s + L\frac{d}{dt}i_s + e_s$$

$$\frac{d}{dt}i_s = -\frac{R}{L}i_s + \frac{1}{L}(v_s - e_s)$$

- **PMSM motor has the same electric model as Brushed-DC (BDC) and Brushless-DC (BLDC) motors**

 Sensorless FOC for PMSM Slide 42

What we use instead of back EMF zero crossing detection, is back EMF voltage estimation using a simplified electric model of the PMSM motor. If we look at the model per each phase, we have a phase resistance, phase inductance, and the back EMF generation of the motor. Right next to the electric diagram we have the equation representation of the PMSM motor, which is similar to a brushed DC motor or Brushless DC motor.

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Position Estimation

$$\frac{i_s(n+1)-i_s(n)}{T_s} = -\frac{R}{L}\cdot i_s(n) + \frac{1}{L}\cdot\left(v_s(n)-e_s(n)\right)$$

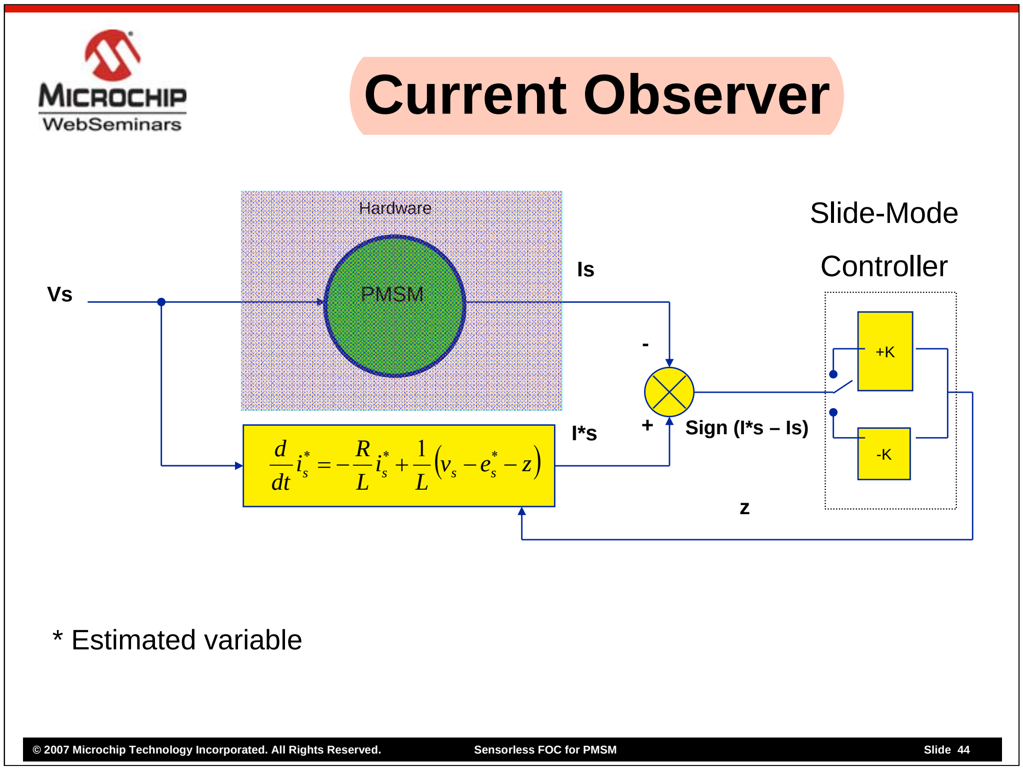
$$i_s(n+1) = \left(1 - T_s\cdot\frac{R}{L}\right)\cdot i_s(n) + \frac{T_s}{L}\cdot\left(v_s(n)-e_s(n)\right)$$

 Sensorless FOC for PMSM Slide 43

We solve the equation for the derivative of the current, and we get the digital interpretation of the phase current. All variables with a subscript of S represent a vector with two components: alpha and beta. The vector variables we have are:

Is (n+1) is the most recent phase current vector. Is(n) is the current vector on the previous sample. Vs(n) is the phase voltage vector on previous sample, and es(n) is the back EMF vector on the previous sample.

The constants we have in the equation are: Ts for the sampling period, so if we have current samples at a 20 kHz rate, Ts will be 50 microseconds. R is the phase current and L represents phase inductance. Some motor datasheet have line to line resistance and inductance specification, so they need to be divided by two for this equation.

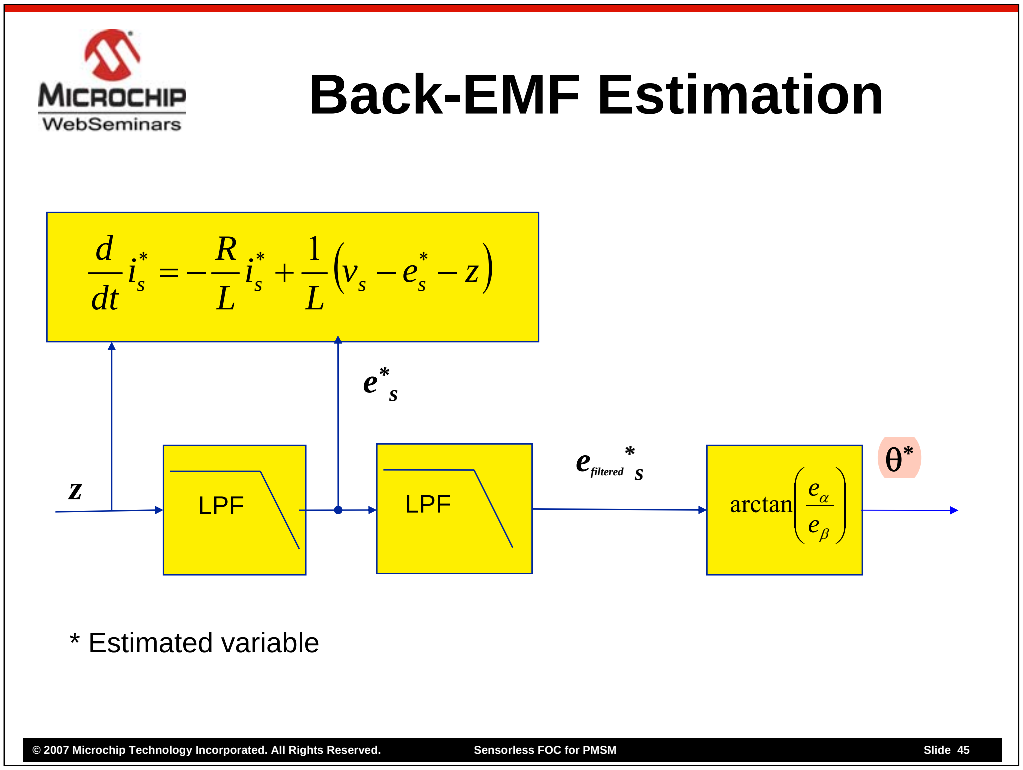


The position and speed estimator is based on a current observer. This observer is a digitized model of the motor, as represented by Equation on the yellow block diagram. Variables and constants include:

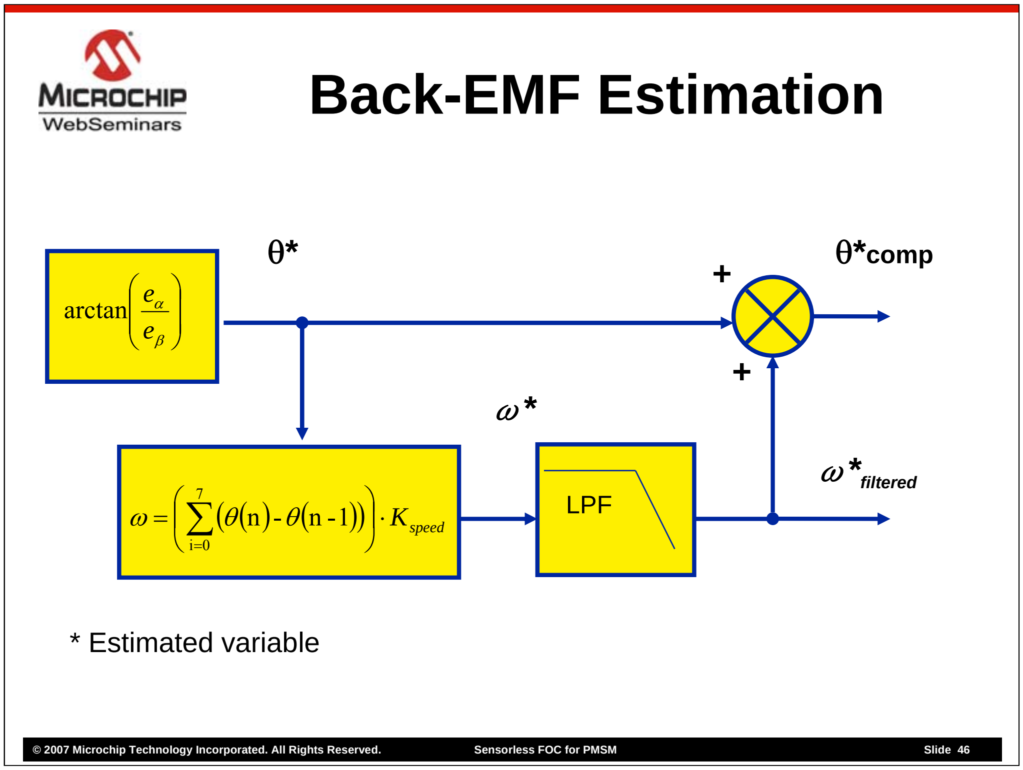
- Motor Phase Current (is)
- Input voltage (vs)
- Back EMF (es)
- Winding resistance (R)
- Winding inductance (L)
- Control period (Ts)
- Output Correction Factor Voltage (z)

The digitized model provides a software representation of the hardware. However, in order to match measured current and estimated current, the digitized motor model needs to be corrected using the closed loop. Considering two motor representations, one in hardware (shaded area) and one in software, with the same input (vs) fed into both systems, and matching the measured current (is) with estimated current (is*) from the model, we can presume that back EMF (es*) from our digitized model is the same as the back EMF (es) from the motor.

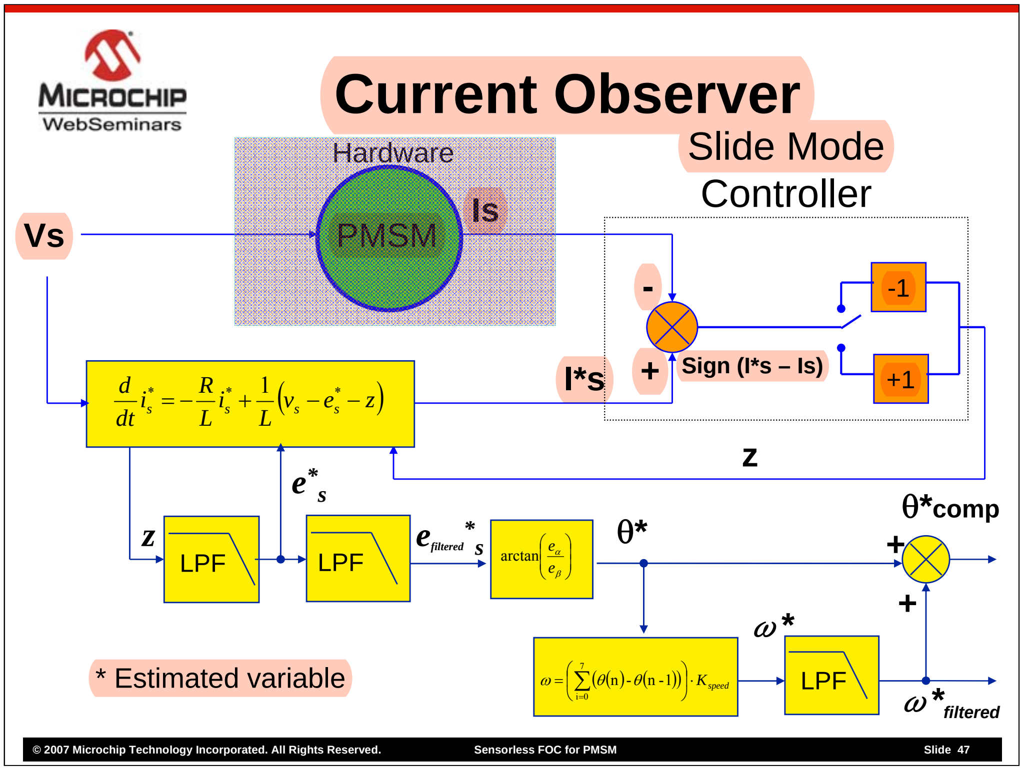
A slide mode controller, or SMC, is used to compensate the digitized motor model. An SMC consists of a summation point that calculates the sign of the error between measured current from the motor and estimated current from the digitized motor model. The computed sign of the error (+1 or -1) is multiplied by an SMC gain (K). The output of the SMC controller is the correction factor (Z). This gain is added to



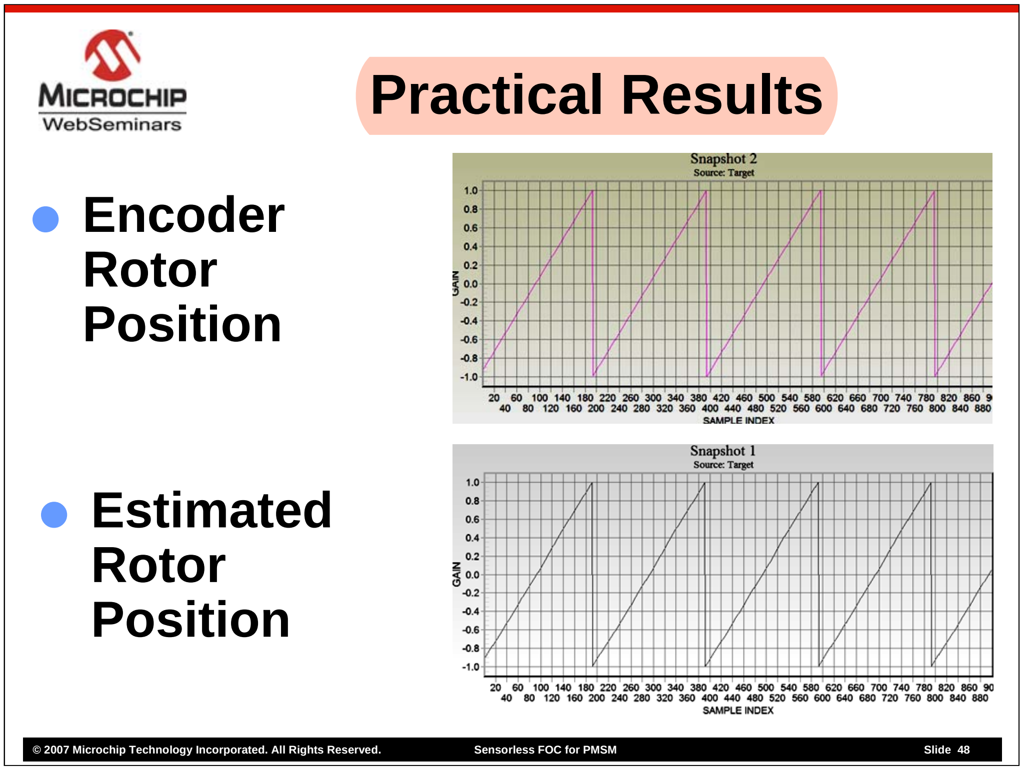
After compensating the digitized model, you have a motor model with the same variable values for the input voltage (Vs) and for current (is*). Once the digitized model is compensated, the next step is to estimate Back EMF (es*) by filtering the correction factor (Z), as shown in the block diagram. The back EMF estimation (e*s) is fed back to the model to update the variable es* after every control cycle. Values eα and eβ (vector components of es) are used for the estimated theta calculation.



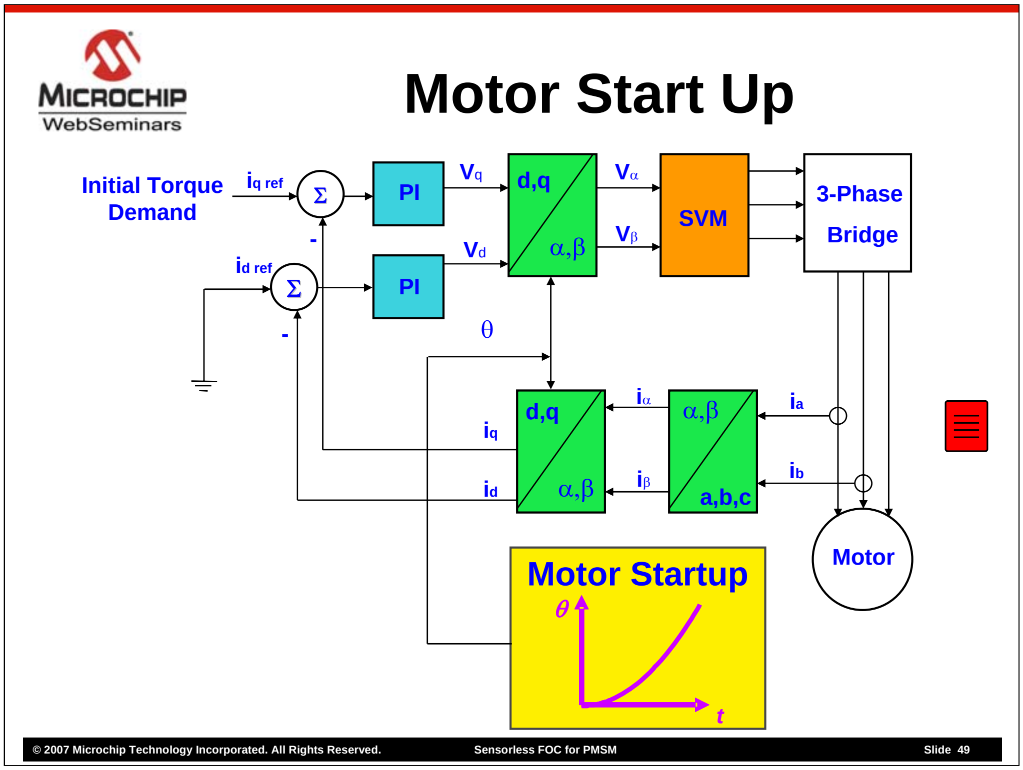
Due to the filtering function applied during the theta calculation, some phase compensation is needed before the calculated angle is used to energize the motor windings. The amount of theta compensation depends on the rate of change of theta, or speed of the motor. The theta compensation is performed in two steps. First, the speed of the motor is calculated based on the uncompensated theta calculation. Motor speed is calculated by accumulating theta values over *m* samples and then multiplying the accumulated theta by a constant. Once we have a speed calculation based on uncompensated theta, the calculated speed is filtered and used to calculate the amount of compensation.



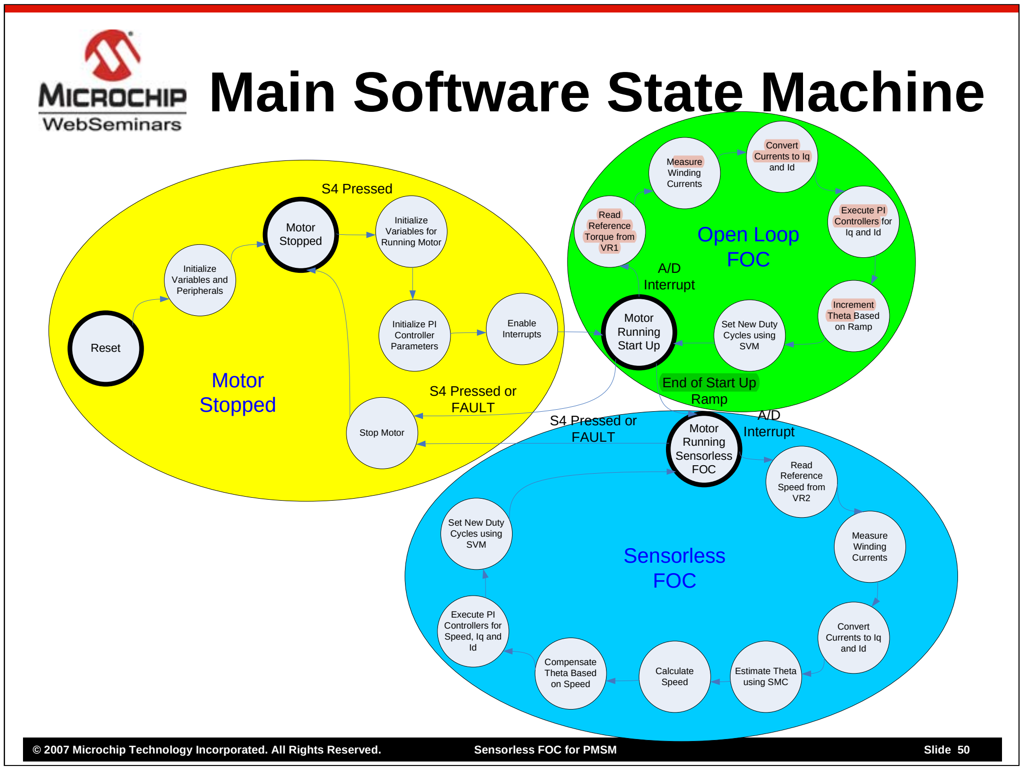
The complete position and speed estimation block diagram is shown here. Inputs to this estimator are voltage vector Vs and current vector Is and the outputs are the estimated theta and estimated speed of the motor.



We can see how the estimator generates an estimated position very similar to a measured position using an encoder. Once we have this position information of the rotor, we can continue to do our field oriented control algorithm.



Since the sensorless FOC algorithm is based on the back EMF estimation, a minimum speed is needed to get the estimated back EMF value. Therefore, the motor windings must be energized with the appropriate estimated angle. To handle this, a motor start-up subroutine was developed. When the motor is at standstill, and the start/stop button has been pressed, the dsPIC generates a series of sinusoidal voltages to get the motor spinning. The motor spins at a fixed acceleration rate, and the FOC algorithm controls the currents Id and Iq. The angle Theta (or commutation angle) is incremented based on the acceleration rate. As shown in the Motor Startup block, phase angle is incremented at a squared rate to get a constant acceleration on the motor. Even if Theta is being generated by the open loop-state machine, Field Oriented Control blocks are still being executed and are controlling torque component current and flux component current. An external potentiometer is used to set the desired torque required to start the motor. This potentiometer is set experimentally depending on mechanical load characteristics. This start-up subroutine provides a constant torque to start up the motor. At the end of the start-up ramp, the software switches over to closed-loop, sensorless control, taking Theta from the position and speed estimator.



It is helpful to visualize the FOC algorithm as a software state machine. First, the motor windings are de-energized and the system awaits the user to press the start/stop button. Once the user presses start/stop button, the system enters initialization state, where all variables are set to their initial value and interrupts are enabled. Then the start-up subroutine is executed, where current components for torque (Iq) and flux production (Id) are being controlled, and commutation angle (Theta) is being generated in a ramp fashion to get the motor spinning. After going through the start-up subroutine, the system switches over to sensorless FOC control, where the speed controller is added to the execution thread, and the slide mode controller (SMC) starts estimating theta as previously explained. When the motor enters sensorless FOC control state, the reference speed is continuously read from an external potentiometer and the start/stop button is monitored to stop the motor. Any fault in the system causes the motor to stop and return to Motor Stopped state. The state diagram shows all the different states of the software and the conditions that make the system transition to a different state.

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Resources

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

PIC18CXXX/PIC16CXXX Servomotor	AN696
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
Sinusoidal Control of PMSM Motors with dsPIC30F	AN1017
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

We have application notes on motor control. These documents can be obtained from the Microchip 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 Permanent Magnet Synchronous Motors. Thank you for your interest in the dsPIC30F Family of Digital Signal Controllers.