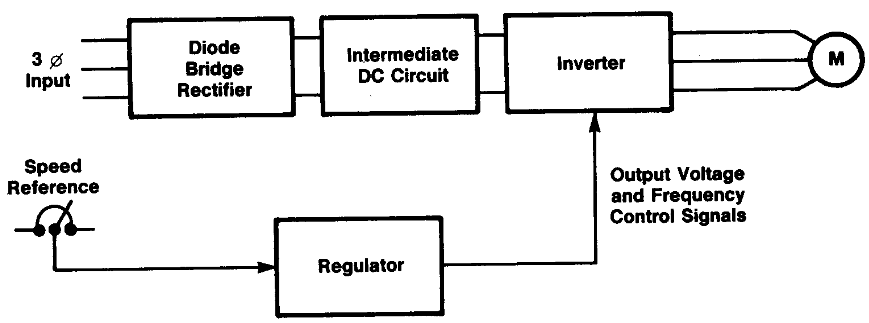
Pulse Width Modulated (PWM)

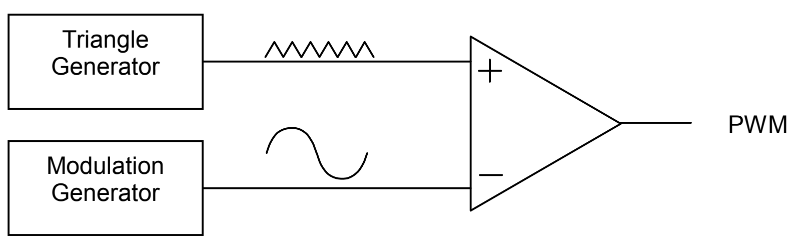
Figure 1.8 shows a block diagram of the power conversion unit in a PWM drive. In this type of drive, a diode bridge rectifier provides the intermediate DC circuit voltage. In the intermediate DC circuit, the DC voltage is filtered in a LC low-pass filter. Output frequency and voltage is controlled electronically by controlling the width of the pulses of voltage to the motor.
Essentially, these techniques require switching the inverter power devices (transistors or IGBTs) on and off many times in order to generate the proper RMS voltage levels.

Power Conversion Unit (PWM)



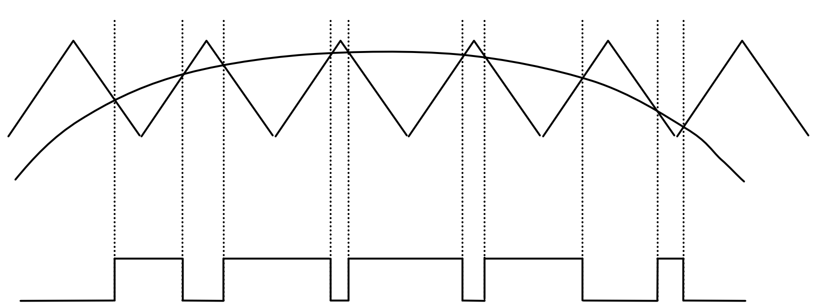
This switching scheme requires a more complex regulator than the VVI. With the use of a microprocessor, these complex regulator functions are effectively handled. Combining a triangle wave and a sine wave produces the output voltage waveform.

PWM Generator

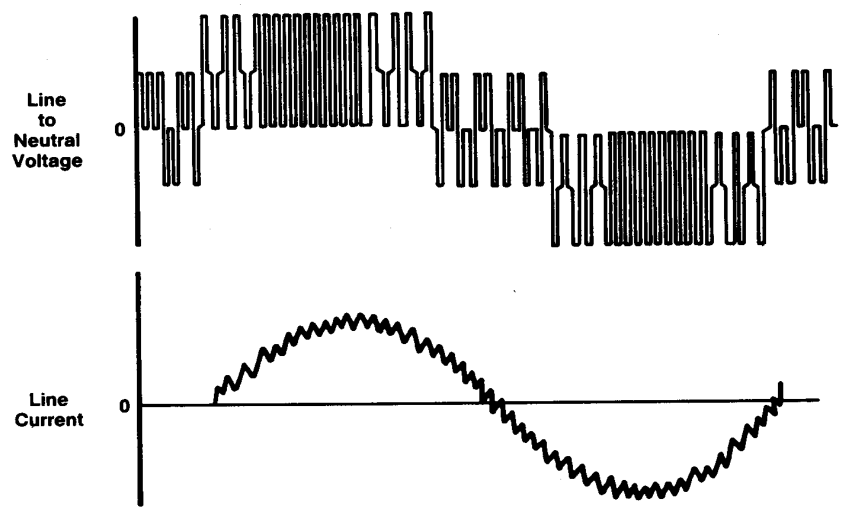


The triangular signal is the carrier or switching frequency of the inverter. The modulation generator produces a sinewave signal that determines the width of the pulses, and therefore the RMS voltage output of the inverter.

Output of PWM Generator



PWM Output Waveforms



AC drives that use a PWM type schemes have varying levels of performance based on control algorithms. There are 4 basic types of control for AC drives today. These are Volts per Hertz, Sensorless Vector Control, Flux Vector Control, and Field Oriented Control.

V/Hz control is a basic control method, providing a variable frequency drive for applications like fan and pump. It provides fair speed and torque control, at a reasonable cost.

Sensorless Vector control provides better speed regulation, and the ability to produce high starting torque.

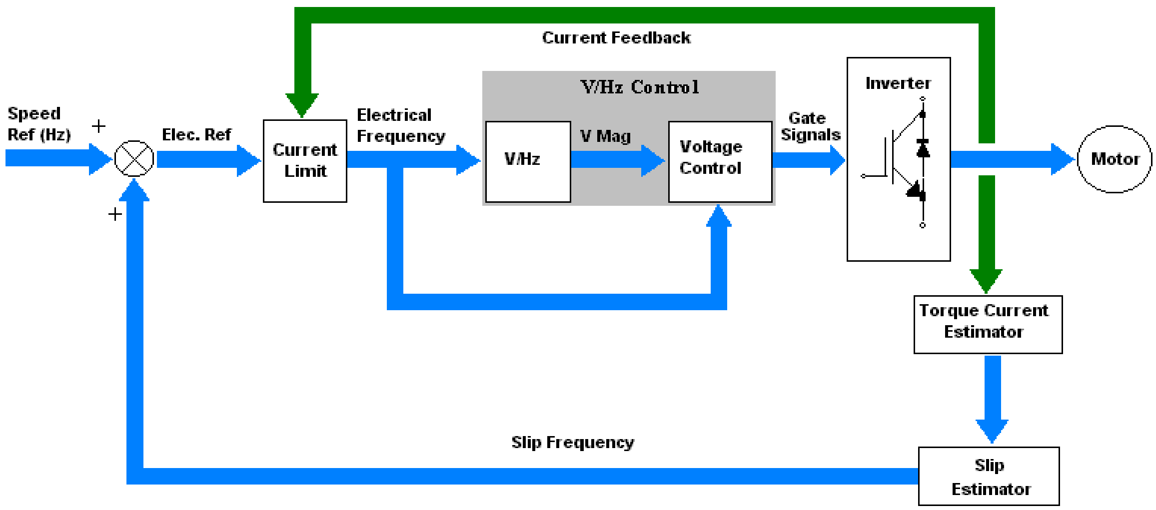
Flux Vector control provides more precise speed and torque control, with dynamic response.

Field Oriented Control drives provide the best speed and torque control available for AC motors. It provides DC performance for AC motors, and is well suited for typical DC applications.

Volts/Hertz

Volt/Hertz control in its simplest form takes a speed reference command from an external source and varies the voltage and frequency applied to the motor. By maintaining a constant V/Hz ratio, the drive can control the speed of the connected motor.

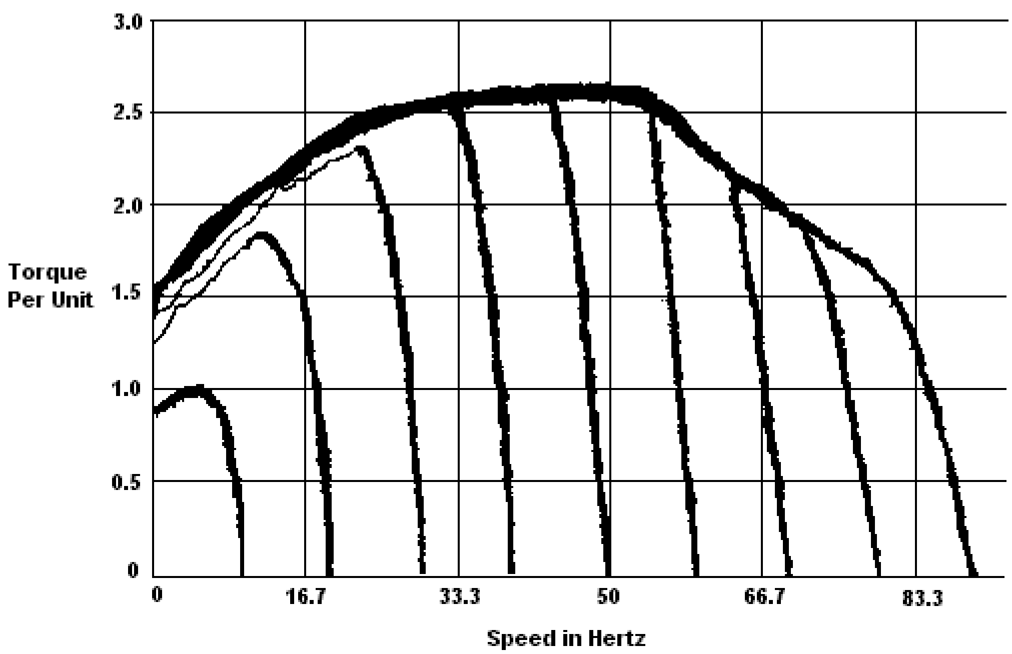
V/Hz Block Diagram



Typically, a current limit block monitors motor current and alters the frequency command when the motor current exceeds a predetermined value. The V/Hz block converts the current command to a V/Hz ratio. It supplies a voltage magnitude command to the voltage control block. The angle of this tells the voltage where it should be with respect to current. This determines flux current to the motor. If this angle is incorrect, the motor can operate unstable. Since the angle is not controlled in a V/Hz drive, low speeds and unsteady states may operate unsatisfactorily. An additional feature in newer drives, a “slip compensation” block, has improved the speed control. It alters the frequency reference when the load changes to keep the actual motor speed close to the desired speed.

While this type of control is very good for many applications, it is not well suited to applications that require higher dynamic performance, applications where the motor runs at very low speeds, or applications that require direct control of motor torque rather than motor frequency.

V/Hz Speed vs. Torque



The plot above shows the steady state torque performance of a Volts/Hertz drive. A torque transducer directly on the motor shaft supplied the data that is plotted. The drive is given a fixed speed/frequency reference. Then load on the motor is increased and actual shaft torque is monitored.

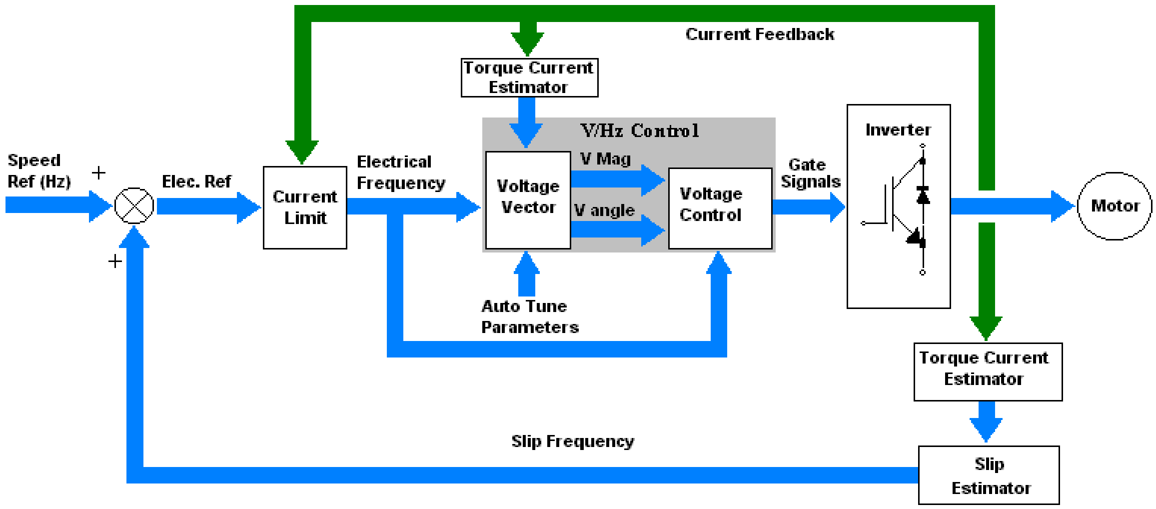
Notice that the ability of the drive to maintain high torque output at low speeds drops off significantly below 3 Hz. This is a normal characteristic of a Volts/Hertz drive and is one of the reasons that the operating speed range for Volts/Hertz drives is typically around 20:1. As the load is increased, the motor speed drops off. This is not an indication of starting torque. This only shows the ability of the drive to maintain torque output over a long period of time.

The next type of control was developed to address some of these concerns.

Sensorless Vector

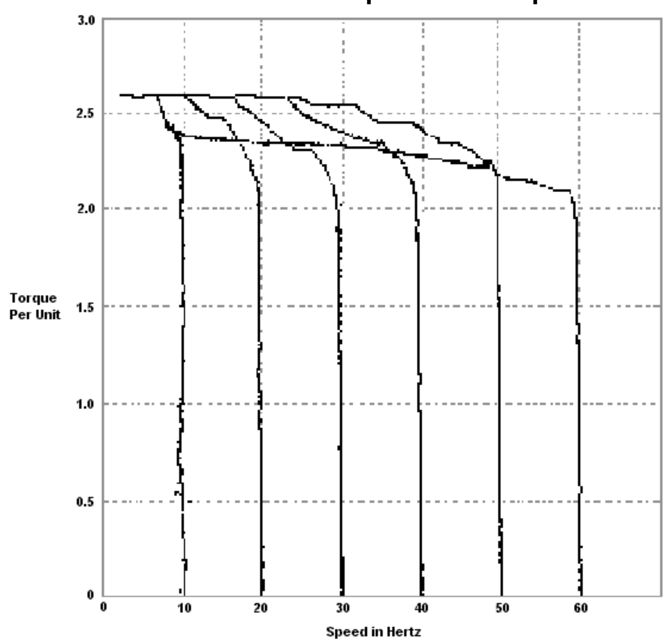
Sensorless Vector Control, like a V/Hz drive, continues to operate as a frequency control drive, with slip compensation keeping actual motor speed close to the desired speed. The Torque Current Estimator block determines the percent of current that is in phase with the voltage, providing an approximate torque current. This is used to estimate the amount of slip, providing better speed control under load.

Sensorless Vector Block Diagram



The control improves upon the basic V/Hz control technique by providing both a magnitude and angle between the voltage and current. V/Hz drives only control the magnitude. Vangle controls the amount of total motor current that goes into motor flux enabled by the Torque Current Estimator. By controlling this angle, low speed operation and torque control is improved over the standard V/Hz drive

Sensorless Vector Speed vs. Torque



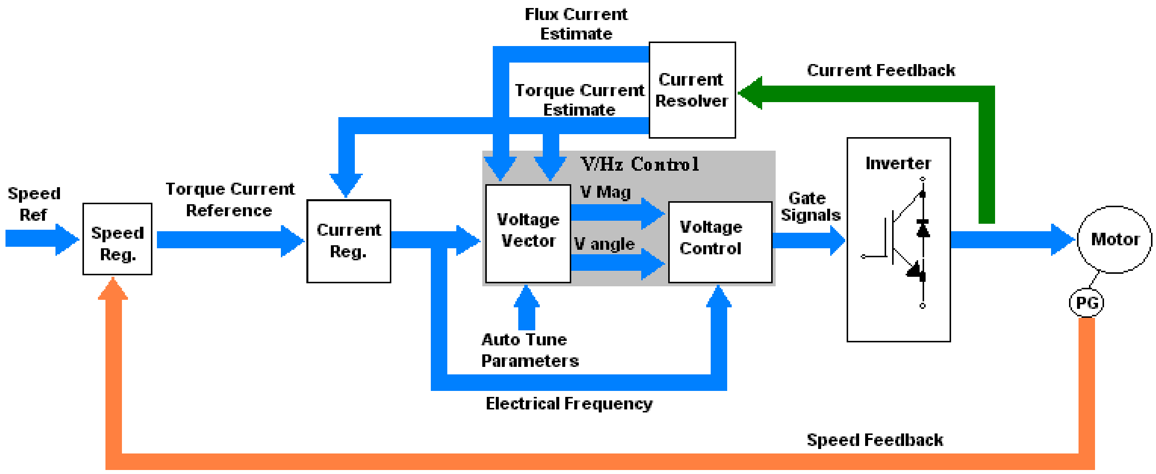
Flux Vector

The flux vector control retains the Volts/Hertz core and adds additional blocks around the core to improve the performance of the drive. A "current resolver" attempts to identify the flux and torque producing currents in the motor and makes these values available to other blocks in the drive. A current regulator that more accurately controls the motor replaces the current limit block. Notice that the output of the current regulator is still a frequency reference.

The early versions of Flux vector required a speed feedback signal (typically an encoder) and also detailed information about the motor in order to properly identify the flux and torque currents. This led to the requirement for "matched motor/drive" combinations. While there is nothing inherently wrong with this approach, it does limit the users motor choices and does not offer independent control of motor flux and torque.

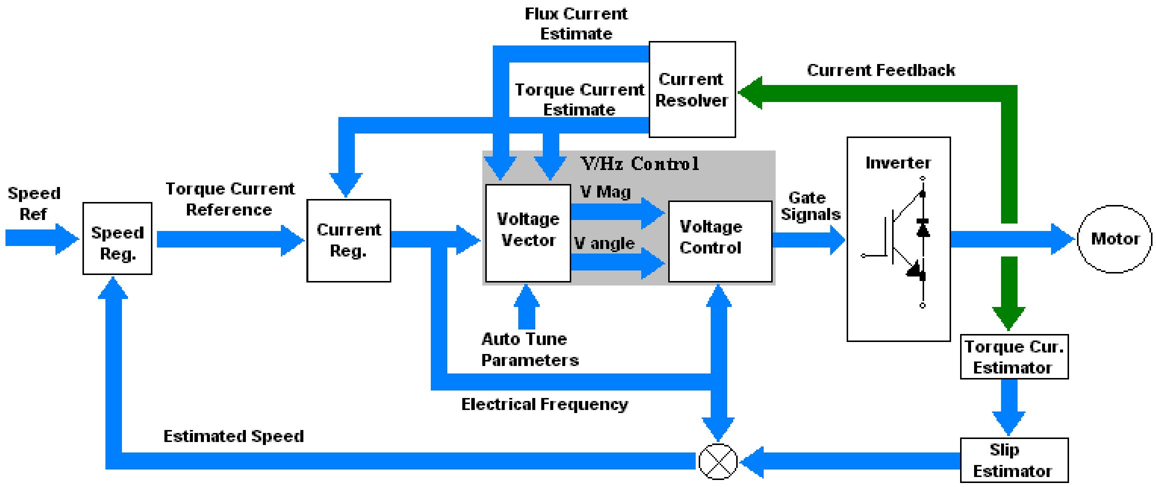
Flux vector control improves the dynamic response of the drive and in some cases can even control motor torque as well as motor speed. However, it still relies on the basic volts/Hertz core for controlling the motor.

Flux Vector Block Diagram

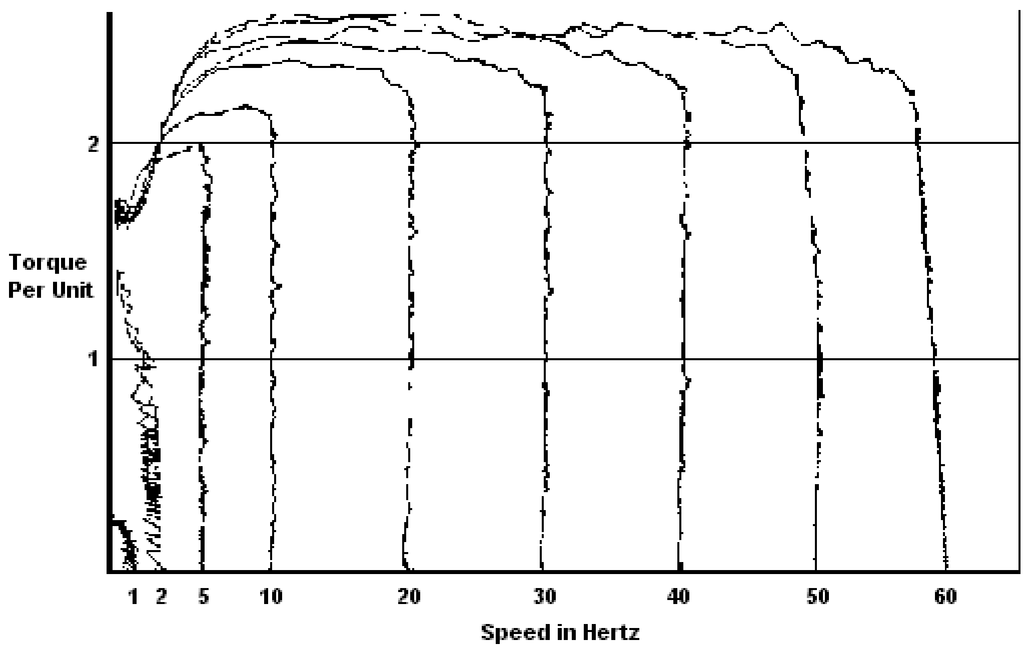


Recently, flux vector control has been enhanced to allow the drive to operate without the use of a speed feedback device, relying instead on estimated values for speed feedback and slip compensation. Again, the basic Volts/Hertz core is retained.

Sensorless Flux Vector Block Diagram



Flux Vector Speed vs. Torque



This graph shows the steady state torque capability of a flux vector drive. The speed control has been improved. Second, the torque output capability is better. Note however that there is still a decrease in the available torque at low speeds. This occurs primarily because the drive still contains the Volts/Hertz core.

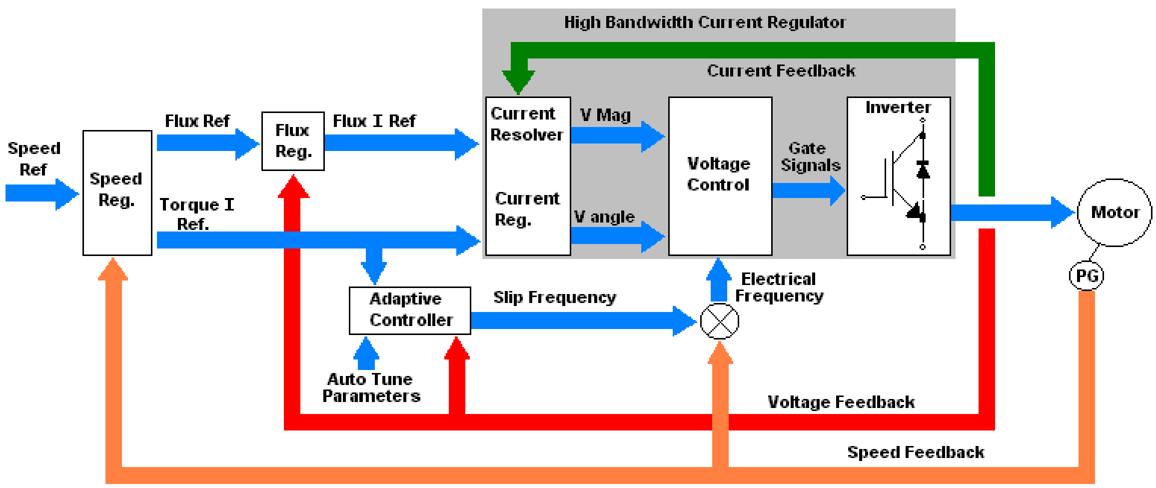
Vector control in its simplest form acknowledges that the motor current in an AC drive is the vector sum of the flux and torque producing currents. It is because of this that some people would point out that even a Volts/Hertz drive could be considered a vector product.

Field Oriented Control

What distinguishes a product using Field Oriented Control from a traditional vector product is its ability to **separate and independently** control (or regulate) the motor flux and torque. This will be explained in greater detail later in this presentation. Notice that in the definition of Field Oriented Control we did not say "currents in an AC motor". That's because the concept applies equally well to DC motors and is the reason we can demonstrate "DC like" performance using Field Oriented Control on AC drives.

Force Technology uses patented, high bandwidth current regulators in combination with an adaptive controller, to separate and control the motor flux and torque. This is a fundamental difference between Force Technology and other vector control techniques.

Field Oriented Control Block Diagram



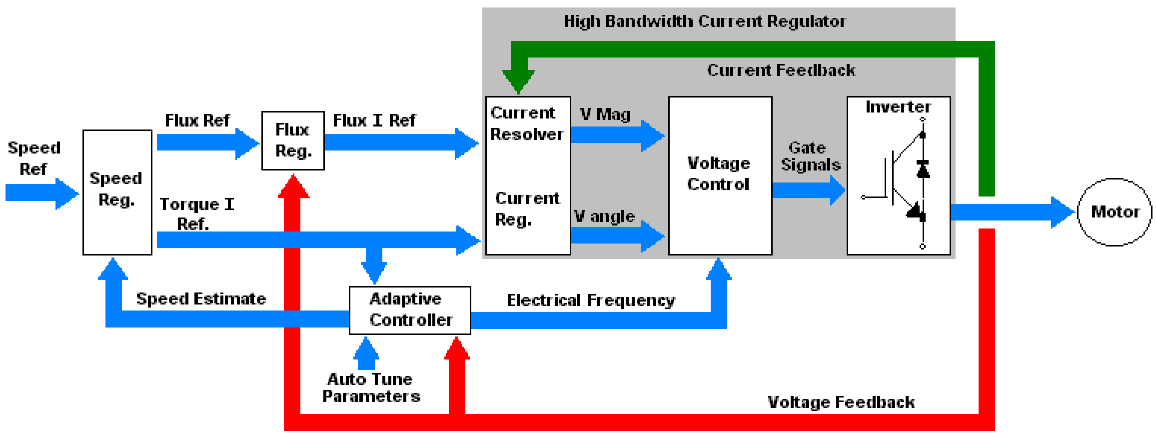
A high bandwidth current regulator that separates and controls the components of stator current replaces the Volts/Hertz core. The high bandwidth characteristics of this control eliminate nuisance trips due to shock loads and continuously adapt to changes in the motor and load characteristics.

A separate adaptive controller uses information gained during auto tuning, actual reference information, and motor feedback information to give independent torque and flux control. This allows continuous regulation of the motor speed and torque.
Also notice that *Force Technology* generates separate flux and torque references to improve the overall control of those quantities.

Sensorless Field Oriented Control

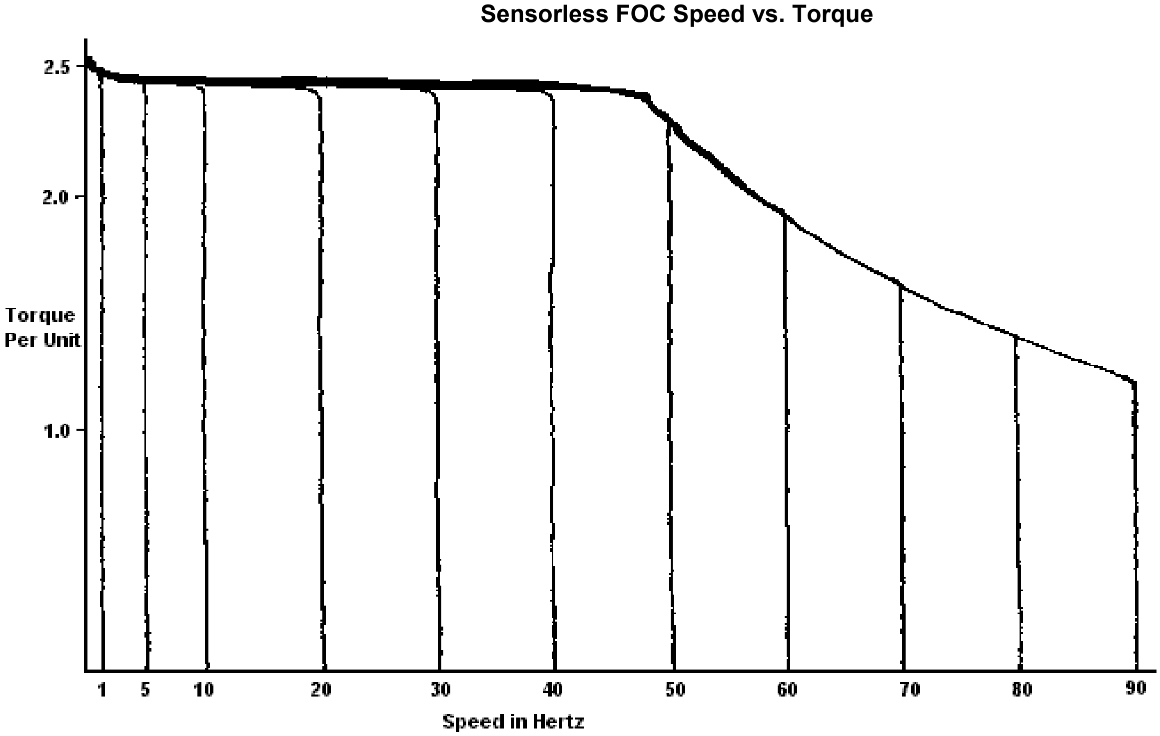
As with flux vector products the newest versions of *Force Technology* allow users to control the motor without the use of a speed-sensing device. A major difference is that the drive continues to operate with Field Oriented control, instead of reverting back to Volts/Hertz control.
This provides significant benefits with dynamic performance, tripless operation, and torque regulation.

Sensorless Field Oriented Control Block Diagram



Below is a plot of a drive using the Sensorless version of *Force Technology*. Notice that the torque output is consistent from no load to full load over a very wide speed range. You can also see that the motor has a speed/torque characteristic that is very similar to its DC counterpart, even when operating above base speed.

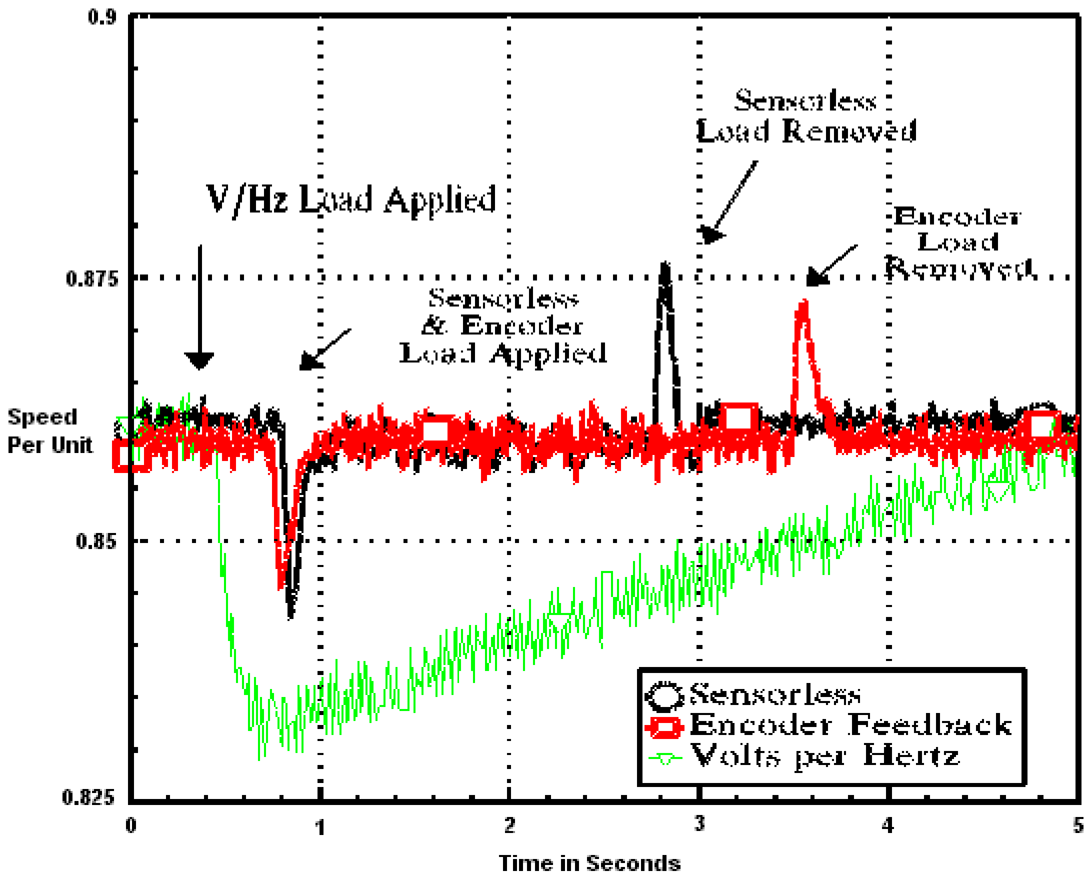
Sensorless FOC Speed vs. Torque



Performance Comparison

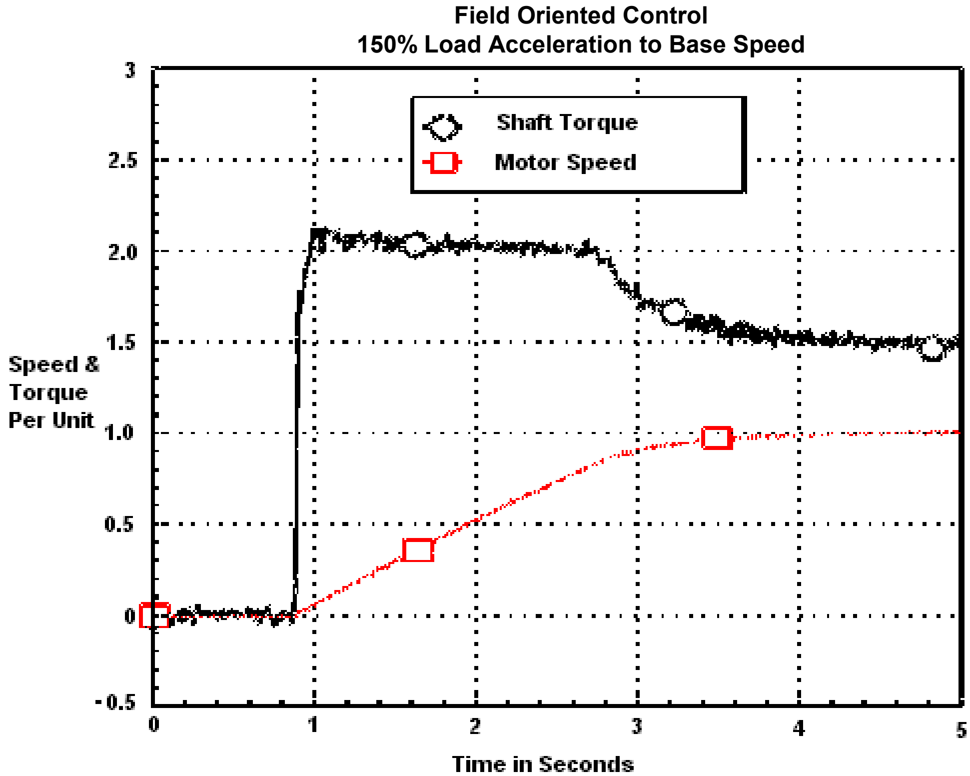
The graph below shows a drive using *Force Technology* operating with and without an encoder, and a Volts/Hertz drive. Notice that there is very little difference in operation with or without an encoder. You can clearly see the response to the step load and the recovery time. The same can be seen when the load is removed.

Load Disturbance Response



Contrast that against the Volts/Hertz response, which recovers much slower. The high bandwidth current regulators and high performance speed regulator ensure that the drive using *Force Technology* delivers high dynamic performance.

Speed Control	Force Technology w/encoder	Force Technology w/o encoder	Typical Vector Drive	Digital DC Drive
Speed Regulation	+/- 0.001%	0.5%	+/- 0.05%	+/- 0.001%
Dynamic Response	100 Rad	30 Rad	15 Rad	100 Rad
Speed Range	1000:1	120:1	100:1	1000:1
Torque Control				
Regulation w/RTD	+/- 2%	+/- 5%	+/- 20%	+/- 5%
Regulation w/o RTD	NA	NA	+/- 3%	NA
Dynamic Response	2500 Rad	2500 Rad	300 Rad	950 Rad

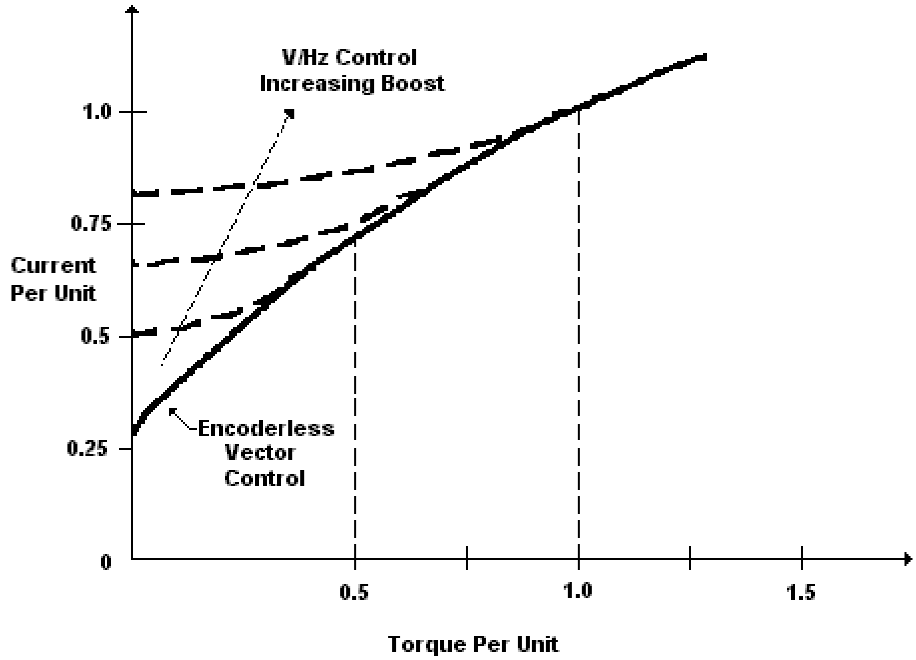


This graph shows the ability of a drive using *Force Technology* to maintain control over torque and speed, even under extreme conditions.
The black trace shows actual shaft torque as the drive accelerates a 1.5 per unit load. As you can see the drive produces 2 times rated torque (set by torque limit parameter) until the motor reaches the desired speed. At no time does the drive loose control of the motor; the torque simply sits at the limit until the speed error is satisfied.

Also note the rapid response to the speed error. Unlike flux vector products, which may take up to 100mses to respond, the Force Technology drive reacts within 1msec.

Torque per Amp
One of the other differences between a product using *Force Technology* and a Volts/Hertz drive is the torque-per-amp. Notice that the ratio of motor current to motor torque on a sensorless vector drive (using *Force Technology*) is relatively constant. The offset is due mainly to the flux current component. This is not true for a Volts/Hertz product, depending on the boost setting used, the motor may see close to rated current, even though the motor is only producing relatively low torque.

Torque per Ampere Comparison



The result is that a motor run at low loads will dissipate higher losses when controlled by a Volts/Hertz drive. At slower speeds, this could cause unnecessary motor overheating.