Allen-Bradley

Sensorless Vector Technology: What separates this technology from the rest?

Allen-Bradley Automation

Rockwell Automation

Bringing Together Leading Brands in Industrial Automation

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What separates this technology from the rest?

The control philosophies and technologies used in today's variable frequency AC drives

I. Introduction

Figure 1

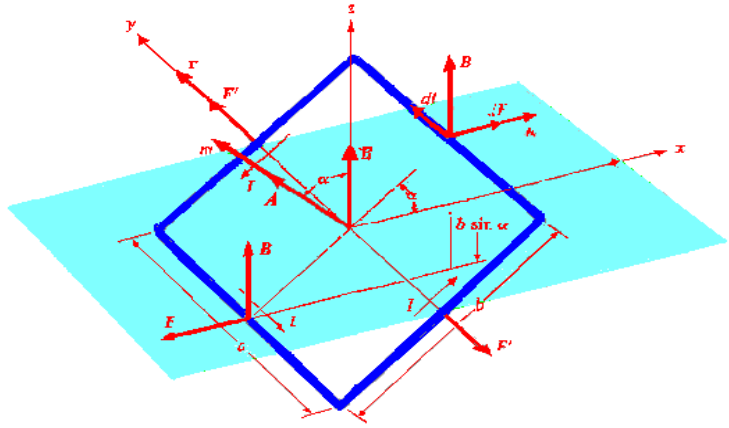
Today's drive users are applying AC Variable Frequency drives in applications that require more demanding speed and torque performance. In order to maintain a competitive position and improve product quality, users have created a wide variety of application demands. Drive technology has had to keep pace with these ever more demanding expectations. Additionally, today's business climate produces an ever-present need to lower total life cycle costs. Eliminating the tendency towards 'overkill' (applying more technology than an application requires) and properly matching the drive size or rating to the application need are two very effective ways of managing these costs. But how does a drive user first identify the technology that is appropriate for the situation and then properly select a drive to match that application?

Rockwell Automation has been a leader in the factory automation business for nearly a century and a leader in variable frequency AC drives since their introduction. We offer a broad spectrum of technologies including Volts / Hertz products for general purpose conditions, Flux vector for torque control, Field Oriented Control (Force Technology™) for high response / high bandwidth torque or speed regulation applications, and Sensorless Vector Control for higher performance speed regulated applications. The technology that creates the greatest confusion to drives users is sensorless vector control, which is used for increased torque production and higher performance speed regulated applications. This white paper will attempt to clear up some of the confusion by defining the terminology, comparing the various technologies and separating "fact from fiction" performance.

II. Vector Definition

"Vector", in general, has been one of the more abused terms in the industry. It has been used to incorrectly describe and position products that actually use earlier technologies. But there is more to the vector puzzle than just technology. The ultimate judgment of the value of a vector product is the performance that it offers to process improvement, and not all vector drives operate equally. To start the clarification process, we must first define the terminology, beginning with "vector" itself. As shown in figure 2, vector combines both the size and direction of forces to quantify the result. All vector drive technologies have these basic and common tenets:

1. The current in an ac motor can be separated into two distinct components:
   A. Id, or the FLUX producing current
   and
   B. Iq or the TORQUE producing current
2. The total current is the vector sum of those two current components.
3. Torque produced in the motor is based on a "cross product" of the vectors
4. The level to which these components are identified and controlled defines the level of performance.



Forces on the sides of a current carrying loop in a magnetic field. The resultant of the set of forces is a couple of moment $\Gamma = I(A \times B)$

Figure 2

Different technologies implement different levels of control over one or more of these components (flux producing current, torque producing current and the vector angle between them) to produce varying levels of vector or non vector performance. Higher performance will manifest itself in increased starting torque, increased low speed torque, increased shock load capability, tighter speed regulation, torque regulation and other measurable parameters.

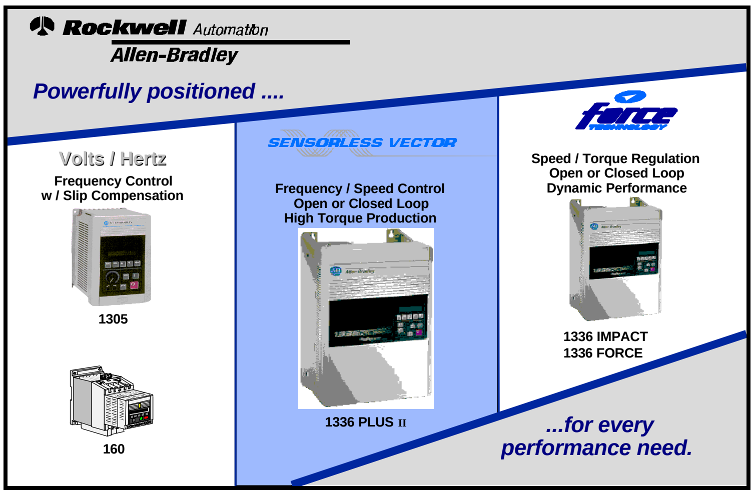


Figure 3

III. Technology Capabilities

Volts / Hertz drives, often used in simple open loop frequency control applications, do not control any of the components unique to vector technology. A V/Hz drive regulates applied motor frequency, thus producing the desired speed. Most V/Hz drives cannot separate flux current and torque current, dealing instead only with total motor current. These drives depend on simple current limiting schemes and generally use increased voltage boost in an attempt to produce additional breakaway torque. While this voltage boost method can produce additional starting torque, it requires significantly more current and can often produce “current limit” situations that may diminish performance. While Volts / Hertz technology can be made to “look like” vector, comparison of the operation shows “non-vector” performance in almost all areas including starting, acceleration, low speed operation and torque control.

Flux Vector drives use the output of the current regulator as a frequency reference. This can improve the dynamic response of the drive and in some cases can even control motor torque as well as motor speed.

Field Oriented Control drives are capable of **both** speed and torque regulation because they control both current components and the angle (vector sum) between them. They provide excellent torque characteristics plus tighter speed regulation, wider speed range and higher bandwidth (response). A separate adaptive controller gives independent torque and flux control, allowing continuous regulation of the speed and torque of the motor.

Sensorless Vector technology offers an intermediate level of performance, greater than V/Hz but less than true field oriented control. Sensorless or Open Loop vector control can produce superior starting, accelerating and shock load torque capability, a wide constant torque speed range (including above base speed) and improved low speed performance but are not torque control drives and, therefore, *cannot* ***regulate*** the amount of torque produced in a motor. They also do not challenge field oriented control in the areas of dynamic response, high performance speed regulation or speed range. What they should do is provide the highest possible torque per amp in the motor. By building full stator flux and constantly monitoring to eliminate an "over fluxed " condition, Sensorless Vector should be capable of supplying maximum (near breakdown) motor torque when required. This includes all critical areas of operation; breakaway, acceleration and deceleration, shock load, low speed and during "field weakening" or operation above base speed.

	Volts/Hertz	**Sensorless Vector**	**Field Oriented Control**
Speed Control	Freq Control w/ slip comp	Freq Control w/ slip comp or Encoder Feedback	Velocity Control or Encoder Feedback
Speed Regulation	1%	Slip Comp .5% Encoder .1%	Open Loop .5% Closed Loop .001%
Torque Regulation	NA	NA	Motor Dependent 2 – 5%
Speed Range	40:1	120:1	Open Loop 120:1 Closed loop >1000:1
Starting Torque	150%	250%	Drive/Motor Dependent 150 % Minimum 400% Maximum
Fast Accel Torque	150%	150%	Drive/Motor Dependent 150 % Minimum 400% Maximum
Peak Running Torque	250%	260%	Drive/Motor Dependent 150 % Minimum 400% Maximum
Dynamic Response	N/A	6-12 Radians	30 Rad Open Loop 100 Rad Closed Loop

Figure 4

IV. Philosophy of Control

Drive hardware is only a portion of the equation. There are many factors beyond the hardware that affect performance, and the most basic of these is the philosophy of the control approach. Testing has shown that sensorless vector performance is vastly superior to other control approaches. A closer examination will highlight the differences.

Many control approaches rely solely on Universities or technical organizations to provide the technology. It is often felt that the cutting edge of technology is defined by these organizations, and solutions without the appearance of leadership are assumed to be lower performing. Those familiar with the plant floor environment, however, understand that, while the academic view of technology often points the way to the future, the practical application of technology is often on a different schedule. An approach that ignores established technology and may actually complicate the user's task by leaning towards a "one drive fits all" approach.

The opinion and practice that “complex is better” is one of the prime factors in reduced performance. Most of these approaches attempt to use a relatively complicated scheme of multiple current loops, each with multiple gains. Current regulated drives inherently rely on velocity control that places a velocity loop around the current loop. When a speed error is sensed, the drive reacts with a current command that must produce the desired result. Since there are two loops, there are two sets of gains that make stability more difficult. It requires solid slip estimation and a detailed “model” of the motor including parameters that have little actual impact on performance. These values, such as the rotor time constant, can be much more difficult to identify. Other values may change over time, degrading performance. This method also requires a high performance flux identifier that may contain 2 or 3 integrators, each with its own time constant. This requires increased processing time and is more difficult to keep from drifting. It makes it more difficult to get accurate values for low speed operation and adds complexity to the tuning routines. In order to overcome the time delays caused by multiple loops and integrators, additional motor parameters / data are required and more drive adjustment is necessary. These adjustments, meant to increase performance, often have the opposite effect of sacrificing basic steady state stability. The additional adjustments and increasingly complex motor parameters also necessitate a more complex “auto-tune routine” which often does not give the best performance. When manual adjustment is then required, there is often difficulty in understanding which units or values to override and how to access them. This may mean that a drive will only operate well with a specific motor that is supplied by the drive vendor so that its parameters are well known. While there is nothing inherently wrong with a matched motor approach, it does limit the user’s motor choices.

A simpler, more effective approach is seen in the 1336 PLUS II with Sensorless Vector technology. By focusing on the precise implementation of two basic tasks; maintaining optimum motor flux and identifying motor parameters that have the highest impact, the 1336 PLUS II creates flexibility, easy tunability and Sensorless Vector performance. It also accomplishes this performance without the need to supply a special motor with well defined parameters.

Closed loop phase current sensors and hardware stationary-to-synchronous circuits provide precise current information. Software algorithms for analog offset correction, calculation of Vq and Vd angle plus true vector voltage calculations provide unusually precise vector implementation. Only two motor parameters (those having the highest impact on torque) must be identified to produce maximum torque; stator resistance (Rs) and rated flux amps (Id), a much simpler model of the motor. The default values chosen for the motor model are very precise, leaving many users with no need to tune. If an additional step in performance is required, simply programming motor nameplate data into the drive may suffice. Only the toughest applications require tuning, and the necessary values are easily identified through a simple, straightforward, three step tuning routine. To make it even more comfortable for the user, Rs is expressed in Volts (a familiar term) as an IR drop for the motor.

Figure 5

The true power in Sensorless Vector comes through control of motor flux to a value at or very near the motor’s rated value. Motors with efficient designs operate very near saturation with rated flux to get optimum performance. Allowing more “flux amps” (Id) in the motor does not produce additional torque, but only saturates the motor, wasting energy. Allowing less Id will alternately require more total current to produce the same torque, again wasting energy. Operating at rated flux allows the highest torque / amp value and optimizes motor performance.

A high performance current limiter accomplishes the control of current with adjustable gains for recovery.

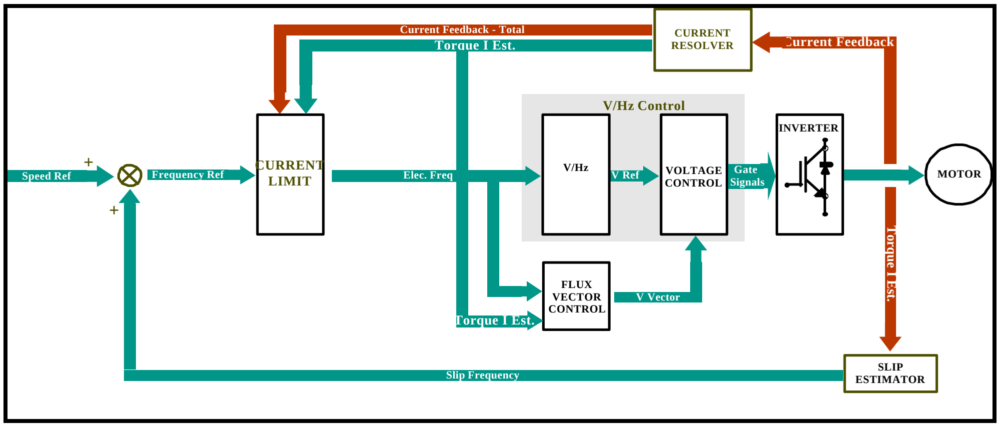


Figure 6

This creates simple voltage control for the motor, an inherently stiffer system that responds more quickly to speed changes. The advantage of a current limiter (a current regulator that only regulates when current is above the limit) is that it only affects the dynamics of the system during excess current situations. The key to exceptional performance in this scheme is to anticipate and precisely manage the transition from unregulated to regulated.

By utilizing the slip estimator algorithm and the pertinent motor parameters, the 1336 PLUS II provides excellent slip compensation (w/ adjustable time constant or gain) to accomplish the proper slip in the motor. This means a lower speed dip under shock load and a faster recovery under high gain without sacrificing stability. Few values need to be calculated or tested for, and if manual adjustment is required, the procedure is simple and quick. This scheme operates well with any motor because no special motor data is required for optimum performance.

V. Application Realities

Unless these technologies are converted to customer benefit, however, no value is gained. The 1336 PLUS II with Sensorless Vector technology provides needed performance in all of the critical areas required by tough applications. Starting torque up to 260% of motor rated torque can be generated for breakaway of heavy loads and, in most cases, will not require over sizing the drive. Examination of the speed / torque curves (see Figure 7) shows exceptional torque producing capability when starting a high inertia or high "stiction" load.

The torque producing capability of the Sensorless Vector algorithms make dynamic response to load changes fast and accurate. This results in superior performance in the area of speed regulation. The torque capability combined with a tunable speed loop allows quick speed recovery due to changes in load. While speed regulation is normally defined under a steady load state, the drive's reaction to step load changes gives an accurate picture of the torque performance.

Figure 8 demonstrates the tunability of the 1336 PLUS II speed loop. This drive / motor is running at full speed when a 100% load step is applied dynamically. The drives response respective of tuning is indicated - 1.3 second recovery to steady state speed with default tuning and 64 mSec return with user tuning. Current increases proportional to the load step but remains stable and under control.

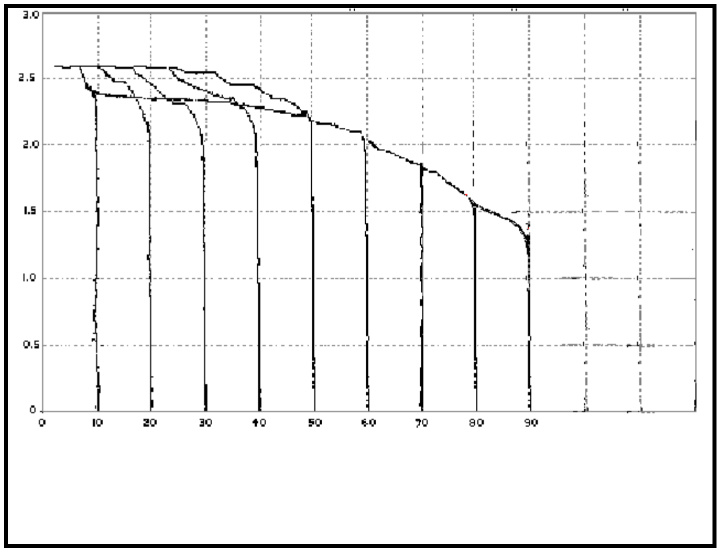


Figure 7

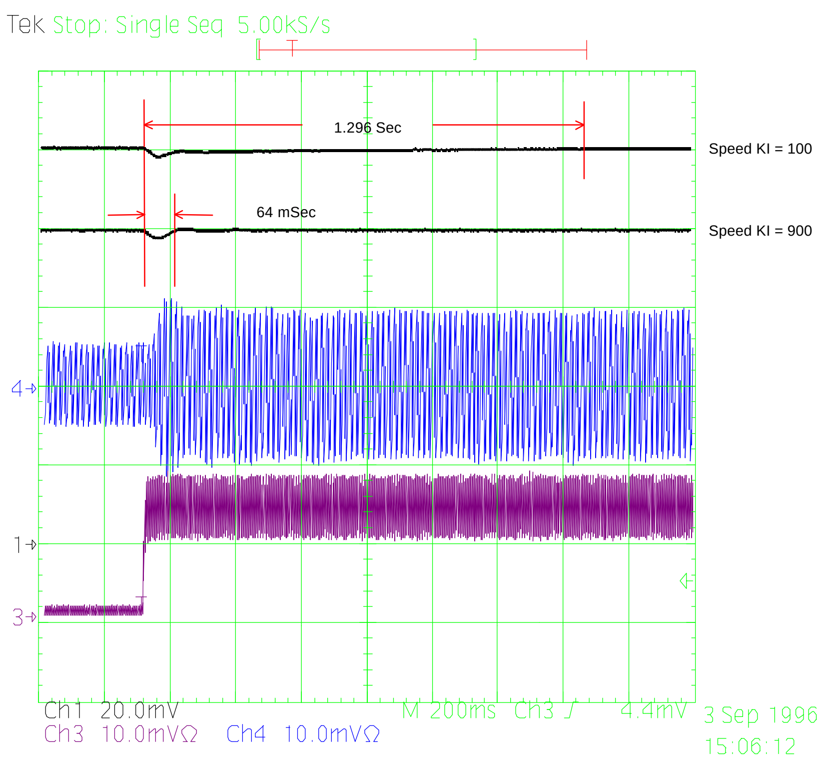


Figure 8

The 1336 PLUS II also has a number of features that allow high acceleration torque and very rapid acceleration under certain circumstances. Many volts / hertz drives may be able to produce higher starting torque, but that torque may quickly fall to lower levels once the motor begins to accelerate towards full speed, limiting the acceleration performance. The ability of the 1336 PLUS II Sensorless Vector algorithms to maintain high torque production even under acceleration separates it from competitive products. Referring back to Figure 8, it can be seen that torque in excess of 200% can be maintained even up to rated speed if needed, providing smooth acceleration at maximum rate. Figure 9 shows another feature of the algorithms, namely Adaptive Current Limit. The high performance current limiter of the drive assures that current limit does not interfere with the acceleration of a high inertia load. If however, the load has little inertia, this current limit may unnecessarily extend the acceleration time. In cases where the inertia is easily documented at very low values, the Adaptive Current Limit can be disabled, thereby introducing an additional feed forward factor into the acceleration ramp to provide fastest possible response.

The graph in Figure 9 shows a low inertia motor doing a full speed reverse move (1640 RPM forward to 1640 RPM reverse) in 272 mS.

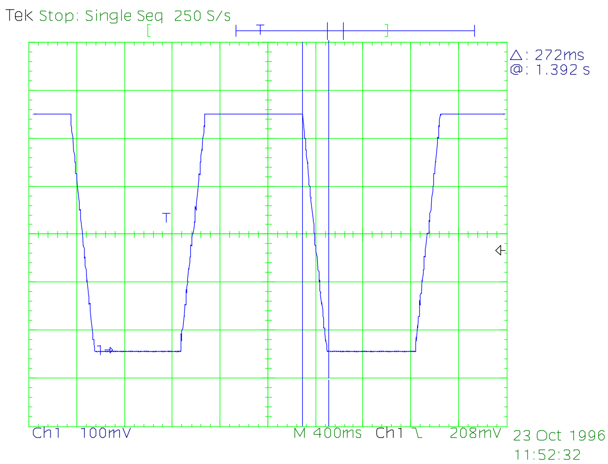


Figure 9

The ability to produce exceptional levels of torque in the motor, combined with smooth current control, also provides a wide speed range of operation. Previous technologies that could produce higher levels of starting torque almost always lacked the ability to produce rated torque at low speeds. As the motor speed decreases, the Sensorless Vector algorithms have less and less measurable motor data available on which to base control decisions. Low speed torque, then, is difficult to control. The 1336 PLUS II has been documented at 120:1 at rated torque. This means that while other technologies may not be able to produce full torque below 38 - 40 RPM (40:1 speed range), the 1336 PLUS II with Sensorless Vector technology can produce greater than rated torque at speeds as low as 12 - 15 RPM or less (120:1 speed range) and still remain within published performance limits for all other specifications (such as speed regulation). Figure 10 shows how the speed range is extended as the Sensorless Vector is tuned.

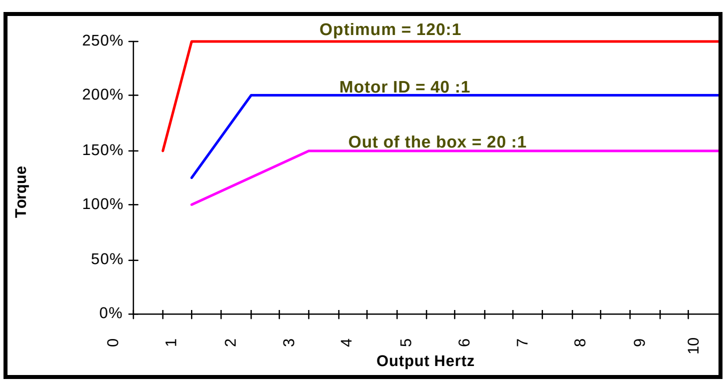


Figure 10

VI. Application Example

Looking at a recent application situation demonstrates how the powerful performance of 1336 PLUS II with Sensorless Vector control is helping to make one manufacturer a leader in his industry. A plant expansion to increase production required the addition of new, 150 HP dough mixers. The mixer OEM's standard was a two-speed motor / starter combination, but the user requested that the mixers be equipped with variable frequency drives, partly to avoid the maintenance liability of the starter combination and partly to gain the process flexibility offered by variable speed. The OEM balked at the request both because of his standard and because of previous experience with drives. Tests conducted three years earlier proved that a drive three times larger than the motor (in this example, a 500 HP drive) was required to produce the needed torque. In conjunction with both parties, a test was arranged using a 150 HP 1336 PLUS II on a mixer with a 150 HP two speed consequent pole motor. To truly test the Sensorless Vector capability of the

1336 PLUS II, everything possible was done to the drive including a heavy dough load, a low water recipe stress (thicker, more viscous dough) and overspeeding the mixer to 120% of base speed. The 1336 PLUS II produced all the necessary motor torque in all the areas of operation using the appropriate sized drive. Because of the ability to manage flux current and optimize the available drive current, no over sizing was required. Both OEM and User mixing experts also agreed that the mixer performance was better under variable speed control, a pleasant surprise for them. The end result for the customer is increased productivity, product quality and profit. Whether the application calls for mixing cookie dough, starting high inertia conveyors, or running other key equipment, the right torque for the load can be produced with Sensorless Vector control.

VII. Future Developments

As Sensorless Vector development moves forward, performance will most certainly continue to improve. Speed ranges of 300:1, greater torque at or very near zero speed, higher bandwidth and other improvements will offer even greater benefit to tough applications. Combined with the necessary drive features, this technology creates a powerful package for the future. Applications requiring rough positioning, rapid acceleration and deceleration and other “higher performance” requirements will be increasingly handled by general purpose products. Faster microprocessors, DSP technology and higher response algorithms will provide even higher levels of drive capability. Allen-Bradley drives will continue to strive to turn the newest technology into real products that offer customers exceptional ease of use, the opportunity for greater flexibility, higher productivity, and lower total life cycle costs.

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