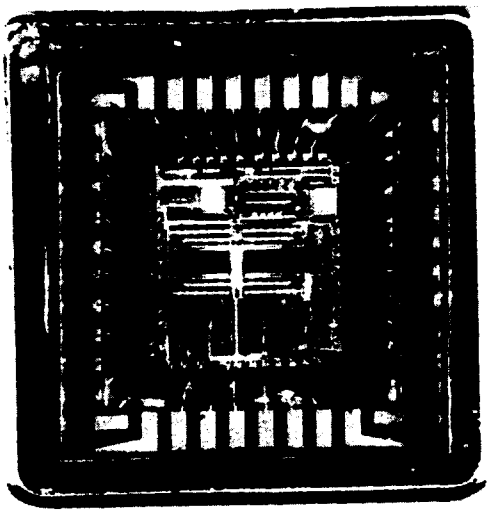
ANALOG DEVICES

AN-267
APPLICATION NOTE

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"Vector Control Using a Single Vector Rotation Semiconductor for Induction and Permanent Magnet Motors"

by F. P. Flett



ABSTRACT

This paper describes the implementation and architecture of an integrated circuit which is dedicated to the role of vector rotation for AC induction and DC-Permanent Magnet synchronous, PMSM, brushless motors.

Sampling time and resolution are normally the factors which limit the performance of software control schemes in motor control. Now with the ever increasing tasks required by digital processing in motor control the gains in performance are often limited by the additional software computation time taken to achieve them.

At the other end of the spectrum many control schemes only require one, or, two vector transformations. In these cases the choice of a hardware solution that avoids the pitfalls of software intensity which either limits the bandwidth of control, or even worse, number truncation which reduces the signal-to-noise ratio, can be avoided.

A new semiconductor - AD2S100 - that has been developed and built in concert with an AC induction vector controller now removes the time intensive task of calculating vector coordinate transformations in software and realizes an extremely economic and efficient approach to vector control.

The AC Induction Motor

It is quoted that the implementation of variable speed drives could save between 22 and 27 percent of the total electricity used in the USA. This refers in particular to the use of AC induction motors with variable speed control.

Induction motors are often determined as asynchronous device when operating either under constant, or, adjustable frequency control. For control purposes however the induction motor can be thought of as a synchronous brushless motor where the rotor magnets rotate in the air gap between the stator winding and the squirrel cage rotor.

Additionally the induction motor likens itself to the DC brushless motor in that the rotor flux interacts with current in the stator to produce torque. Torque is maximized when the stator current is perpendicular, or in quadrature, with the rotor flux.

A fixed relationship exists between the rotor magnets and flux in a permanent DC permanent magnet motor. Thus, by applying stator current in time quadrature with the flux optimum torque is achieved.

The same relationship does not hold for the induction motor, however. There are two components from the modulus of stator current which must be generated and managed in this motor. The first realizes the in-phase flux component while the second concludes the quadrature torque component. Both currents hold no fixed natural phase relationship to the shaft position.

It is the rotating magnetic field generated by the electromagnets in the induction motor which constitutes the major control differentiation between the induction and DC permanent magnet motor.

The diagrams below aid this explanation:

DC PERMANENT MAGNET MOTOR

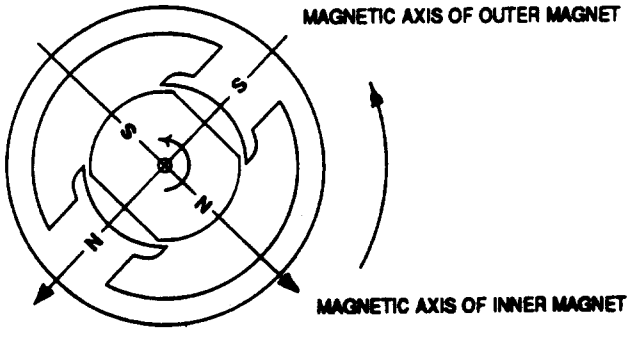


Figure 1.

AC INDUCTION MOTOR

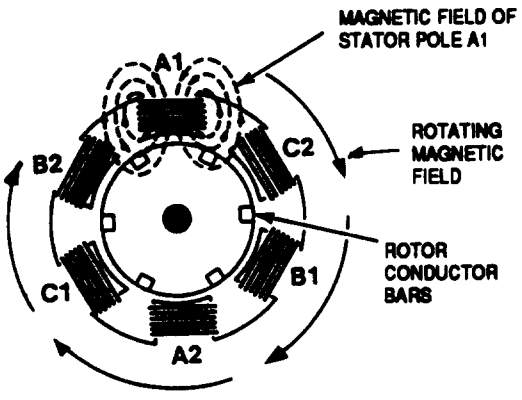


Figure 2.

Figure 1 identifies a DC motor where the armature winding is normally on the rotor and the field winding is on the stator. Permanent magnets mounted in the rotor interact with the field winding on the stator to produce maximum torque when both sets of magnets, those fixed on the rotor and the rotating magnetic field, are at ninety degrees to one another.

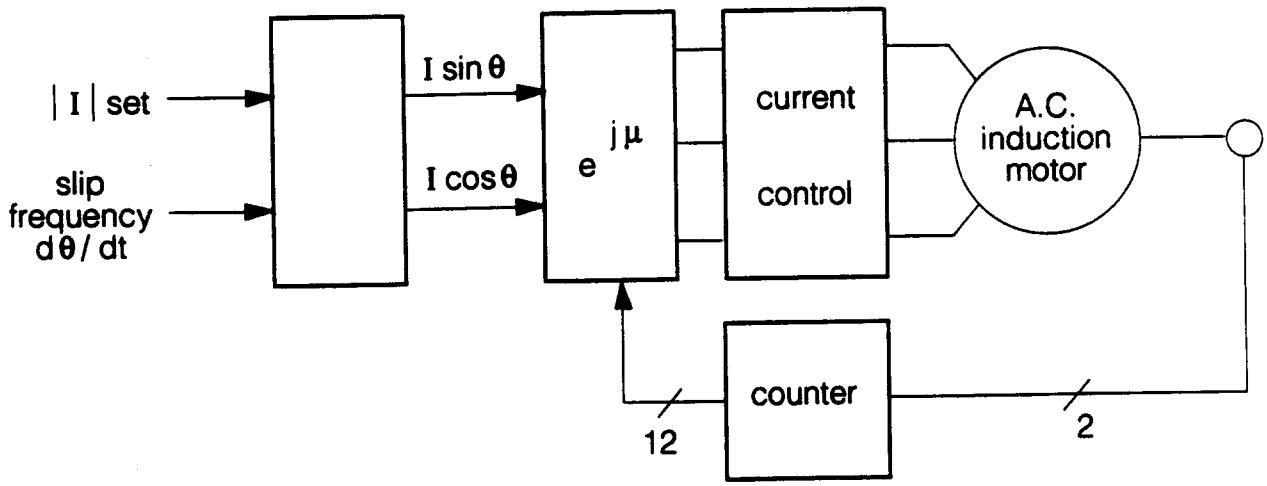
In contrast the armature winding of an AC induction motor is associated with the stator. The three phases A, B, and C, on the two pole motor, identified in figure 2, create a rotating magnetic field which follows the armature field as it rotates around the motor. This rotating magnetic field is a product of the electromagnets created by the stator induced field current in the rotor bars of the squirrel cage rotor.

AC induction motor control must therefore manage both the flux and torque current simultaneously while in the case of the DC permanent magnet motor these can be controlled independently. This is where the necessity for vector control arise.

Applied Vector Control

Three variables are attributed to the torque component of induction motors. These are stator current, slip frequency and flux. Vector control of induction motors calls for the independent control of two of these components, namely, current and slip.

At the simplest level of control a configuration which identifies the application of a vector control block is shown below. More complicated configurations will be discussed later.



Constant slip frequency control using a vector rotation block

Figure 3.

Current and slip control was pioneered by Leonhard in 1973.

A control strategy such as the one depicted above results in good torque control over a wide speed range and high efficiency of AC induction motors when a constant slip frequency is applied [Jian, 1983].

The optimal slip frequency is dependent on the rotor resistance and saturation which varies with temperature.

If it is essential to maintain a constant torque at all times the rotor slip should increase with the rotor resistance and saturation [Bossche, 1991].

A position feedback device is also required and this can be either a resolver, or, an incremental encoder. Normally an incremental encoder featuring a line count of 1024 is adequate for the majority of controllers. In the case of a DC permanent magnet motor absolute position feedback is necessary and a resolver is the natural choice, here.

This form of control may be applied in applications where a slow dynamic response is adequate, pumps, fans and compressor for example, and where optimal motor efficiency is important. This is also the most opportunistic area for electricity cost reduction highlighted earlier.

Alternatively dynamic control applications demand the rotor be kept magnetized in order to react to sudden changes in load inertia by simultaneously exerting the corresponding torque current requirements. Normally for this purpose the high dynamic velocity and position loops contain an inner control loop. This inner loop is a major contributor to the overall performance of the system. Gain changes above 30% seriously affects the speed and position performance of dynamic systems and is one of the fundamental reasons for the adoption of vector control algorithms.

The key merits of vector control have often been stipulated as

(1) High motor efficiency due to magnetization current control related to RPM.

(2) Constant torque over the complete range of motor speed, inclusive of zero speed.

(3) An increase in the speed/torque envelope due to field weakening schemes.

(4) Good velocity control under varying load conditions.

Drawbacks to vector control schemes normally quote both economics and sampling performance as deterrents to adoption.

There is of course a direct relationship between these electives. The sampling interval is the most critical element in the application of digital signal processing systems and one

that has a fundamental bearing on the cost/performance of the controller. To preserve the information in the analog signal it must be sampled at a rate that is at least twice the rate of the highest frequency component.

In digital control systems the sampling rate is usually chosen to be between 8 to 10 times the system bandwidth.

Common sampling rates start at 1kHz and can reach up to 100kHz. However the hardware used in many motion controllers for factory automation limit the sampling frequency to around 2kHz.

This has dramatic effects on system stability and slows down the response time considerably.

The complexity of the vector calculations normally carried out by software is one overriding reason why the sampling time is reduced. This is not only due to the actual matrix multiplication, which normally carries out the Cartesian to polar coordinate conversion, but also to the "round off noise" caused by intermediate truncation when inadequate computing power is applied. A higher order DSP solution to solve these limitations can be implemented - but at a cost which many would be adopters have failed to justify to themselves.

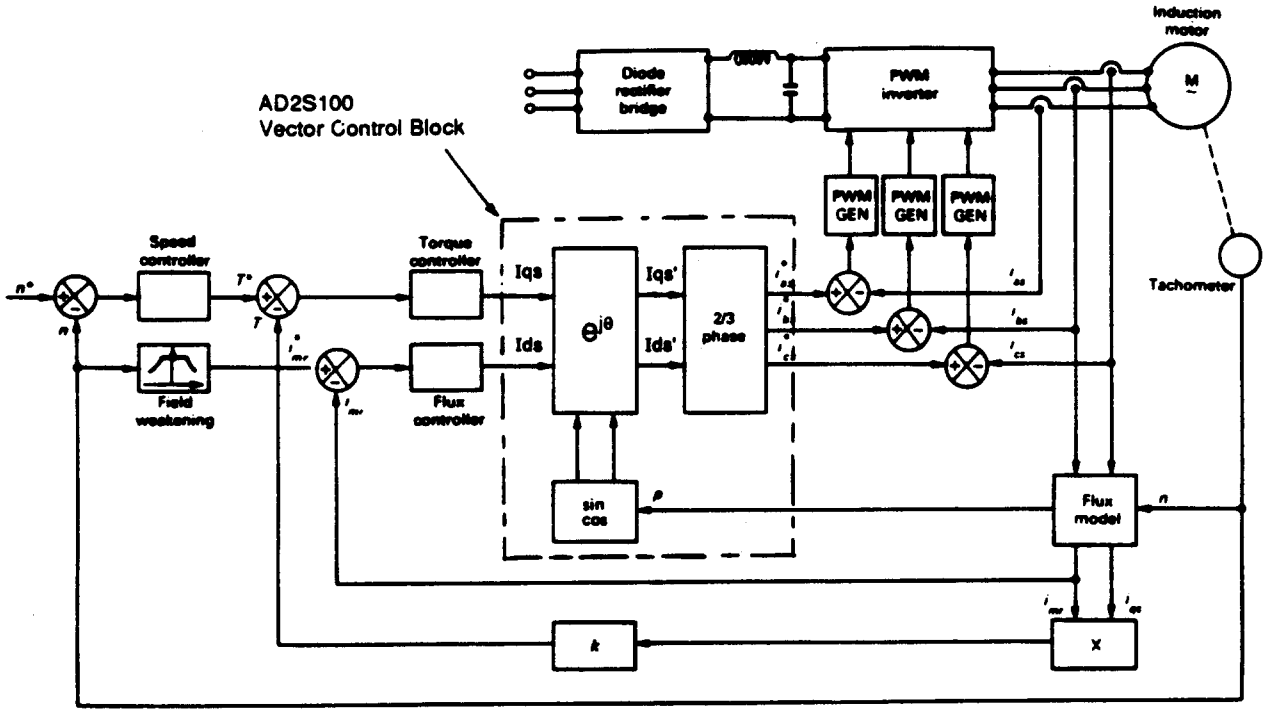
With the advance of DSP technology many of these drawbacks have been overcome. However, there is now more demands being required from the processor to achieve superior controller performance.

Adaptive control to changes in rotor resistance and real time diagnostics with predictive maintenance routines that calculate fail-safe control strategies are just two tasks which many drive designers would like to see adopted as standard. These tasks sound futuristic but will become a reality as specific motion control computing devices become available.

A dedicated vector control IC - the AD2S100 - is now available to perform the time intensive complex vector rotation calculations. Control schemes that use this semiconductor will be described and the performance and economic benefits analyzed

Vector Math

As previously quoted, the main objective of vector control is to determine the torque and flux constituents from the applied magnitude of stator current and relate these currents to the moving rotor reference frame. In many articles denoting these currents the nomenclature used is "Iqs" for torque current and "Ids" for the flux current. These conventions will be carried through here.



Induction motor speed control by direct field orientation with a current-controlled PWM inverter.

Figure 4.

Figure 4 relates a complete field oriented scheme used in adjustable-frequency induction motor drives. The vector block identified will be the topic of concern in this section. The scheme shown here is commonly known as indirect field control due to the fact that the rotor flux position 'ρ' is deduced from a shaft position transducer and the slip frequency of the rotor.

The rotor flux vector has an instantaneous value which is the sum of the shaft angular velocity, ωm, and the corresponding slip angular velocity, ωs.

If we are trying to determine the actual position of the rotor flux vector ωr, then the following holds:

Instantaneous value of rotor flux vector = ωr
Instantaneous value of shaft angular velocity = ωm
Instantaneous value of slip angular velocity = ωs

$$\omega r = \omega m + \omega s \quad \text{---------- 1}$$

also $\omega r = \omega m + \dfrac{Iqs}{\tau r\ imr}$ **where** $\omega s = \dfrac{Iqs}{\tau r\ imr}$

$$\omega s = \omega r - \omega m \quad \text{---------- 2}$$

and is also equal to sωr

$$\therefore \omega s = s\omega r \quad \text{---------- 3}$$

Where s is the frictional slip of the rotor with respect to rotor flux vector ωr.

The parameter ωr is normally represented by a digital number and is one of the input ports on the AD2S100 vector controller.

The kernel of the coordinate transformation is the vector operator:
ejθ or e-jθ, where ejθ = [cosθ + jsinθ].

It is this operator which relates the stator currents to the moving rotor reference frame.

We can describe the flux current Ids and torque current Iqs in complex numbers as:

$$Ids + jIqs$$

As previously described these current are the in-phase and quadrature currents respectively.

If we now want to relate these currents to the rotor frame reference the vector operator is used as follows:

$$Ids' + Iqs' = [\ Ids + jIqs\ ]\ [ej\theta]$$

if we expand this we get:

$$[\ Ids + jIqs\ ]\ [Cos\theta + jSin\theta]$$

which ends up as $Ids' = IdsCos\theta + IqsSin\theta$
and $Iqs' = -IdsSin\theta + IqsCos\theta$

The outputs Ids' and Iqs' are shown at the output of the vector control block. The 2/3 phase block is simply the conversion from sine and cosine signals to a three phase 120 degree representation.

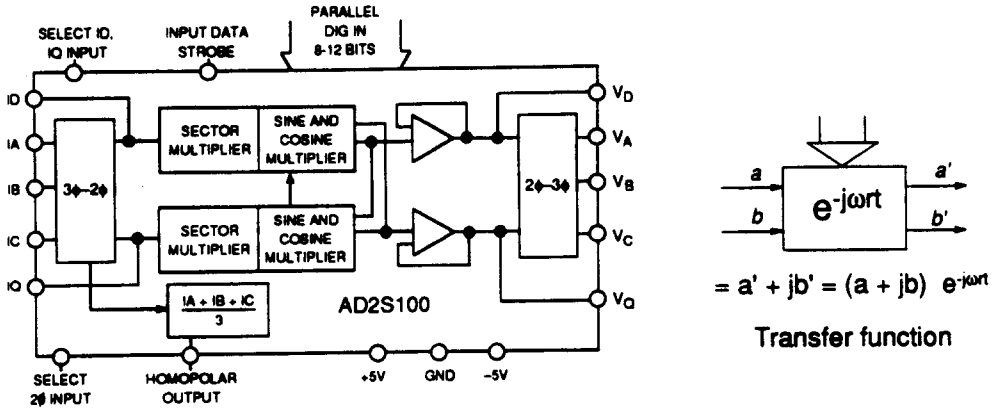
The matrix representation that is used by digital processing is

$$\begin{bmatrix} Ids' \\ Iqs' \end{bmatrix} = \begin{bmatrix} Cos\theta & -Sin\theta \\ Sin\theta & Cos\theta \end{bmatrix} \begin{bmatrix} Ids \\ Iqs \end{bmatrix}$$

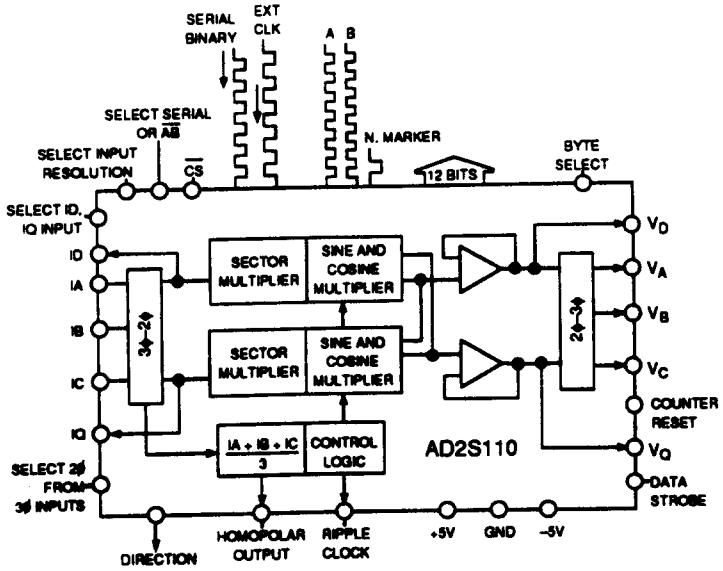
There are two other points of note in figure 4 which relate to field weakening and the multiplication of the rotor magnetizing current, imr, and iqs at the output of the flux model. Field weakening is a technique where the base speed of the induction motor can be extended at a constant torque by reducing the rotor magnetization current. It also lowers the problem of pulsating torque at low speeds but only at the expense of fundamental torque, however.

The multiplication of imr and iqs is quite simply to determine the actual motor torque T and relate this to the input speed controller for compensation.

Systems on Silicon in Motion Control - The AD2S100 & 2S110



AD2S100



AD2S110

Figure 5.

The block diagrams above represent the key elements of the AD2S100 and AD2S110 vector controllers.

The prime difference between the two components relates to the position transducer selected. An absolute position device, a resolver, is used with the AD2S100 while the AD2S110 accepts both an incremental encoder A quad B input and serial absolute position input. This serial absolute position input is also generated by a resolver and can be converted by a low cost resolver to digital convertor such as the AD2S90.

General Product Description

These three-port device provide a digital input port that accommodates the most popular sensors used for rotor position and velocity measurement.

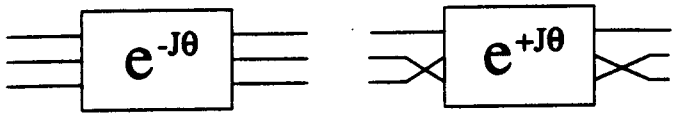
The parallel binary input on the AD2S100 accepts a twelve bit digital word which is derived from a resolver via a resolver to digital converter, (R/D). Another input form accepts incremental A quad B signals from an optical encoder, (AD2S110).

In the case of resolver based systems a natural by-product of the type-two tracking loop conversion used in monolithic R/D converters is the availability of a velocity signal which can be used to replace a tachogenerator.

An analog input port which senses three phase stator currents, normally commuted by hall effect devices, is shown at the left side of the vector controllers above. These real time signals may either be three phase 120 degree separated signal, or, quadrature sine and cosine signals.

These signals undergo the coordinate transformation according to the vector equations previously disclosed and are then presented as analog output in either three phase, or, quadrature representation. A complete vector transformation is completed in two microseconds.

The partitioning of the input and output sections allows these blocks to be used either for forward, or, reverse vector transformations. The implementation is shown below.



3 Phase in - 3 Phase out

Figure 6.

Additionally decode logic has been incorporated in the vector control chips to allow a user to select only two of three 120 degree phases at the input. This assumes that the sum of the three phases is zero and that the third phase can be deduced from the knowledge of the other two.