SECTION 19

MOTOR CONTROL CIRCUITS

- BACKGROUND
- AC INDUCTION MOTORS
- VARIABLE VOLTAGE VARIABLE FREQUENCY CONTROL
- VECTOR CONTROL
- SLIP CONTROL
- HIGH PERFORMANCE DYNAMIC CONTROL
- GENERAL DESCRIPTION OF AD2S100/110 AC VECTOR PROCESSORS
- GAMANA - A PROJECT IN MOTION
- GAMANA VT
- GAMANA GMCDS
- CHIPSETS/ALGORITHMS
- APPLICATIONS

SECTION 19

MOTOR CONTROL CIRCUITS

Fred Flett, Matthew Finnie

Long known for its simplicity of construction, low-cost, high efficiency and long-term dependability, the ac induction motor has been limited by the inability to control its dynamic performance in all but the crudest fashion. This has severely restricted the application of ac induction motors where dynamic control of speed, torque and response to changing load is required. However, recent advances in digital signal processing (DSP) and mixed-signal integrated circuit technology are providing the ac induction motor with performance never before thought possible. Manufacturers anxious to harness the power and economy of Vector Control can reduce R&D costs and time to market for applications ranging from industrial drives to electric automobiles and locomotives with a standard chipset/development system .

It is unlikely that Nikola Tesla (1856-1943), the inventor of the induction motor, could have envisaged that this workhorse of industry could be rejuvenated into a new class of motor that is competitive in most industrial applications.

BACKGROUND

Before discussing the advantages of Vector Control it is necessary to have a basic understanding of the fundamental operation of the different types of electric motors in common use.

Until recently, motor applications requiring servo-control tasks such as tuned response to dynamic loads, constant torque and speed control over a wide range were almost exclusively the domain of dc brush and dc permanent magnet synchronous motors. The fundamental reason for this preference was the availability of well understood and proven control schemes. Although easily controlled, dc brush motors suffer from several disadvantages; brushes wear and must be replaced at regular intervals, commutators wear and can be permanently damaged by inadequate brush maintenance, brush/commutator assemblies are a source of particulate contaminants, and the arcing of mechanical commutation can be a serious fire hazard in some environments.

The availability of power inverters capable of controlling high-horsepower motors allowed practical implementation of alternate motor architectures such as the dc permanent magnet synchronous motor (PMSM) in servo control applications. Although eliminating many of the mechanical problems associated with dc brush motors these motors required more complex control schemes and suffered from several drawbacks of their own. Aside from being costly, dc PMSMs in larger, high-horsepower configurations suffer from high rotor moment-of inertia as well as limited use in high speed applications due to mechanical constraints of rotor construction and the need to implement field weakening to exceed baseplate speed.

In the 1960's, advances in control theory, in particular the development of Indirect Field-Oriented Control, provided the theoretical basis for dynamic control of ac induction motors. Because of the intensive computation required by Indirect Field-Oriented Control, now commonly referred to as Vector Control, practical implementation was not possible for many years. Available hardware could not perform the high-speed precision sensing of rotor position and near real-time computation of dynamic flux vectors. The current availability of precision optical encoders, isolated gate bipolar transistors (IGBTs), high-speed resolver-to-digital converters and high-speed digital signal processors (DSPs) has pushed Vector Control to the forefront of motor development due to the advantages inherent in the ac induction motor. Until now, however, the lack of advanced development tools has limited development to in-house custom designs and restricted Vector Control to the privileged few with the resources necessary to design a DSP based system from the ground up.

POPULAR TYPES OF ELECTRIC MOTORS

- DC Brush
- DC Permanent Magnet
- AC Induction

Figure 19.1

LIMITATIONS OF DC MOTORS

- Power Rating is Limited at High Speeds due to Commutation
- Commutator and Brushes Require Maintenance
- Power-to-Weight Ratio is Much Less than for AC Induction Motor
- Arcing

Figure 19.2

AC Induction Motors

With the definition of control algorithms and availability of hardware capable of implementing Vector Control the major problem in using ac induction motors in traditional dc PMSM applications is conceptual, i.e. understanding that the ac induction machine can operate almost identically to a dc machine. This requires understanding the fundamental mechanism underlying the generation and orientation of the rotor magnetic field (flux). In the dc PMSM, rotor flux is produced by permanent magnets and rotates in synchronism with the rotating stator field with a phase lag dependent on load. Figure 19.3 identifies this fixed relationship between the rotor magnets and flux in the dc machine. As load on the rotor increases, the rotor phase lag also increases until torque is at maximum when the stator flux is perpendicular or in time-quadrature (90°) to the rotor flux. Beyond this load the motor will stall.

The same relationship does not occur in the ac induction motor. Induction motor rotors are basically two rings with bars placed between them like a tread wheel for a mouse, hence the name squirrel-cage. Unlike the permanent magnet motor, rotor flux in an ac induction motor is produced by current induced in the bars of the squirrel-cage by the rotating stator field. Because of this there are two components that must be decoupled from the modulus of stator flux. The first is the flux component of current, usually referred to as direct current (Ids) that must first be manufactured and maintained to create the rotating magnetic field in the air gap between the stator and squirrel cage rotor. The second flux component is the torque producing current induced on the squirrel cage rotor. This is usually referred to as quadrature current (Iqs).

Figure 19.3 depicts the rotating magnetic field that is produced by the circulating flux current in the stator and its interaction with the rotor conductors in the caged rotor which in turn creates the rotating magnetic field.

DC PERMANENT MAGNET MOTOR AND AC INDUCTION MOTOR

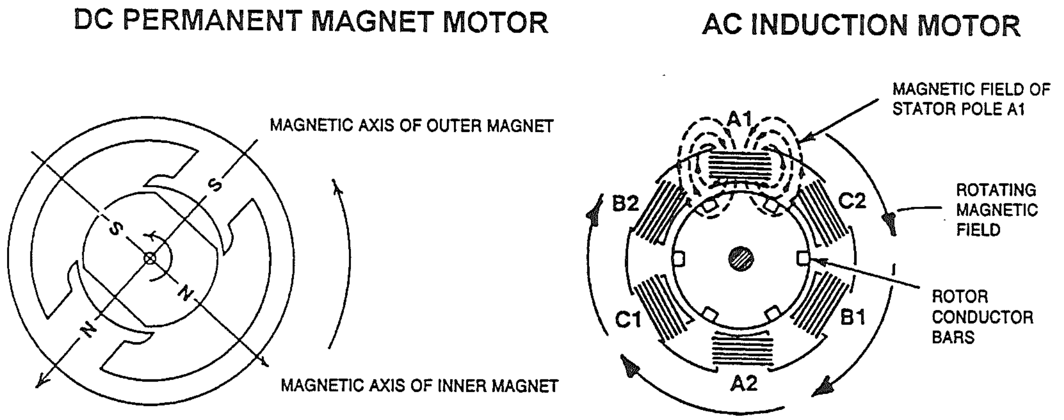

Figure 19.3

Unlike the case with synchronous motors, rotor flux in induction motors is not fixed relative to the rotor position. This is where the analysis of ac induction motors become complicated. As with any inductor, squirrel-cage rotors have a time constant dependent on temperature and saturation of the rotor material. Because of this 'rotor time constant', the rotor acts as a lowpass filter. The delay of the rotor time constant causes the rotor flux to lag behind (rotate slower) than the stator field. This difference in rotational speed is referred to as *slip*. Slip is measured as an angular velocity expressed as a frequency, typically around 3 Hz, and is important in understanding the limitations of the ac induction motor without Vector Control.

When a greater load is placed on the rotor, slip increases and the torque current component (rotor current) of the motor increases as the vector of the rotor flux relative to the stator field moves closer to 90° where maximum torque is produced. Like the PMSM, if the load on the motor is sufficient to force the rotor flux/stator field relationship beyond 90° the motor will stall.

WHY CONTROL IS IMPORTANT

- Velocity Control of Motor Reduces Losses
- More Efficient Use of Energy
- Lower Vibration and Noise
- Eliminates Need for Mechanical Gearing

Figure 19.4

WHAT IS ELECTRIC MOTOR CONTROL?

- Control of Rotational Velocity of the Motor
- Control of Torque (Load)
- Control of Position
- Interpolation and Coordination Between Motors

Figure 19.5

TYPES OF ELECTRIC MOTOR CONTROL

- Simple Control
- Adjustable Speed Drives - ASDs
- Servo Control
- Vector Control

Figure 19.6

VARIABLE VOLTAGE VARIABLE FREQUENCY CONTROL

Central to much of this discussion on motion control is the AD2S100 AC Vector Processor. This device has been developed as a central part of a vector control scheme. Before describing the use of the AD2S100 in vector control of an ac induction motor, the device can also be used to orient and control the phase of an induction motor for the simplest and commonest form of variable speed control called *variable voltage variable frequency control.*

As stated in the section on AC induction motors, the AC induction motor produces torque as a function of the slip, i.e the lag between the rotor frequency and the stator frequency. Inducing slip in the rotor is achieved by driving a load from the rotor. This forces the rotor to lag the stator: the greater the lag, the greater the torque. It is the constant action of the rotor trying to maintain synchronism with the stator which produces the torque.

The speed of the motor is controlled by the rotating frequency of the rotor. One 3 phase electrical cycle would equate to a single mechanical rotation in a single pole motor. For example, a 300Hz stator frequency produces 300 rps rotor velocity.

While varying the speed the voltage has to be controlled to be proportional to the frequency to prevent the motor from stalling. This need to maintain a constant voltage:frequency ratio leads to the name V/F Drive (this name has *no* connection with voltage-frequency converters).

The AD2S100 can be configured for use in V/F drives by simply controlling the update rate of the digital angle.

Figure 19.7 shows how the AD2S100 is used to manipulate the inverter's voltage and input frequency.

VARIABLE VOLTAGE/VARIABLE FREQUENCY
CONSTANT V/F RATIO DRIVE

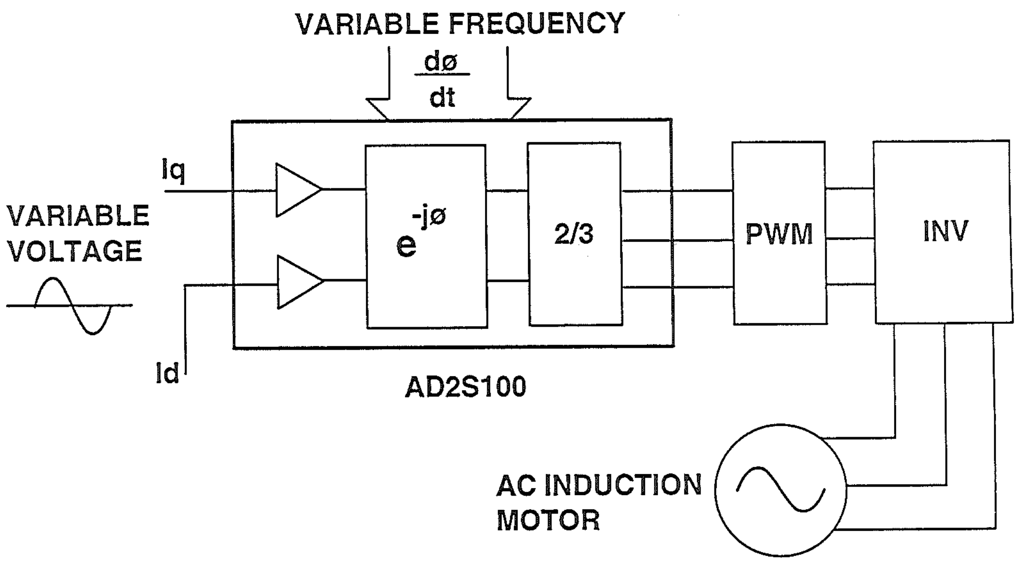

Figure 19.7

Vector Control

For an ac induction motor to attain dynamic performance comparable to a dc brushless PMSM motor, the amplitude of the stator mmf vector, as well as its position with respect to the rotor flux vector must be controlled at all times. One of the prime tasks in Vector Control is to decouple the torque and flux based currents from the modulus of stator current and keep them in quadrature to one another at all times in a reference frame that is related to *rotor* coordinates. This requires sensing the three phase stator currents, transforming them into a coordinate frame that rotates in synchronism with the rotor flux and comparing them with set points for direct and quadrature axis components. The required current/voltage reference to be impressed upon the motor is then calculated, and finally a coordinate transformation from the rotating frame to the stationary or stator frame is carried out.

19

ADVANTAGES OF VECTOR CONTROL

- Constant Torque from Zero and Over the Complete Range of Motor Speed
- Constant Horsepower Available Above Base Speed
- Increased Velocity Precision even under Varying Load Conditions
- High Motor Efficiency due to Magnetization Current Control Related to RPM

Figure 19.8

There are several control schemes that can be implemented using Vector Control. Two common approaches are presented here to illustrate the power and versatility of the technique.

SLIP CONTROL

To illustrate the use of vector rotators, a current and slip control is presented in Figure 19.9. This control strategy offers very high efficiency with good torque control over a wide speed range. Torque control in this configuration is somewhat slow at low torque loads due to the time required for the rotor flux to build up as a function of the rotor time constant. This control scheme works well in applications such as refrigeration compressors, or fans for heating and ventilation, where efficiency is more critical than a fast response to changing loads.

CONSTANT SLIP FREQUENCY CONTROL USING THE AD2S100 VECTOR ROTATION COPROCESSOR

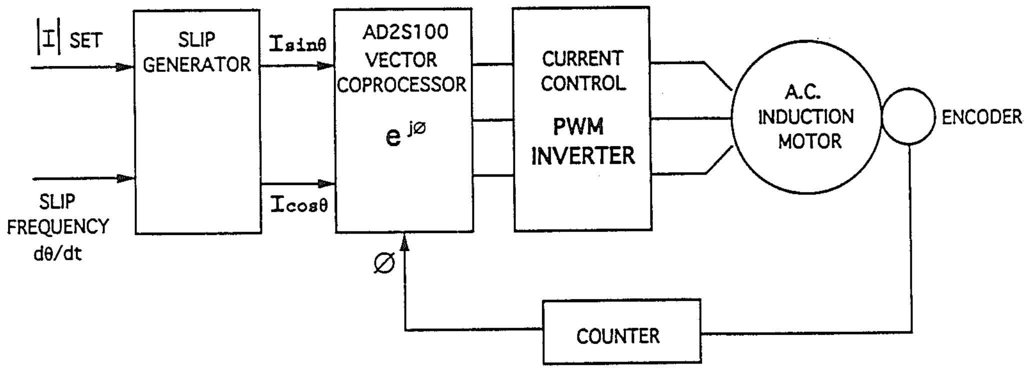

Figure 19.9

Optimal slip frequency depends on rotor resistance, which varies with temperature, and on the saturation characteristics of the motor. To achieve the ideal efficiency, rotor slip should increase with rotor resistance and saturation.

A slip generator calculates the Isinθ and Icosθ parameters from the set point current, |I| set, and the slip frequency demand. This computation can be carried out by the AD2S100 vector processor. The outputs are then vector rotated in the AD2S100 and three sine wave signals are generated for PWM use.

HIGH PERFORMANCE DYNAMIC CONTROL

In contrast to the simplicity of the scheme described above, there are many alternative approaches and more complex control architectures that are employed in more demanding applications. The dynamic behavior of the ac induction motor in the rotor flux reference frame is represented in Figure 19.10. The motor block consists of three sections. In the first section the three phase currents in the stator winding, Is(1), Is(2) and Is(3) are converted into equivalent two phase stator currents Isa and Isb. The second section merges these two phase currents with the rotor flux oriented operators, Ids and Iqs. In Figure 19.10, ρ (Rho), is used to identify the instantaneous position of rotor flux with respect to the stator axis. The third section represents the control strategy, where the magnetizing current is derived from the Ids current, and the build up of rotor flux takes place. Manufactured torque Md, is dependent upon the magnetizing current Imr, and the prevailing rotor time constant Tr.

DYNAMIC MODEL OF AN AC INDUCTION MOTOR

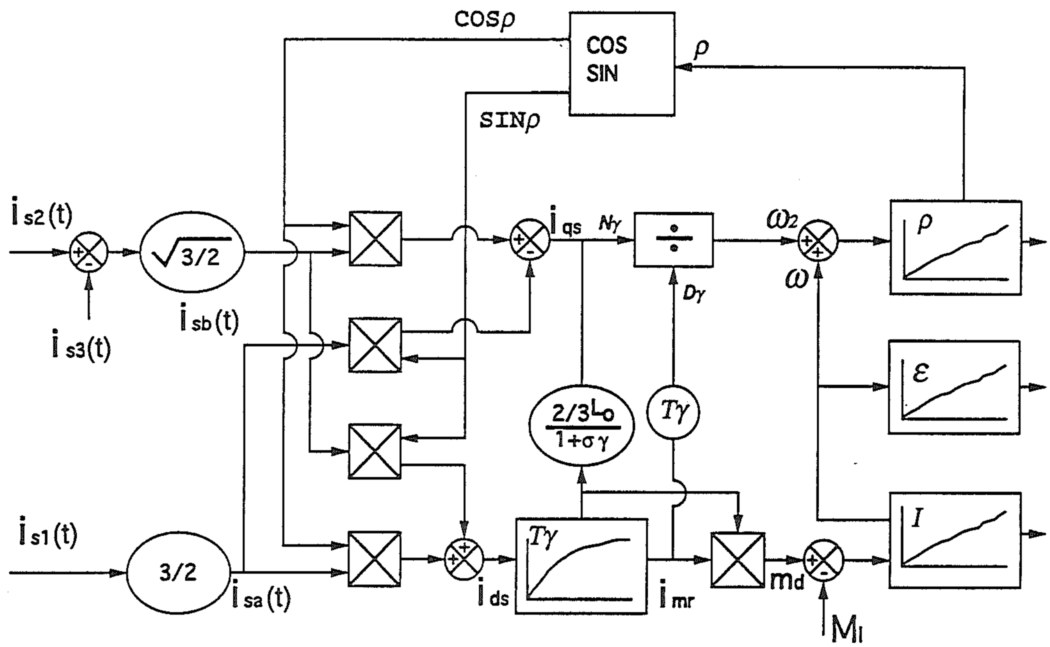

Figure 19.10

COMPLETE DYNAMIC CONTROL SYSTEM FOR AC INDUCTION MOTOR

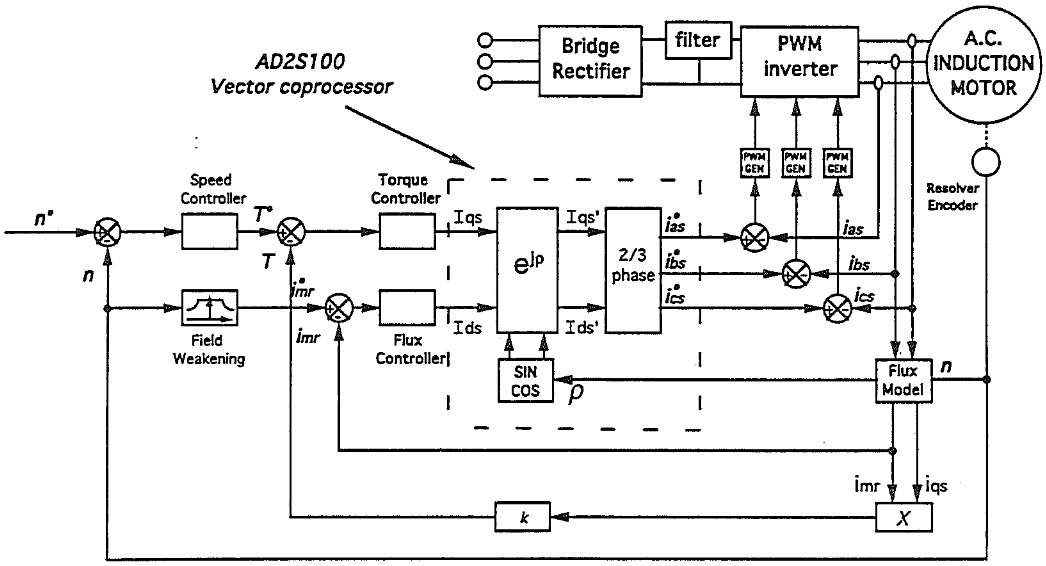

Figure 19.11

One of the major advantages of operating in the rotor reference frame is the ease of calculating magnitude and position of rotor flux and implementing a robust control scheme. In the rotor reference frame, the rotor behaves as a simple low pass filter for the magnetizing current. For example in the area of operation above base speed known as the *field weakening area,* the flux current must be reduced to attain the possibility of speeds above base speed. This creates a desaturated motor, and if a constant magnetization current is used the torque or voltage estimate may have a 100% error! By taking this nonlinearity into account the stability and robustness of control can be greatly improved.

Unlike the simple slip control, high-performance dynamic control in servo applications requires much greater signal processing power to provide fast loop response. The effect that limitations in processor capacity have on system performance is highly dependent on the specific loop involved. The servo-loop most sensitive to processor speed in a Vector Control system is usually the torque control loop. Most control architectures are implemented using nested control loops, commonly referred to as a cascade structure, with the actual controlling functions, in this case the torque and flux control loops, lowest in the hierarchy. In order to react to sudden changes in torque demand the torque loop must be fast enough to maintain the correct rotor flux vector at all times. Gain changes of more than 30% in the torque loop can severely restrict velocity and position performance. These limitations are avoided in the digital Vector Control system by designing the torque loop with sufficient bandwidth to allow precise control of both the torque component of stator current and of the flux base current necessary to maintain the correct magnetization current in the rotor over the operating speed range for the application.

Bandwidth requirements in servo applications vary considerably. For example a velocity bandwidth of 20 Hz may be adequate for many industrial applications where slip control is adequate but a machine with multi-axis control can require servo bandwidths of 200 Hz and more. Trends to higher bandwidth and increasing task demands on the controller are evident in all drive applications. DSP based systems are capable of dynamically allocating resources by optimizing algorithms to reduce computational overhead in less important areas of performance to free processor time for more precise control of critical parameters.

Controller hardware and software are normally the limiting factor at sampling rates beyond 1 kHz and with many advanced algorithms, this sampling rate will be inadequate. Lowering the sampling rate limits the stability of the system and slows the torque response to changing loads. One solution is to use greater computing power with the associated increase in cost and complexity. Another solution available to control engineers are control architectures using new mixed signal integrated circuits which perform operations previously performed by the CPU, and thus reduce the demands placed upon it.

GENERAL DESCRIPTION OF AD2S100/110 AC VECTOR PROCESSORS

As previously stated, the ability of a system to decouple torque and flux components is critical to the implementation of vector control. The operation required to perform this is an in-line matrix calculation which transforms the 3 phase polar coordinates into the 2 phase rotor Cartesian ones. Practical implementation of the transformation can be performed using DSP or discrete analog solutions. The time taken to perform the task represents a phase lag in the system which effectively translates into a positioning error in the commutation of the motor. Minimizing the error is critical to the bandwidth and performance of the drive.

It is this mathematically intensive task that has hindered the commercial acceptance and use of vector control for ac induction motors.

The AD2S100 is a mixed signal hardware multiplier which performs the acquisition of the three phase currents and performs the coordinate transformation. This three-port device provides a digital input port that accommodates the most popular sensors used for rotor position and velocity measurement.

The AD2S100 has a parallel binary input which accepts a twelve bit digital word derived from a resolver via a resolver-to-digital converter (RDC) such as the AD2S80A. The AD2S110 accepts incremental A quad B signals from an optical encoder.

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.

The AD2S100 has an analog input port which interfaces to three phase stator currents, normally sensed by hall effect devices. These real time signals may either be three phase 120 degree separated signals or quadrature sine and cosine signals.

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

The partitioning of the input and output sections allows these blocks to be used for forward or reverse vector transformations. The vector transformations performed by the AD2S100/110 are shown in Figure 19.12.

AD2S100/110 VECTOR TRANSFORMATIONS

AD2S100/110

Stationary to Rotating Frame
Forward Rotation

Rotating to Stationary Frame
Reverse Rotation

Figure 19.12

Additional decode logic has been incorporated in the vector control chips to allow the 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 knowledge of the other two.

AD2S100 AC VECTOR PROCESSOR BLOCK DIAGRAM

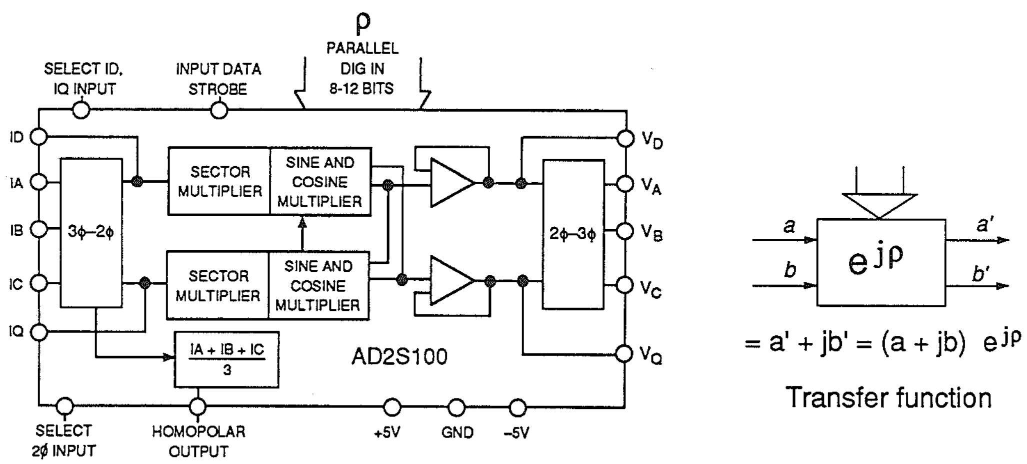

Figure 19.13

The AD2S100 has a homopolar output which senses if there is an imbalance between any of the three phase inputs, and therefore requires that all three inputs are used in a three phase system. Therefore the economy of using only two hall effect devices is made at the expense of the homopolar output. This output can be very useful in the detection and prediction of a dielectric breakdown resulting in an earth leakage condition.

The AD2S110 differs from the AD2S100 in ways which reflect the different functions required to process information from an optical incremental encoder rather than a resolver, when it is used as a rotor position sensor.

AD2S110 AC VECTOR PROCESSOR BLOCK DIAGRAM

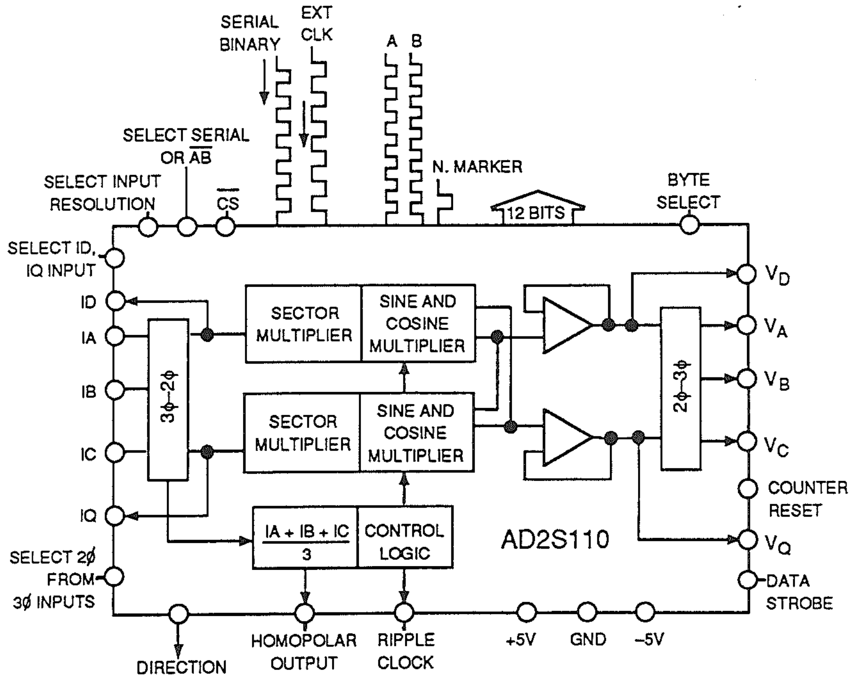

Figure 19.14

Inputs to the AD2S110 can have either absolute serial binary or incremental encoder format. The parallel digital port is an output in this case. The instantaneous incremental position input is converted to a parallel digital number which can be sent in that format to a peripheral device. Two other signals, direction sense, and a ripple clock which senses a once-per-revolution marker, are also available as output logic states.

GAMANA - A PROJECT IN MOTION

Analog Devices, Inc. has worked with Infosys Manufacturing Systems Pvt. Ltd. on development of an advanced motion control system. This system incorporates the combined expertise of both companies to produce a development environment for motion control hardware and software engineers. The vector control algorithms may be written and implemented without the typical learning curve associated with developing DSP code. The result of this combined effort is *GAMANA*, a chipset and software development system.

The name GAMANA is derived from the Indian Sanskrit root *GAM*, which means *go* or *move*. GAMANA is a revolutionary project that provides motion control engineers with a development system comparable in complexity to those which computer system designers have been using for many years. GAMANA reduces the complexity of implementing vector control for motors. This is done in three phases: Simulation/Training phase; CAD phase; and the Implementation phase.

The simulation and training phase uses GAMANA VT, a vector control tutorial program. GAMANA VT is a WINDOWS-based application that allows motor control engineers to simulate motor control in the laboratory.

The CAD phase is accomplished with GAMANA Motion Control Development System (GMCDS). GAMANA GMCDS is a menu-driven application that operates via a pair of IBM PC plug-in boards. The plug-in boards incorporate the AD2S100 and ADSP-21XX which are used in conjunction with the software to allow an engineer to create a motor model and develop the control architecture. The resulting simulated control system can be connected to a power inverter and motor to verify and tune the control strategy.

The implementation phase occurs once the control strategy is ready to be put into production. The software algorithms that were created with GAMANA GMCDS can be burnt into EPROM and run with the DSP device. The control algorithms for the system have been developed without the designer having to write any DSP code. The GAMANA code development process is illustrated in Figure 19.15. The corresponding hardware architecture for the advanced motion control engine is shown in Figure 19.16.

GAMANA MOTOR CONTROL CODE DEVELOPMENT PROCESS

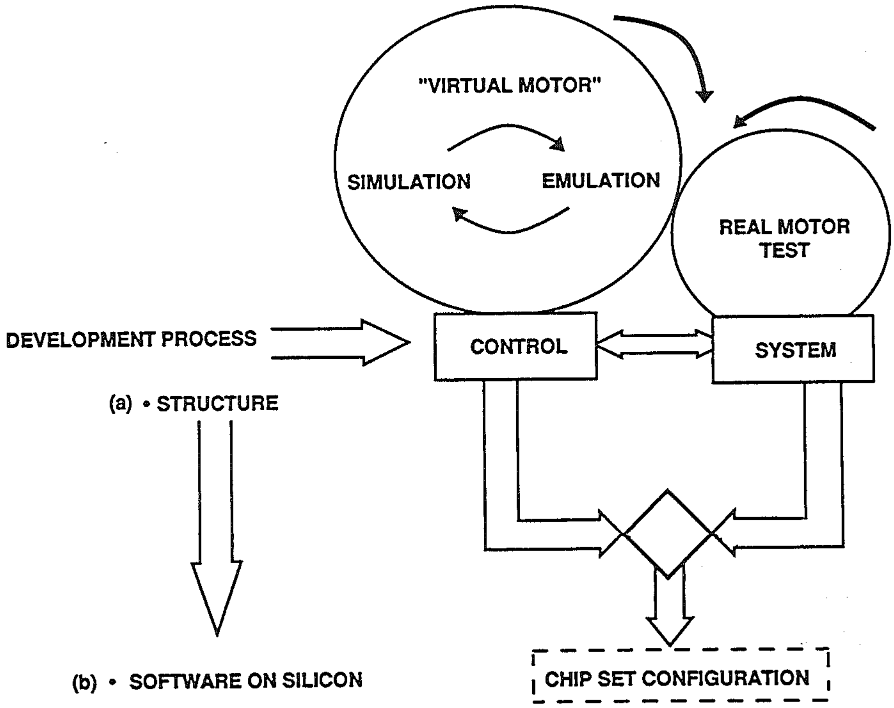

Figure 19.15

ADVANCED MOTION CONTROL ENGINE OF GMCDS HARDWARE

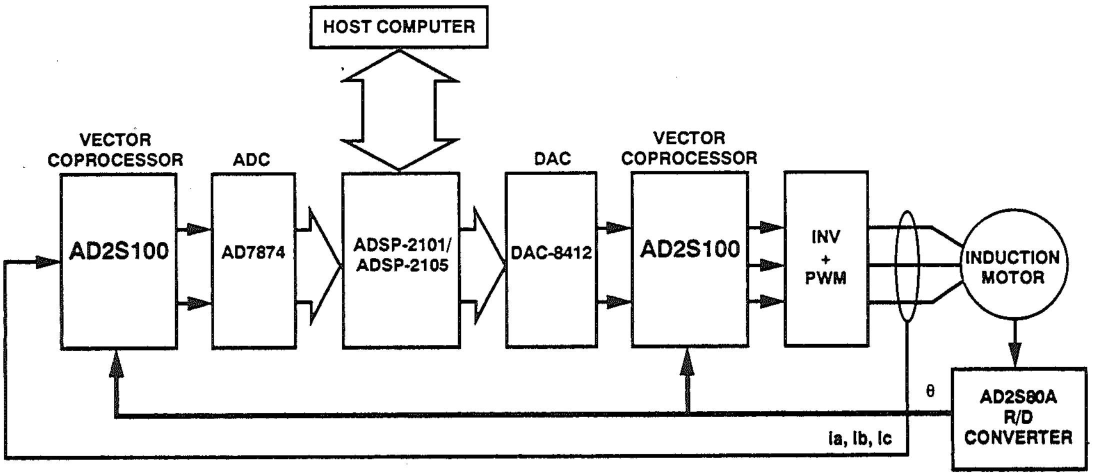

Figure 19.16

In addition to the AD2S100 Vector Coprocessors, the ADSP-21XX DSP, and the AD2S80A R/D Converter, the motion control engine uses a quad 12-bit ADC (AD7874) and a quad 12-bit DAC (DAC-8412).

The AD7874 ADC is a quad 12-bit simultaneous sampling ADC which digitizes the rotor flux oriented operators, Ids and Iqs. The AD7874 has a conversion time of 8μs per channel and a sample-and-hold acquisition time of 2μs allowing all channels to be sampled at a maximum rate of 29kSPS.

The DAC-8412 is a quad 12-bit DAC used to convert the ADSP-21XX digital outputs into analog signals which drive the second AD2S100. The double-buffered digital inputs allow simultaneous updating of all internal DACs.

GAMANA VT

GAMANA VT, as mentioned previously, is the first phase of developing a microprocessor-based vector control strategy. It is a development toolkit that simulates the vector control operation of an ac induction motor. GAMANA VT is easy to use and is useful for engineers whatever their background in vector control. Included with GAMANA VT is an extensive users manual that contains a detailed tutorial on vector control including detailed discussions of ac drives, synchronous machine operation, induction motors, pulse with modulation (PWM) inverter fed drives, permanent magnetic synchronous motors (PMSM), and field-oriented control of PMSM and induction motors.

GAMANA VT allows a user to simulate a vector control algorithm running as a group of high speed servo loops. The servo loops are *torque current, flux, velocity,* and *position.* The user can also choose between small, medium, and large motors. Each motor size has individual locked-rotor test parameters, which can be viewed and altered if necessary. The user can also access and change the gain, integral, and derivative parameters of each control loop. Figure 19.17 illustrates the software partitioning which is shown in greater detail in Figure 19.18.

GMCDS SOFTWARE PARTITIONING

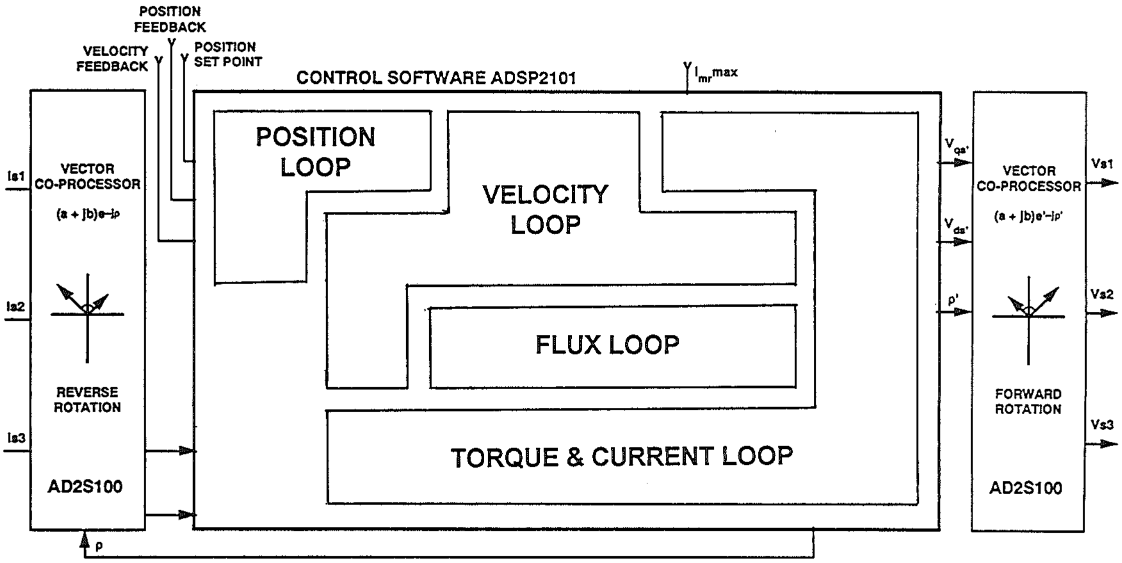

Figure 19.17

GAMANA ROTOR REFERENCE FRAME ARCHITECTURE

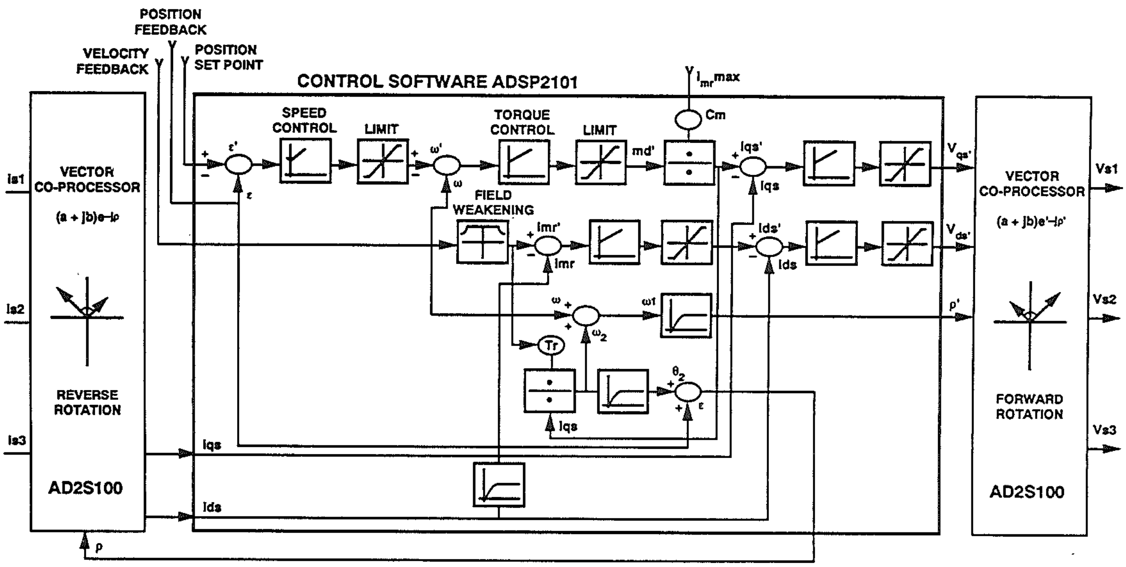

Figure 19.18

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The vector control algorithm drives the ac induction motor software model and graphically displays the dynamic characteristics of the motor being controlled. At the start of each simulation the motor parameters are either created or read from a file, and the motor states are calculated. This data is fed into the vector control module, and the algorithms perform the calculations necessary to decouple the direct (Ids) and quadrature (Iqs) current vectors from the stator and rotate these into the rotor reference frame. At this stage the active control loops are invoked, and the modified current vectors are rotated back into the stator frame and fed to the motor model. The resultant behavior is displayed as a graph which shows the results of the modified speed, load, torque, or position motor parameters that were entered at the start of the simulation.

GAMANA VT can also be used to display motor data acquired via GAMANA GMCDS.

GAMANA GMCDS

The second phase of the GAMANA development tool kit is a Computer Aided Design CAD and development package for motion control. This consists of two plug-in boards for PC compatibles with a hardware architecture consisting of the Analog Devices ADSP-21XX series DSP and AD2S100 vector coprocessors as the computing core (see Figure 19.16). With GAMANA-GMCDS an engineer can design and benchmark control schemes in real-time on a simulated motor configured to duplicate the motor being considered. Once satisfied with the stability and performance of the control algorithms, the designer can connect an inverter and motor to verify the results of the simulation. Not only does this approach drastically shorten the design cycle, it allows the designer to verify the system software/hardware and motor performance before committing to the manufacturing stage.

CHIPSETS/ALGORITHMS

The third phase of the Vector Control process is implementation of the control system designed and tested on the GAMANA-GMCDS. Once satisfied with system performance, design is simply a matter of duplicating the DSP/Vector coprocessor hardware. The Vector Control algorithms needed to run the hardware will be provided by Analog Devices.

In purely DSP based Vector Control systems, performance limitations occur because sampling times and resolution are limited by the complexity of the algorithms required to perform the coordinate transformation. In this control architecture, vector ac processors (AD2S100s) perform the coordinate transformation from the rotating to stationary reference frame allowing the DSP to operate entirely in the slower rotor reference frame. This permits a low-end fixed-point DSP controller to work with torque current loop execution times under 75 microseconds. By off-loading application specific operations to the AD2S100, the subsequent cost effective architecture provides the capability for expansion via new software algorithms or enhanced user interfaces.

The higher Pulse Width Modulation frequencies that can be accommodated by power devices such as IGBT's will mean even faster sampling times may be necessary to maintain control in a flux reference frame. The vector coprocessors are extremely fast computing the complete d-q transformation in under 3 microseconds. The sampling period is extended by approximately ×4 because all currents and fluxes are rotating at the slip frequency. Torque response does not have any limiting time constants under this type of control and therefore torque response is almost instantaneous.

APPLICATIONS

Vector Control promises to bring a new level of sophistication to industrial motor control as well as to consumer applications where precision motor control was previously thought to be too expensive or too difficult to implement.

Although added performance is a strong inducement, the energy savings that result from the increased efficiency afforded by Vector Control will most likely be the driving force behind replacement or modification in many current installations. The energy saved by converting to a flux Vector Control depends on the application but will be greatest in applications where induction motors are operated under less than full load conditions such as compressors and HVAC fans.

A 1989 U.S. Department of Commerce report on energy consumption states that electric motors use more than half of all electricity generated worldwide.

The report continues that a 1% increase in efficiency for motors of 1 HP or greater in the U.S. would equal the output of a 1 M Watt generating plant. Considering that a typical industrial motor consumes 10 to 20 times its acquisition cost in electricity per year the payback for switching to Vector Control is obvious financially as well as ecologically.

Another area of research where there is great interest in Vector Control is electric vehicles (EVs). Because of their inherent dependability and low-cost, ac induction motors are ideal for EVs. However, the lack of inexpensive control hardware/software capable of operating under the wide range of conditions required has prevented their use. The availability of design tools and low-cost silicon will make Vector Controlled ac induction motors the preferred choice in future EV design.

ADVANTAGES OF VECTOR CONTROL FOR AC INDUCTION MOTORS

- Energy Savings -- Especially Compressors and HVAC Fans
- Enhanced Performance
- Ideal for Electric Vehicles
- Expands Use of AC Induction Motors in Industrial Drives

Figure 19.19

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