

***Digital Signal Processing Solution
for
AC Induction Motor***

**Application Note
BPRA043**

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Abstract

This document presents a solution to control an AC induction motor using the TMS320C24x. This new family of DSP controllers enables cost-effective design of intelligent controllers for brushless motors which can yield enhanced operation, fewer system components, lower system cost and increased efficiency. This method presented is the Field Orientated Control (F.O.C.). The algorithm maintains efficiency in a wide range of speeds and takes into consideration torque changes with transient phases by processing a dynamic model of the motor. Among the solutions proposed are ways to suppress phase current sensors and use an observer for speed sensorless control.

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1. Introduction

The Motor Control industry is a strong aggressive sector. Each industry to remain competitive, must reduce costs but also has to answer to power consumption reduction and EMI radiation reduction issues imposed by governments and power plant lobbies. The results of these constraining factors are the need of enhanced algorithms. DSP technology allows to achieve both, a high level of performance as well as a system cost reduction.

Texas Instruments launches a new DSP, referenced TMS320C240, specifically designed for the Digital Motor Control segment. This device combining a 16 bit fixed-point DSP core with microcontroller peripherals in a single chip solution is part of a new generation of DSPs called the DSP controllers.

2. The DSP in Motor Control

2.1 Motor Control Trend

Market analysis shows that most of all industrial motor applications use AC induction motors. The reasons for this include high robustness, reliability, low price and high efficiency (up to 80%). However, the use of induction motors also has its disadvantages, these lie mostly in its difficult controllability, due to its complex mathematical model, its non linear behaviour during saturation effect and the electrical parameter oscillation which depends on the physical influence of the temperature.

Traditionally motor control was designed with analog components, they are easy to design and can be implemented with relatively inexpensive components. However, there are several drawbacks with analog systems. Aging and temperature can bring about component variation causing the system to need regular adjustment, as the parts count increase the reliability of the system decreases. Analog components raise tolerance issues and upgrades are difficult as the design is hardwired.

Digital systems offer improvements over analog designs. Drift is eliminated since most functions are performed digitally, upgrades can easily be made in software and part count is also reduced since digital systems can handle several functions on chip.

Digital Signal Processors go on further to provide high speed, high resolution and sensorless algorithms in order to reduce system costs. Providing a more precise control to achieve better consumption or radiation performances often means performing more calculations, the use of some 1-cycle multiplication & addition instructions included in a DSP speeds-up calculations.

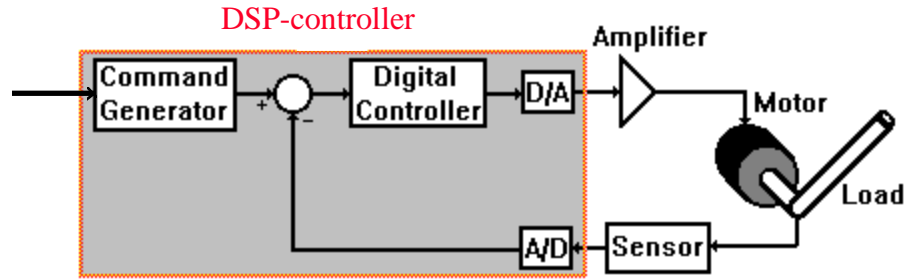
Generally fixed point DSPs are preferred for motor control for two reasons. Firstly, fixed point DSPs cost much less than the floating point DSPs. Secondly, for most application a dynamic range of 16 bits is enough. If and when needed, the dynamic range can be increased in a fixed-point processor by doing floating-point calculations in software.

2.2 Benefits of the DSP Controllers

The performances of an AC induction motor are strongly dependent on its control. DSP controllers enable enhanced real time algorithms as well as sensorless control. The combination of both allows to reduce the number of components and to optimize the design of silicon, to achieve a system cost reduction.

A powerful processor such as a DSP controller does the following:

- favours system cost reduction by an efficient control in all speed range implying right dimensioning of power device circuits
- performs high level algorithms due to reduced torque ripple, resulting in lower vibration and longer life time
- enables a reduction of harmonics using enhanced algorithms, to meet easier requirements and to reduce filters cost
- removes speed or position sensors by the implementation of sensorless algorithms
- decreases the number of look-up tables which reduces the amount of memory required
- real-time generation of smooth near-optimal reference profiles and move trajectories, resulting in better-performing
- controls power switching inverters and generates high-resolution PWM outputs
- provides single chip control system



Control System Using a DSP with Additional Features: The DSP Controller

For advanced controls, DSPs controllers may also performs the following:

- enables control of multi-variable and complex systems using modern intelligent methods such as neural networks and fuzzy logic.
- performs adaptive control. DSPs have the speed capabilities to concurrently monitor the system and control it. A dynamic control algorithm adapts itself in real time to variations in system behaviour.
- provides diagnostic monitoring with FFT of spectrum analysis. By observing the frequency spectrum of mechanical vibrations, failure modes can be predicted in early stages.
- produces sharp-cut-off notch filters that eliminate narrow-band mechanical resonance. Notch filters remove energy that would otherwise excite resonant modes and possibly make the system unstable.

2.3 A Large Range of Applications

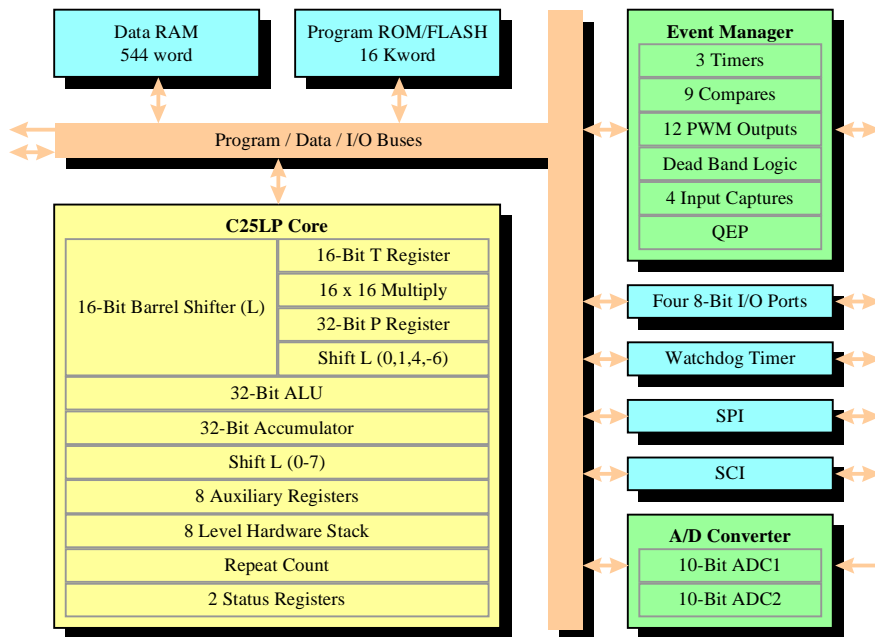
The target applications for a fixed point DSP controller having the necessary features are where the above mentioned advantages meet the customer's needs. Typical end equipment applications with an advanced control are:

- Appliances (washers, blowers, compressors)
- HVAC (heating, ventilation and air conditioning)
- Industrial servo drives (Motion control, Power supply inverters, Robotics)
- Automotive control (electric vehicles).

3. The TMS320C24x Family

As the first DSP optimized for digital motor control, the C240 supports the power switching device commutation, command generation, control algorithm processing, data communications and system monitoring functions.

The TMS320C24x is a single chip solution, based on a 20 MIPS fixed point DSP core associated to several micro-controller peripherals such as Memory, Pulse Width Modulation (PWM) generator, Analog to Digital Converters (ADC), to provide Digital Motion and Motor Control applications.



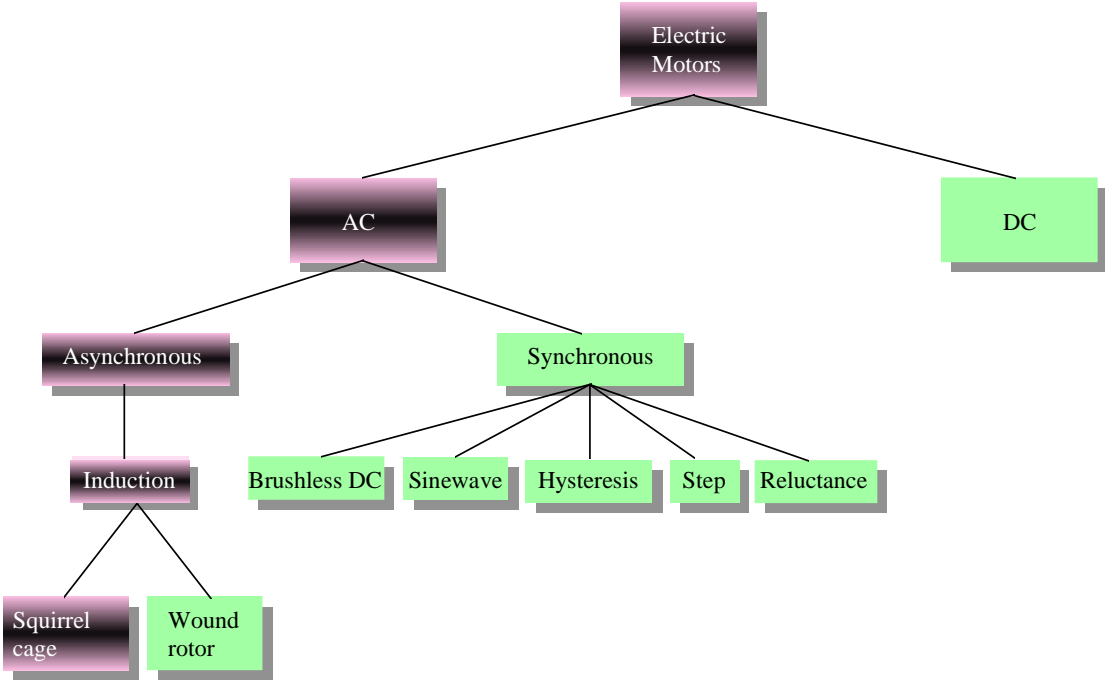
C240 Architecture

A dedicated Event Manager module generates output and acquires input signals with a minimum CPU load. Up to 4 input captures and 12 output PWM are available. Three time bases can be used to generate output signals which can be totally independent, synchronized or delayed between them. Each time base has 6 different modes and supports asymmetrical or symmetrical mode. Depending on the time base used the precision of outputs can be up to 50 ns. Three independent pairs of PWM can be complemented, using a programmable dead-band from 50 ns to 102 μ s. The three pairs of PWM can support Space Vector Modulation, a method to drive a three phases power converter.

The device includes a watchdog timer and a Real Time Interrupt (RTI) module. The watchdog module monitors software and hardware operations. A three pin Serial Communication Interface (SCI) supports communication between CPU and other asynchronous peripherals. A high speed synchronous Serial Peripheral Interface (SPI) is also available for communication between the CPU and external peripherals or another micro-controller. Up to 28 individually programmable I/O pins are available.

4. Control Strategy

4.1 Electric Motors



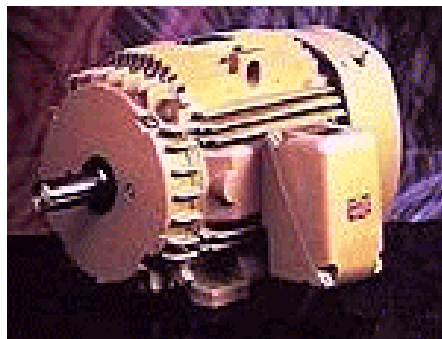
Classification of Electric Motors

Among all the existing motors on the market there are three ‘classical’ motors: the Direct Current with commutators (wound field) and two Alternative Current motors the synchronous and the asynchronous motors. These motors, when properly controlled, produce constant instantaneous torque (very little torque ripple) and operate from pure DC or AC sinewave supplies.

The motor studied in this note is part of the Alternative Current supplied motors. It is the squirrel cage asynchronous motor, named AC induction motor, as the rotor is not in phase, apart from the rotor pole number with the stator phase currents.

4.2 The AC Induction Motor

Asynchronous motors are based on induction. The least expensive and most widely spread induction motor is the squirrel cage motor. The wires along the rotor axis are connected by a metal ring at the ends resulting in a short circuit. There is no current supply needed from outside the rotor to create a magnetic field in the rotor. This is the reason why this motor is so robust and inexpensive. The stator phases create a magnetic field in the air gap rotating at the speed of the stator frequency (ω_e). The changing field induces a current in the cage wires which then results in the formation of a second magnetic field around the rotor wires. As a consequence of the forces created by these two fields, the rotor starts rotating in the direction of the stator field but at a slower speed (ω_r). If the rotor revolved at the same frequency as the stator then the rotor field would be in phase with the stator field and no induction would be possible. The difference between the stator and rotor frequency is called slip frequency ($\omega_{\text{slip}} = \omega_e - \omega_r$).



An Asynchronous Motor

There are several ways to control an induction motor in torque, speed or position, they can be categorized into two groups: the scalar and the vector control.

4.3 The Scalar Control

Scalar control means that variables are controlled only in magnitude and the feedback and command signals are proportional to dc quantities. A scalar control method can only drive the stator frequency using a voltage or a current as a command.

Among the scalar method known to control an induction motor, one assumes that by varying the stator voltages in proportion with frequency, the torque is kept constant.

$$\frac{V}{V_0} = \frac{f}{f_0}$$

The speed-torque curves are obtained by simply shifting the reference curve (V_0, f_0) along the frequency axis, while maintaining its shape. This Voltage on Frequency method is based on steady-state characteristics of the motor and the assumption that the stator voltages and currents are sinusoidal. Applied to the majority of existing variable-speed AC drives by mean of an open-loop constant V/f voltage source converters, this standard control method has no inner current controller. The advantages of this control technique is its simplicity it is easy and fast to program and requires only few calculation capabilities.

The drawbacks are the very poor reaction time for load changes and the efficiency during these operation points. A speed controller that takes into consideration torque changes and avoid undesirable trips can barely be achieved with a V/f open-loop control. This method needs some characteristic plots to describe part of the control. One method to obtain these plots is to pre-calculate and store them in the memory which requires additional silicon costs. The other way is to use a powerful processor and calculate in real time all the characteristics.

4.4 The Vector Control

The vector control is referring not only to the magnitude but also to the phase of these variables. Matrix and vectors are used to represent the control quantities. This method takes into consideration not only successive steady-states but real mathematical equations that describe the motor itself, the control results obtained have a better dynamic for torque variations in a wider speed range. The space phasor theory is a method to handle the equations.

Though the induction motor have a very simple structure, its mathematical model is complex due to the coupling factor between a large number of variables and the non-linearities. The Field Oriented Control (FOC) offers a solution to circumvent the need to solve high order equations and achieve an efficient control with high dynamic.

$$m_M = \frac{2}{3} L_0 \Im \left[i_s (imre^{j\varphi})^* \right]$$

Since the rotor currents cannot be measured with cage motors, this current is replaced by an equivalent quantity described in a rotating system coordinates called d, q and following the rotor flux. The instantaneous flux angle ρ is calculated by the motor flux model. i_{sd} and i_{sq} , the stator current components in the d, q frame, are obtained directly from i_a , i_b and i_c , the fixed coordinate stator phase currents, with the Park transformation:

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} \cos \rho & \cos(\rho - 2\pi/3) & \cos(\rho + 2\pi/3) \\ -\sin \rho & -\sin(\rho - 2\pi/3) & -\sin(\rho + 2\pi/3) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Then the torque can be expressed as follow:

$$m_M = k i_{mr} i_{sq} \quad \text{with} \quad \begin{cases} k = \frac{2}{3} (1 - \sigma) L_s \\ i_{mr} = \frac{1}{L_m} \Psi_R \end{cases}$$

In steady-state conditions the stator current i_s defined in the above mentioned rotating system is considered constant as well as the magnetizing current i_{mr} representing the rotor flux and i_{sq} being equivalent to the motor torque. δ is the load angle that equals to zero when no load, i_{sd} is linked to i_{mr} with the following equation:

$$i_{sd} = i_{mr} + T_R \frac{d}{dt} i_{mr}$$

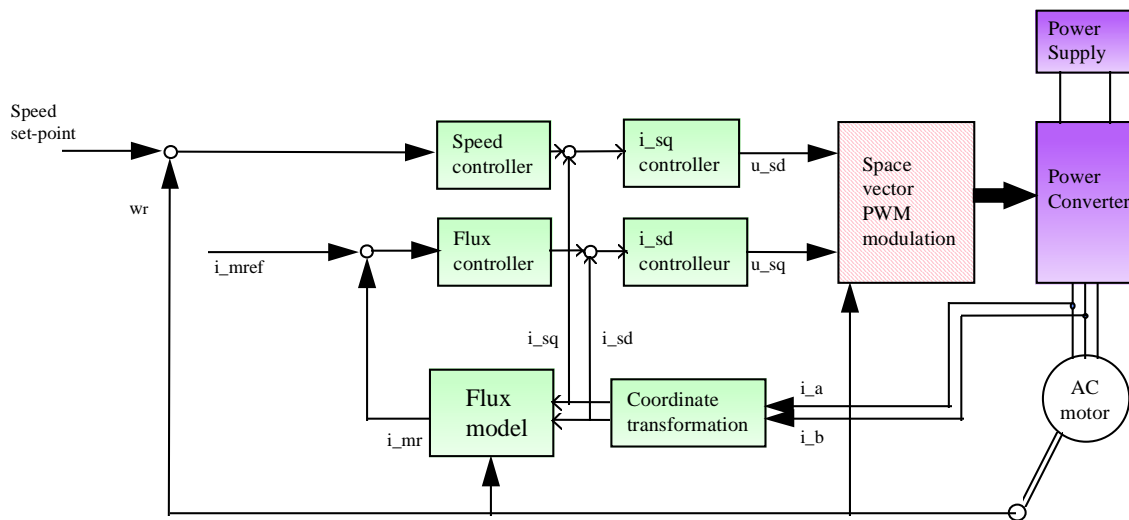
T_R is the rotor time constant.

This system together with the angle transformations change the induction motor into a machine very similar to a DC motor where i_{mr} corresponds to the DC motor main flux and i_{sq} to the armature current.

The field orientated control method achieves the best dynamic behaviour, whereby the lead and disturbance behaviour can be improved with shorter control cycle times. The field orientated control method is a de facto standard to control an

induction motor in adjustable speed drive applications with quickly changing load as well as reference speeds. Its advantage is that by transforming measurable stator variables into a system based on field coordinates the complexity of the system can be enormously reduced. As a result a relatively simple control method very similar to a separated excited DC motor can be applied.

The role of the DSP in such a system is to translate the stator variables (currents and angle) into a flux model as well as compare the values with the reference values and update the PI controllers. After the back transformation from field to stator coordinates the output voltage will be impressed to the machine with a symmetric, an asymmetric PWM whereby the pulse pattern is on-line computed by the DSP or a hardware generated space vector method. In some systems the position is measured by an encoder, this extra cost can be avoided implementing an observer model or in particular cases, a Kalman filter. These algorithms are complex and therefore require a fast processor, a fixed-point DSP is able to perform the above controls with short cycle times.



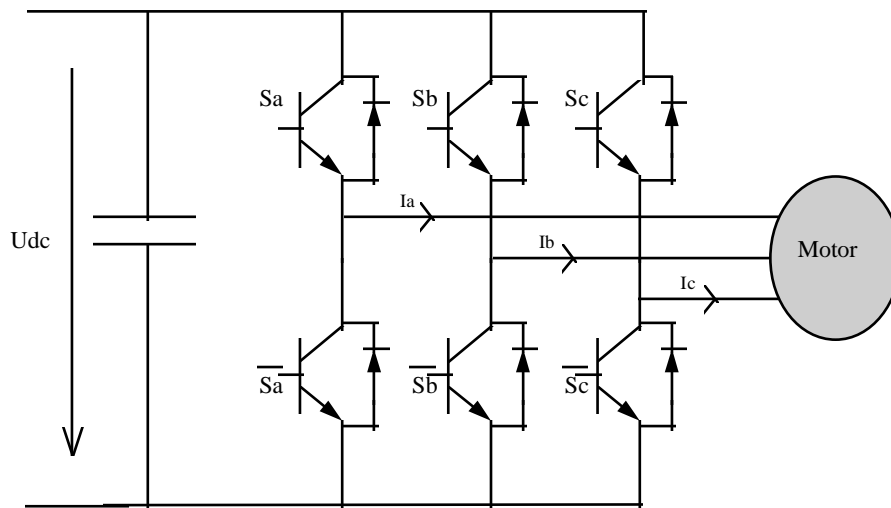
Block Diagram of a Three Phases Asynchronous Motor Driver Using a FOC Structure

5.2 Space Vector Modulation

Pulse Width Modulation technique is used to generate the required voltage or current to feed the motor or phase signals. This method is increasingly used for AC drives with the condition that the harmonic current is as small as possible and the

maximum output voltage is as large as possible. Generally, the PWM schemes generate the switching position patterns by comparing three-phase sinusoidal waveforms with a triangular carrier.

In recent years, the space vector theory demonstrated some improvement for both the output crest voltage and the harmonic copper loss. The maximum output voltage based on the space vector theory is $\frac{2}{\sqrt{3}} = 1.155$ times as large as the conventional sinusoidal modulation. It enables to feed the motor with a higher voltage than the easier sub-oscillation modulation method. This modulator allows to have a higher torque at high speeds, and a higher efficiency.



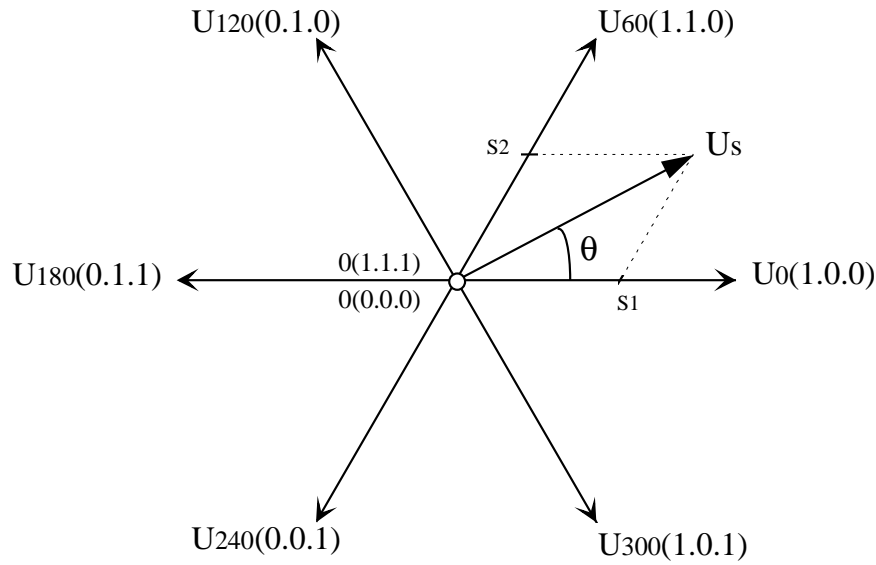
A Three Phase Inverter Fed by 3 PWM Signals S_a , S_b , S_c and Their Respective Complementary \bar{S}_a , \bar{S}_b , \bar{S}_c .

For a better understanding of the space vector process and to represent the switching state of the inverter we define a switching function S_a for phase A as follows: $S_a = 1$ when the upper transistor of phase A is on, and $S_a = 0$ when the lower transistor of phase A is on. Similar definitions can be made for phase B and C.

The signals \bar{S}_a , \bar{S}_b , \bar{S}_c , controlling the lower transistors, are the opposite of S_a , S_b , S_c with an addition of dead-bands.

Dead-band is the name given to the time difference between the commutations of the upper and lower transistor of one phase. The two transistors of each phase are then never conducting at the same time. The aim of the dead-band is to protect the power devices during commutation by avoiding conduction overlap and then high transient current.

In the following graph vectors, \bar{U}_{xxx} are represented with their corresponding switching states between brackets, $\bar{U}_{xxx} (S_a, S_b, S_c)$.



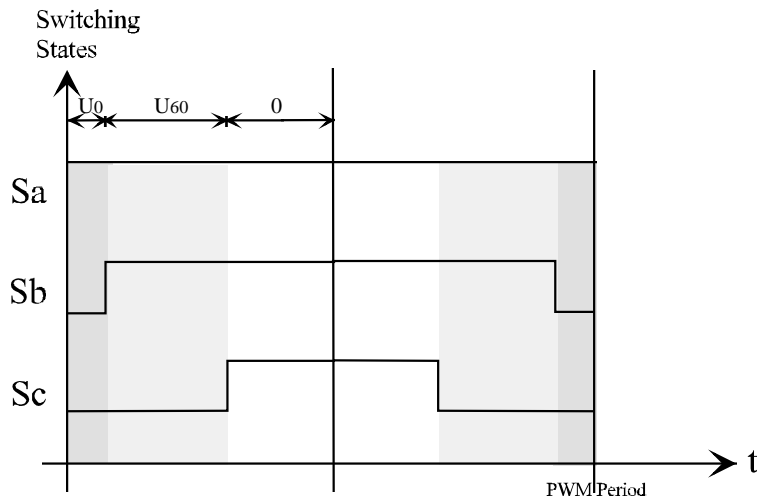
Space Vector Combination of \bar{i}

In the space vector theory the motor voltage vector is approximated by a combination of 8 switching patterns of the 6 power transistors. U_s is decomposed as follows:

$$\bar{U}_s = |\bar{U}_s| e^{j\theta} = s_1 \bar{U}_x + s_2 \bar{U}_y$$

where \bar{U}_x and \bar{U}_y are two consecutive vectors. The third vector $\bar{O}(0,0,0)$ or $\bar{O}(iii)$ is chosen in a way to minimize the number of switching commutations. This can be expressed with the formula:

$$T\bar{U}_s = s_1 \bar{U}_x + s_2 \bar{U}_y + (T - s_1 - s_2) \bar{O}$$



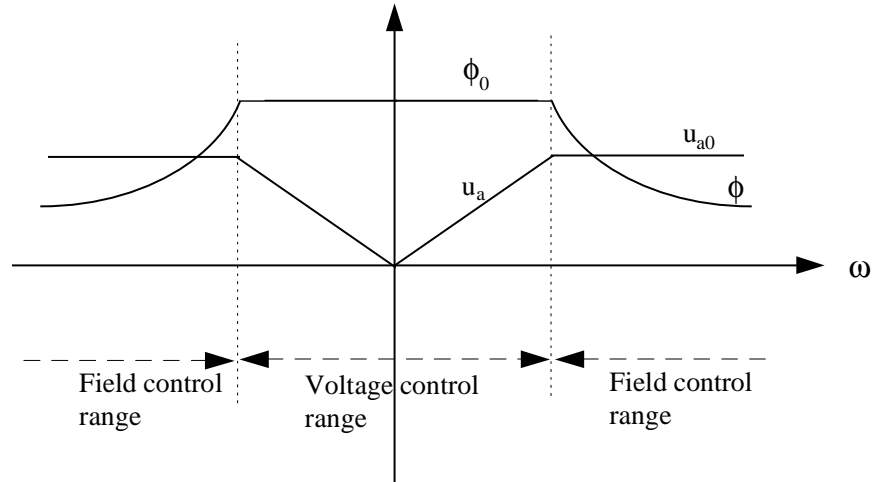
PWM Sstates with $0 \leq \theta \leq 60$ deg

In the above case which is a symmetrical PWM generation, the first half period of a PWM is built with the two PWM configurations U0 and U60 characterized by the switching states (0,0,1) and (1,1,0) and the vector O: (1,1,1). The second half of the period has the same sequence but inverted related to time. This PWM scheme describe a vector U_s with an angle θ as $0 \leq \theta \leq 60$ deg .

The events manager of the TMS320C240 has a built-in hardware to greatly simplify the generation of symmetric space vector PWM waveforms. The user has only to feed the corresponding registers with the above mentioned combination, the two adjacent basic vector (in our example U0 and U60) and the rotation direction. The output control signal update is instantaneous.

5.3 Field Weakening of the Motor at High Speeds with Closed Loop Scheme

In order to achieve high speeds, the stator current frequency is increased. The stator voltage is directly proportional to the motor flux and the angular speed. In normal condition the motor flux is kept constant. A maximum stator speed is reached with the limit output voltage of the power converter. To reach a higher speed the flux is reduced as an invert of the angular speed in order to keep the stator voltage constant and equal to its maximum.



Control Range of an Induction Motor in Steady State

Practically if we consider the stator current in the d,q rotating reference frame and its relationship with the α,β stationary reference frame, below the speed where the maximum output voltage is reached, the best choice is $\delta=\pm\pi/2$ and $i_{sd}=0$. The effect of the field weakening can be achieved by advancing the current vector beyond $\delta=\pi/2$, that means introducing a current component in the negative d-axis. As a consequence i_{sq} and then the torque are reduced in order not to exceed the maximum output current i_{s_max} :

$$i_s = \sqrt{i_{sd}^2 + i_{sq}^2} \leq i_{s_max}$$

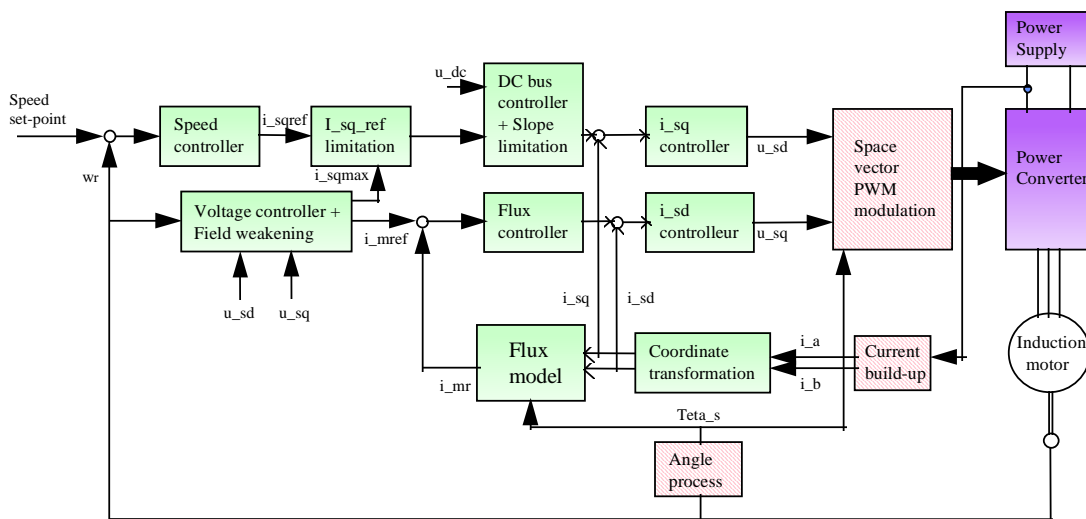
Two schemes are possible to implement a field weakening operation. The simplest is the standard open loop control for the d axis current reference. Despite the relative simplicity of realization, it has the following drawbacks:

- The reference current equation must be set in the worst condition of operation, it corresponds to the lower line voltage. It gives a low utilization of the inverter with higher voltages.
- High speed reliability: to guarantee the correct operation of the control at high speeds it would have been necessary to reduce further the voltage capability of the inverter.
- The reference current equation depends on the motor electrical characteristics, and it's also necessary to consider the characteristics dispersion in its determination.

A closed loop control avoids these negative effects. It consists in feeding back a proportional integral (PI) regulator with the motor d and q axis voltages applied to the motor and calculate a new reference for the magnetizing current. This diagram allows us to exploit the full voltage capability of the inverter, independently from the line voltage and the motor characteristics.

5.4 Maximum DC Bus Voltage of the Inverter Control

In case of a voltage supply variation the motor input phase voltages have to remain constant. The DC bus voltage of the inverter is used to feedback a control loop containing a proportional regulator. The solution allows to use the motor as a brake, without the need of a ballast resistance for power dissipation on the inverter. By means of the DC voltage control it is possible to use the motor to dissipate the braking energy. In this way, the control regulates the maximum possible braking torque in order to keep the maximum allowable DC bus voltage. This algorithm may need one A/D converter input to obtain the voltage, it is also possible to calculate the voltage from the flux and the speed signals to avoid an additional voltage sensor.



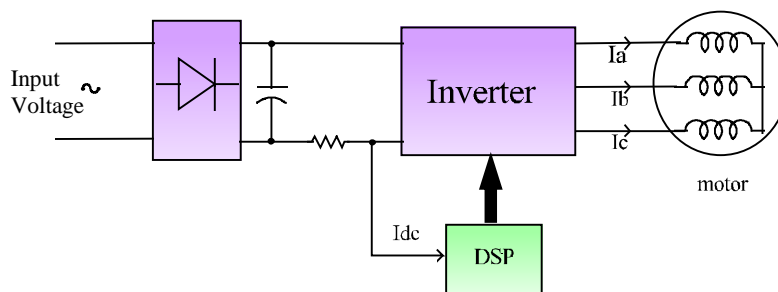
Block Diagram of a Three Phases Asynchronous Motor Driver Using a FOC Structure and Advanced Controls

6. Sensors Reduction

6.1 Current Remote Measurement and Calculation

In most of the inverter systems, information on the phase currents is required. The first method of obtaining those currents is to directly sense them but this requires, depending on the load schematic, at least two sensors applied directly on the motor phases. These types of sensors are usually expensive because they must be isolated and therefore sophisticated.

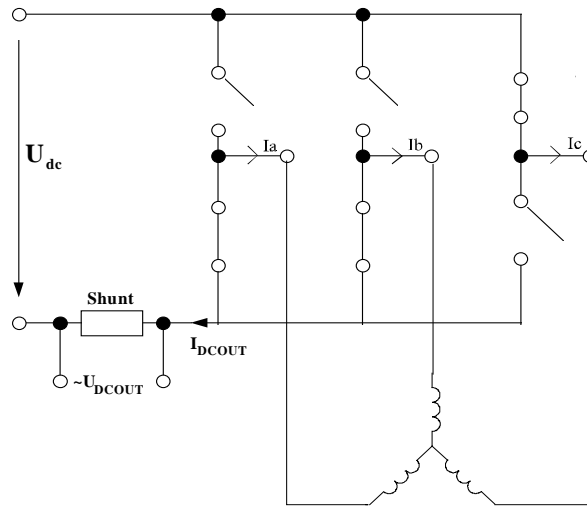
The other way is to sense only the line current, and estimate the 3 phase currents. This second method requires a simple cheap SHUNT as a sensor.



Current Estimator Synoptic

As we directly control the inverters switching state, it is possible to know the exact electrical route taken by the input current through the inverter to the phase. We can then directly link the phase currents to the line current. The information we measure to obtain the phase currents is a result of a real sense on the current and not the result of a simulation requiring a model of the output circuit. The measurement process is totally independent from the input and output hardware of the inverter.

The following figure gives an example of a switching state.



Inverter Supplying a Net of Three Star Windings.

Based on the above example describing the switching state $(S_a, S_b, S_c) = (0,0,1)$, one phase current i_c can be related to the dc line current. Therefore three phase currents can be measured, looking only at the dc line. If the Pulse Width Modulation period frequency is high enough, the phase current will only vary slightly over one or two PWM period. Hence, a measured phase current gives a reasonable approximation of the actual current. Based on this principle, Texas Instruments has developed an algorithm able to make the remote measurements work for current limit conditions¹.

To obtain the three phase currents the DSP needs only one A/D channel and few calculations whereas the classical method requires 2 or 3 A/D channels and use expensive sensors.

6.2 Using a Speed Sensor

The most common ways to sense motor speed on the shaft are the use of an incremental encoder and a tachogenerator.

In the case of an encoder, the TMS320C240 includes a module, the quadrature encoder pulse (Q.E.P.) which perfectly handles the situation and calculates the

¹ Patent pending

speed and the direction of the rotation using only two digital inputs and a 16 or 32 bit internal timer register.

There are several types of tachogenerators, some build a dc voltage proportional to the motor speed, others generate a number of pulses per rotor revolution.

In the first case, one of the 16 A/D converters channel of the TMS320C240 is connected to the tachogenerator output.

For an hall effect sensor, the pulses, enter a capture and a software driver allows the frequency measurement. The implemented software is called at fixed time intervals no longer than the minimum period of the measurable frequency . As there is only one signal, it is not possible to measure the motor speed sign. An artifice is inserted to add the sign to this speed measurement. The speed sign is memorized in a variable and only when the motor speed goes under a predetermined speed this variable is updated with the current sign. This also allows the user to execute fast speed reversing cycles of the motor.

6.3 A Kalman Observer

In many cases it is impossible to use sensors for velocity or position measurement, either because it is technically impossible, or it is too expensive. Among the observers capable of controlling an AC induction speed sensorless motor is the KALMAN observer. It has a good dynamic behavior, disturbance resistance, and it can work even a standstill. On a field orientated control method but its is very dependent on the environment it has been designed for the necessary control variables position, speed, and rotor flux will be estimated with a Kalman observer.

Implementing a Kalman observer is a very complex problem, and it requires the model of the AC motor to be calculated in real time. Also the observer equations must be calculated, which normally means many matrix multiplication and one matrix inversion. These requirements can be fulfilled by a processor with high calculation performance. The DSP is especially well suited for this purpose, because of its good calculation-performance/price ratio.

The Kalman filter provides a solution, that directly cares for the effects of the disturbance noises. The system is describable with the following equations.

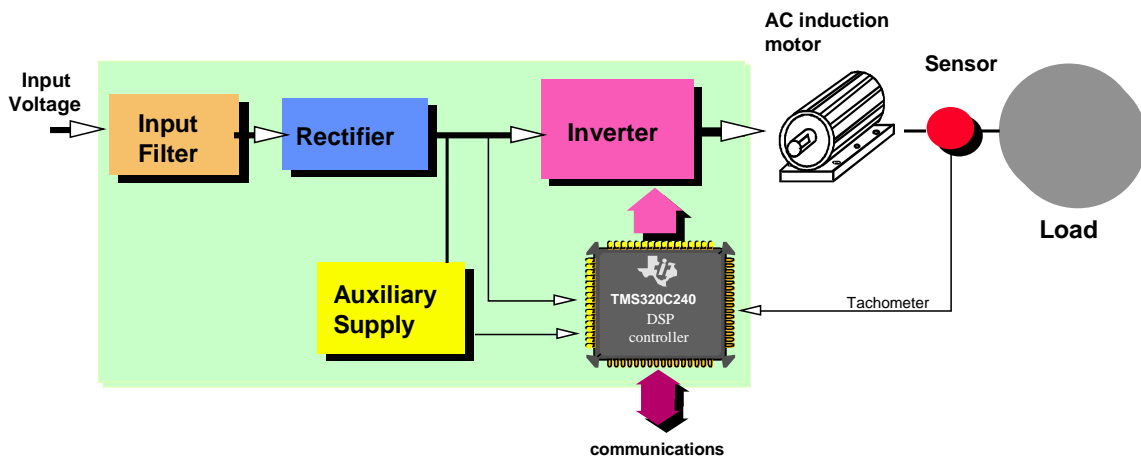
$$\begin{cases} \dot{x} = Ax + B + r \\ y = Cx + \rho \end{cases}$$

Where r and ρ are the system and the measurement noise. The following assumptions are made regarding the noise, it is stationary, white, uncorrelated and Gaussian, and its expectation is 0.

7. An Example Studied

Below is an example of the implementation and realization of an asynchronous motor controlled in speed and connected to an alternative voltage supplier. Few results are given.

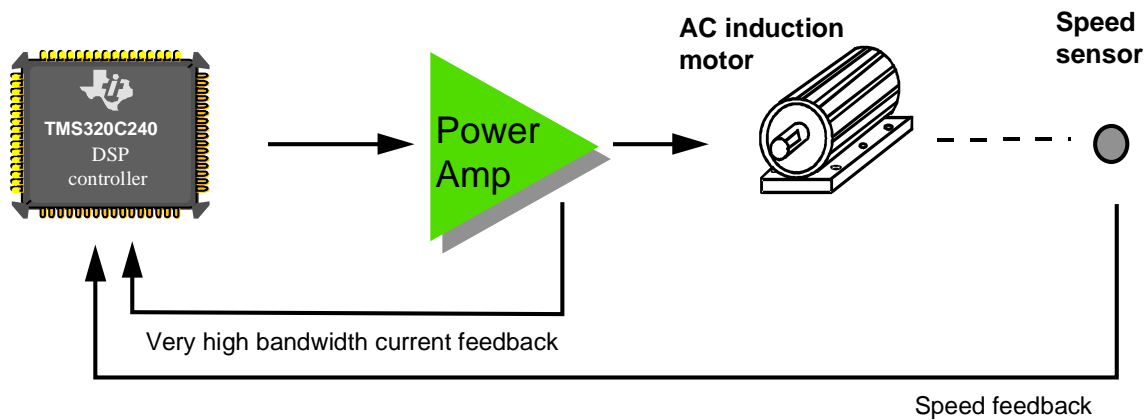
7.1 Power Electronics



Three Phases Asynchronous Motor Driver

The input filter block includes the hardware protections, EMI filter and an optional power factor correction (PFC). The PFC may be active or passive, in the case of active it can be entirely handled by the DSP. To achieve a continuous voltage out of the alternative input signal, a single phase input bridge with tank capacitor is needed represented as the rectifier block. To generate the phase voltages with variable amplitude and frequency a 3 phase inverter is used, based on an IGBT technology. The system is controlled by the DSP TMS320C240. The inputs are, a tachogenerator to measure the speed, a resistor divider to sense the voltage bus (V_{BUS}), a resistor sensor on the line (I_{BUS}) to estimate the phase currents, and a temperature sensor. The controller uses a serial link to communicate. The auxiliary supply feeds the inverter driver and the logic circuitry.

7.2 The Control Strategy



System Schematic

The control uses a space-vector PWM modulator. The voltage controller implements a closed-loop scheme for the motor field-weakening at high speeds. The DC bus voltage controller with i_q limitation for the reference of the q-axis current enables the use of the motor as a brake, keeping the DC bus voltage under a maximum limit. The speed, flux and current controllers are all implemented using a standard PI regulator block, with double precision for integral part. The speed regulator has also a cutting frequency to avoid wind-up of the integral action. The flux model block uses the values for α & β axis currents and the current electrical speed of the rotor to calculate the angle of rotor flux and the value of the equivalent magnetizing current of the motor. The coordinate transformation block is standard and uses the rotor flux angle to transform the stator phase currents values in the d-q axis frame. A software protection against high temperature is also implemented. To reduce the number of sensors, the phase currents are calculated from the DC bus current with the current estimator block.

7.3 Software Implementation

The proposed control scheme is implemented on the TMS320C240. All the control routines are implemented using assembler language with fixed precision numerical representation.

The control algorithm is synchronised by the DSP internal Timer that generates interrupts.

The speed is controlled once among several control cycles and uses a hall effect tachogenerator.

Phase current remote measurements need sampling of the inverter DC current during the 16 kHz PWM period. The sampling time varies as a function of the actual PWM pattern. This is obtained driving the A/D conversion through an other interrupt (Compare Register interrupt) and the result is received through an end-of-conversion interrupt.

7.4 Results

The memory space needed is less than 3K word of ROM, and 544 word of RAM, and use less than 50% (10 MIPS) of the DSP power. The complete control loop is calculated in less than 35 μ s.

The speed range is from 0 to 12,000 rpm with a worst speed error under 1%.

The efficiency of the power electronic stage is in the range of 95%, and the total efficiency of the system is > 85%.

8. Conclusion

This paper presents a new controller architecture the DSP controller. The DSP-Controller TMS320C240 combines the performance of a DSP architecture with the optimized peripherals of a Microcontroller in a single chip solutions for the control of an induction motor. With the DSP controller an intelligent control approach is possible to reduce the overall system costs and to improve the reliability of the drive system.

9. References

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