Digital Signal Processing Solutions for the Switched Reluctance Motor

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ABSTRACT

This document deals with solutions to control a switched reluctance motor using the TMS320C24x. This new DSP family enables cost-effective design of intelligent controllers for switched reluctance motors. Two speed control algorithms are presented, they allow the Switched Reluctance motor drive to reach high efficiency, smooth operation, very good dynamic behavior, very high speed and low acoustical noise. This article also presents some mechanical position sensorless algorithms in order to reduce the overall system cost and to enhance the drive reliability. All these solutions use only TMS320C24x resources, thus providing a single chip cost efficient control structure.

1. Introduction

The general trend in Motor Control is to design low cost, highly energy efficient and high time reliability control systems. Therefore low production cost and very efficient motors such as Switched Reluctance motors are naturally involved in these designs. It also creates a need to implement more effective and efficient control strategies in order to increase the overall electrical input and system power efficiencies by decreasing the size and cost of driver components.

The high performance TMS320C240 DSP, in combination with a numerical advanced control algorithm, completely answers all these requirements. In keeping with these ideas, the switched reluctance motor becomes the natural choice for integration into electrical drives, since it is the cheapest form of electromechanical energy converters.

2. The DSP in Motor Control

2.1 Switched Reluctance Motor Control Trend

In the context of electrical drives the Switched Reluctance motor shows significant advantages. Because of its simple mechanical construction (and thus its low production cost), its efficiency, its torque/speed characteristic and its very low requirement for maintenance, the Switched Reluctance motor is set to become one of the most widely used low-cost electromechanical energy converters.

Traditionally, SR motor control was designed with relative inexpensive analog components. Several inconveniences appeared with analog systems. The first drawback is inherent to any analog component: aging and temperature variations cause the system to need regular adjustment, furthermore the reliability of the system decreases as the component count increases and, finally, any system upgrade would be difficult as the design is hardwired.

The second drawback resides in the limitations in the effectiveness of analog control structures (no system adaptive control algorithms or time constrained control structures).

These problems are solved by making the control structure digital. In fact, digital systems offer many improvements over analog design. 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 by integrating them into an one chip solution.

The TMS320C240 Digital Signal Processor goes still further by providing 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.

2.2 Benefits of the DSP Controllers

The performances of a Switched Reluctance motor are strongly dependent on its control. DSP controllers enable enhanced real time algorithms as well as sensorless control. The combination of both makes it possible 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:

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

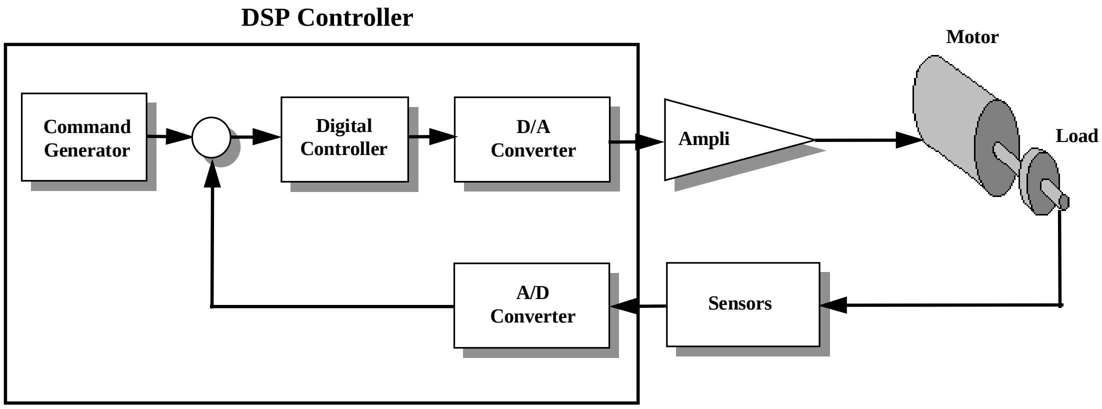

Figure 1: Control System using a DSP Controller

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

- enable control of multi-variable and complex systems using modern intelligent methods such as neural networks and fuzzy logic;
- perform 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;
- provide diagnostic monitoring. Diagnostic monitoring is achieved with FFT of spectrum analysis. By observing the frequency spectrum of mechanical vibrations, failure modes can be predicted in early stages;
- produce 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 having the necessary features may be anywhere where the above mentioned advantages meet the customer's needs. Typical end equipment applications with an advanced control are:

- automotive control (electronic power steering, anti-lock brakes);
- HVAC (heating, ventilation and air conditioning);
- blowers and compressors;
- factory automation;
- major appliances (direct-drive horizontal-axis clothes washers);
- office products (printers, copiers, tape drivers).

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 with several micro-controller peripherals such as Memory, Pulse Width Modulation (PWM) generator and Analog to Digital Converters (ADC) to provide Digital Motion and Motor Control applications.

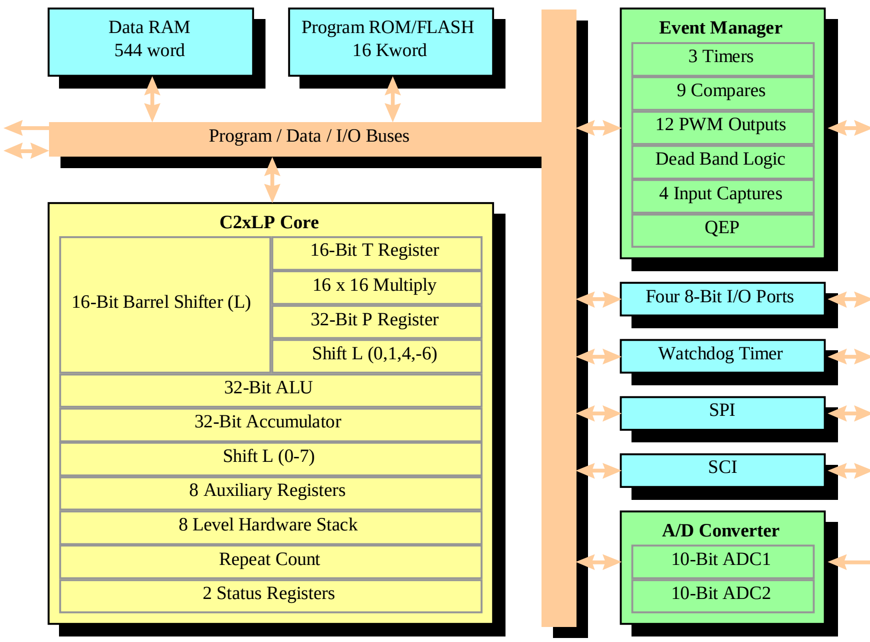

Figure 2: C240 Architecture

A dedicated Event Manager module generates output signals 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 totally independently, either synchronized or delayed with respect to each other. Each time base has 6 different modes and support either, asymmetrical or symmetrical modes with equal ease. Depending on the time base used, the precision of outputs can be up to 50ns. Three independent pairs of PWM can be complemented, and use a programmable dead-band from 50ns to 102 µs. The three pairs of PWM can support Space Vector Modulation to drive a three phase 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 communications between the CPU and other asynchronous peripherals.

A high speed synchronous Serial Peripheral Interface (SPI) is also available for communications between the CPU and external peripherals or another micro-controller. Up to 28 individually programmable I/O pins are available.

For more details, refer to the C24x user’s guide.

4. Control Strategies

4.1 The Switched Reluctance Motor

The Switched Reluctance Motors show promise as potentially low cost electromechanical energy conversion devices because of their simple mechanical construction. The advantages of a Switched Reluctance Motor are the production cost, efficiency and the torque/speed characteristics.

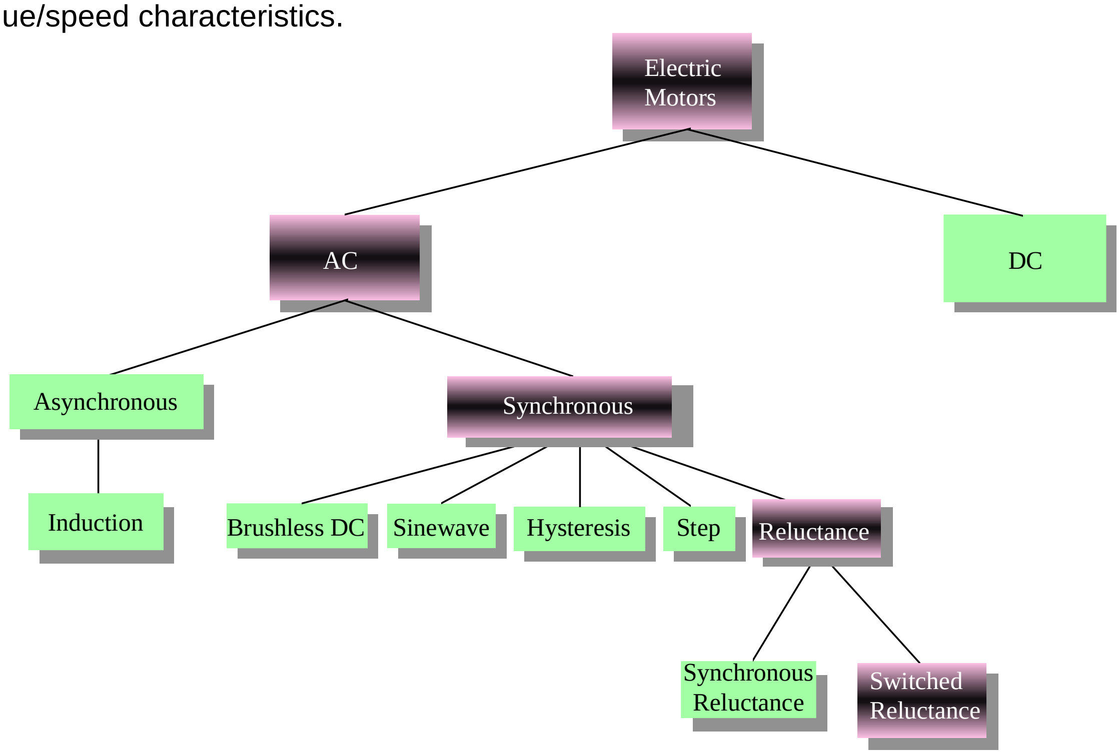

Figure 3: Classification of Electric Motors

The Switched Reluctance Motor is a singly-excited motor with salient poles on both the stator and the rotor. Only the stator carries windings. The rotor has neither windings nor magnets and is built up from a stack of steel laminations. One stator phase consists of two series- connected windings on diametrically opposite poles.

The SR motor is an electric motor in which torque is produced by the tendency of its moveable part to move to a position where the inductance of the excited winding is maximized. During motor operation, each phase is excited when its inductance is increasing, and unexcited when its inductance is decreasing.

The air gap being minimum at the aligned position (the position where a pair of rotor poles is exactly aligned with a stator pole), the magnetic reluctance of the flux flow is at its lowest; it will be highest at the unaligned position. Thus, when for a given phase the rotor is not aligned with the stator, the rotor will start to move to align with the excited stator pole.

An easy way to make the rotor turn is to sequentially switch the current from one phase to the next phase and to synchronize each phase's excitation as a function of the rotor position. The direction of rotation is independent of the direction of current flowing through the phase winding, it only depends on the sequence of the stator winding excitation.

The key to effective control of an SR motor lies in the ability to control the magnitude and the duration of the current flowing in the stator windings from the produced torque can be derived as follows:

$$T = \frac{\partial Wc}{\partial \theta}$$

with

$$Wc = \int_0^i \phi \, di$$

where Wc is called the co-energy, ϕ is the flux-linkage dependent on rotor position and on current, i is the current flowing in the stator windings, θ is the rotor position and T is the torque produced by the SR motor. The co-energy can be interpreted as follows:

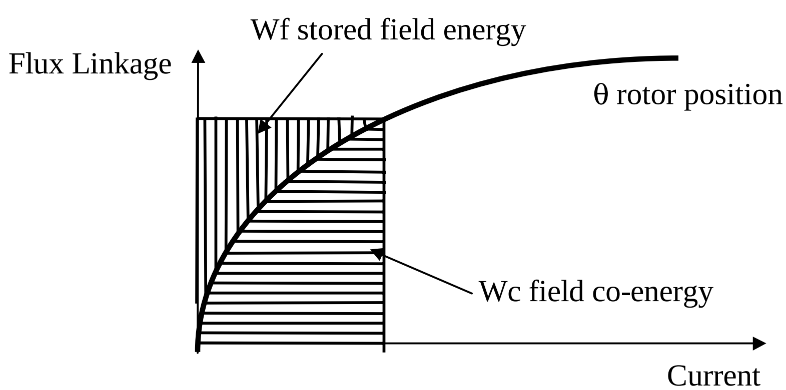

Figure 4: Interpretation of Stored Energy and Co-energy

There are several possible ways to control the SR motor in torque speed and position. Torque can be controlled by two methods: the current control method or the torque control method.

The shaft position information is useful for generating precise firing commands for the power converter, for the position feedback loop and for the velocity feedback, which can be derived from the position data.

The different SR motor designs are commonly referenced as the ratio between the number of stator poles and the number of rotor poles. Typically a 6/8 SR motor has six stator salient poles (hence it is a three phase motor) and eight rotor salient poles (four pole pairs).

4.2 The Current Control

In this first control method the magnitude of the current flowing into windings is controlled using a control loop with a current feedback. The current in a motor phase winding is directly measured with a current/voltage converter or a current sense resistor connected in series with the phase. The current is compared with a desired value of current, forming an error signal. The current error is compensated via a control law, such as a PID, and an appropriate control action is taken. The block diagram below shows that both current and position feedback are needed for controlling the SR motor. Position feedback is needed to synchronize the current flow, with respect to the rotor position, in order to generate the desired motoring torque. Position feedback is also needed to compute the rotor mechanical speed, which is compared with the desired value of speed.

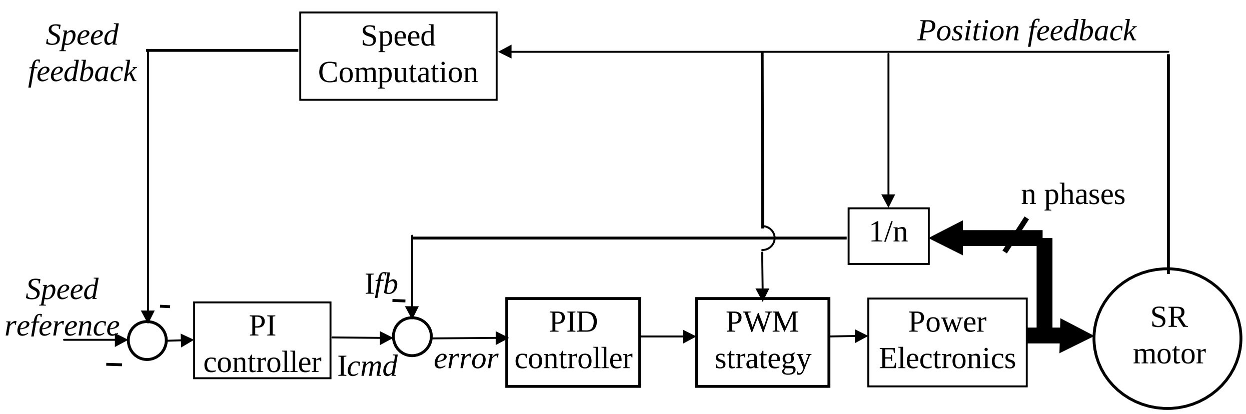

Figure 5: Speed and Current Control Loop for an SR Motor

SR motor control is often described in terms of “low-speed” and “high-speed” control strategies. Low-speed operation is typically characterized by the ability to arbitrarily control the current to any desired value. What is required is that the relationship,

$$\int_0^{\tau} \frac{di}{dt} dt > i_d$$

is satisfied, where id is the maximum desired motor current and τ is the amount of time available for getting the current out of the motor winding. τ is directly related to the speed of the motor. The expression to use for di/dt depends upon the chosen Pulse Width Modulation strategy and in which states the current driver can be operated.

As the motor's speed increases the amount of time τ decreases and so it becomes difficult to regulate the winding current to the desired value. Eventually, a speed is reached where the current can neither rise nor decay quickly enough in the winding to reach the desired level. Because of this, it is desirable to get current in and out of the motor's phase winding while the phase inductance is still relatively small. Two methods are available to solve the problem: phase winding switching or advancing the dwell angle (difference between the two firing angles). Adjusting the dwell angle, so that the phase commutation begins sooner and ends sooner, offers the advantage of getting the current into the winding while the inductance is low, and also of having a little more time to get the current out of the winding before the rotor reaches negative torque region. This principle is depicted in the following scheme.

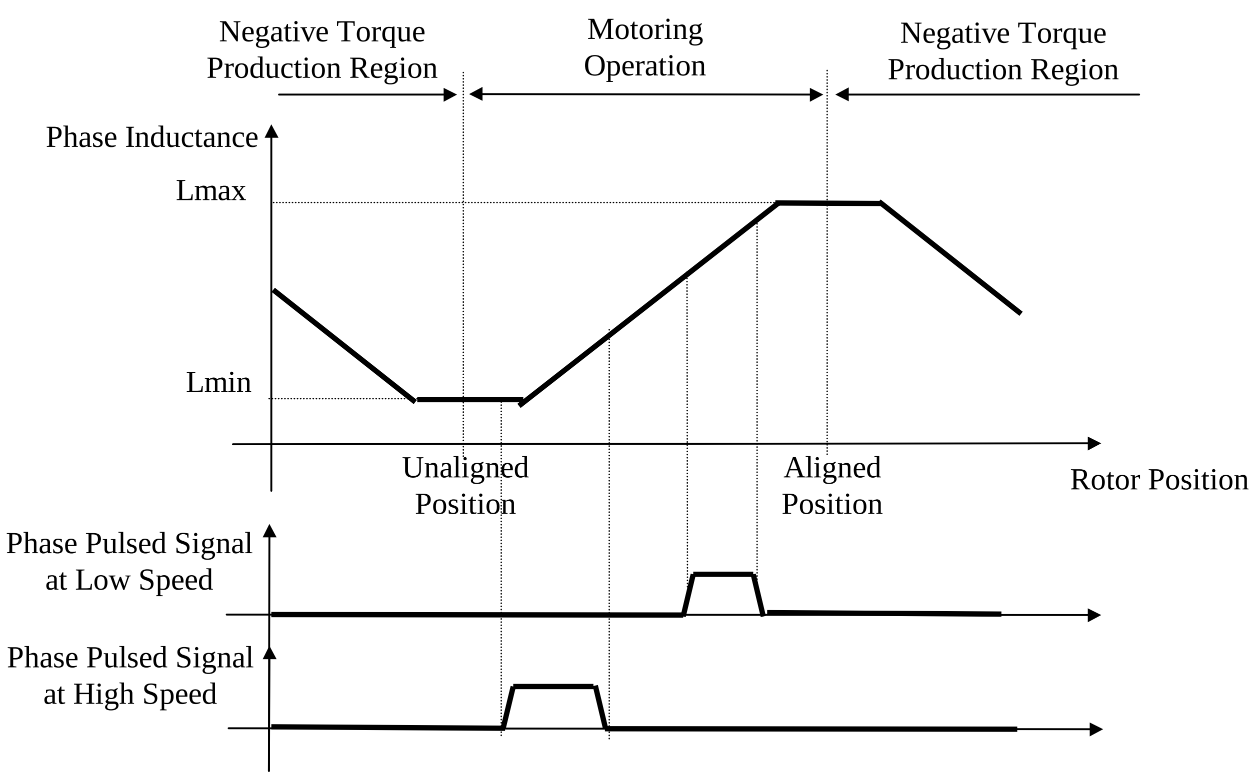

Figure 6: Advancing Dwell Angle Strategy according to the Motor Speed

If the rotor position is not precisely available, and when the motor construction permits, it is possible in high speed mode to switch from the whole phase winding to e half of it. By this means the current rise time constant is divided by two, allowing the desired winding current to be reached even in the short amount of time before phase's commutation.

The torque production and the winding current obtained in Low-speed operation thanks to this *current control* method are given below:

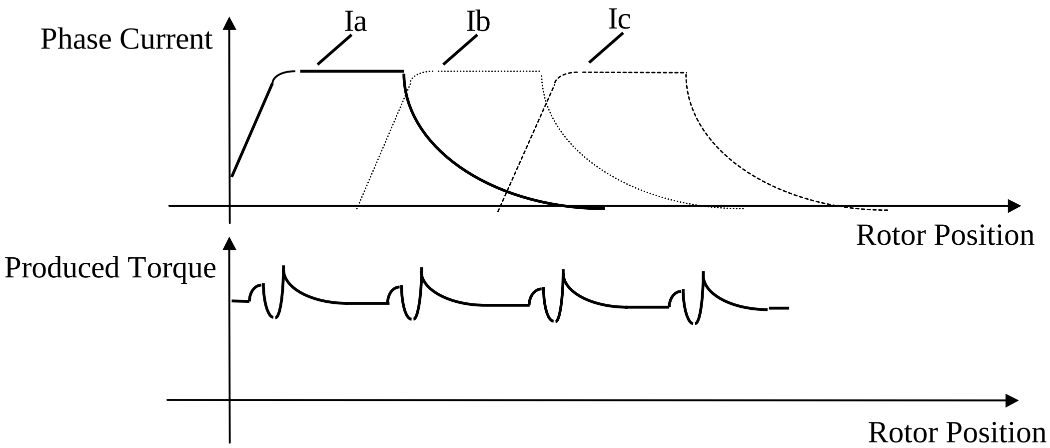

Figure 7: SR Motor Torque and Current Waveforms with the Current Control Method

Note that even if the phase current is maintained constant the torque produced is not smooth. The torque ripple is due not only to the control strategy and to the phase commutation but also to the non-linear relationship between torque and current.

4.3 The Torque Control

Although the above method of controlling the SR motor has many practical applications, a disadvantage exists. Controlling a constant value of current will result in torque ripple because of the non-linearity of the relationship between torque and current for a SR motor. Torque ripple is undesirable because it contributes to the problem of audible noise, it contributes to vibrations and it introduces torque disturbances which manifest as velocity errors.

A solution to the problem of torque ripple and torque constant non-linearity in SR motors is to profile the current such that torque is the controlled variable. Since torque cannot be controlled directly, due to the lack of adequate torque sensors, this can only be accomplished using *a priori* information about the motor's torque-current-angle characteristics. Additionally these characteristics must be known fairly accurately in order to achieve the best results. The torque control strategy is based on following a contour for each of the phases of the SR motor such that the sum of torque produced by each phase is constant and equals the desired torque. The desired total torque is calculated from the velocity loop, and this total torque is split into desired phase torque via shaping function. The control structure is depicted below.

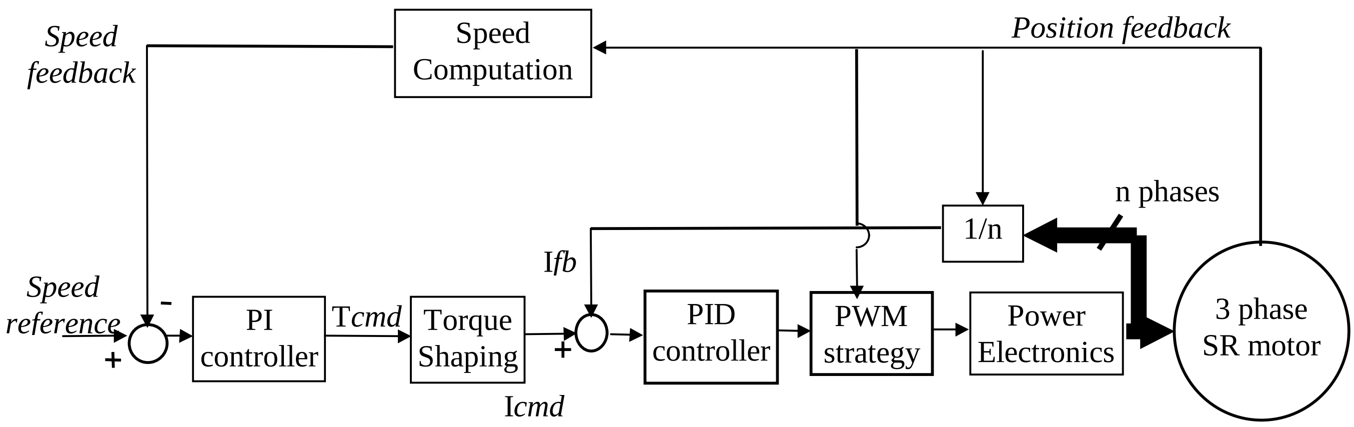

Figure 8: Speed and Torque Control Loop for an SR Motor

In "low-speed" mode and with a suitable PWM strategy it is possible with this torque control method to get much smoother torque and an improved current regulation as well as an improved control of the motor's velocity. The torque production and the winding current obtained in Low-speed operation thanks to this *torque control* method are given below:

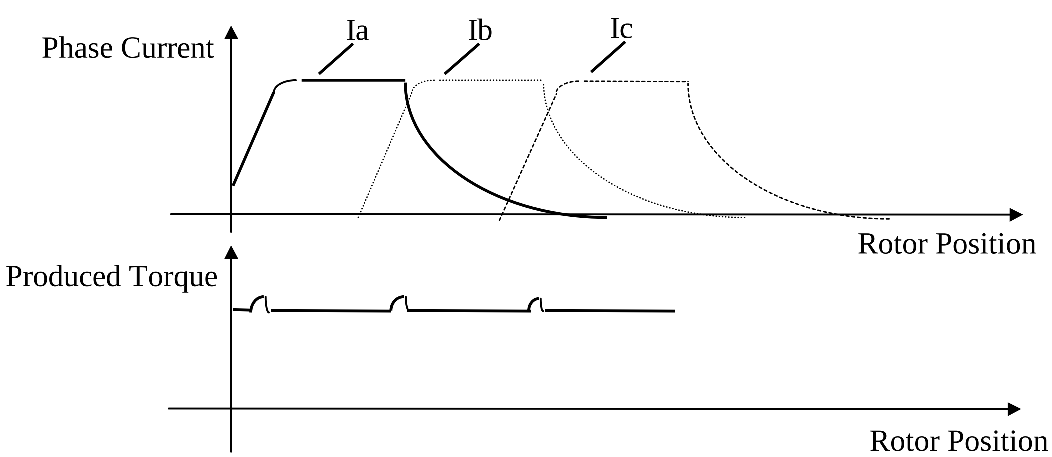

Figure 9: SR Motor Torque and Current Waveforms with the Torque Control Method

Some torque ripple will remain if the torque shaping functions do not fully address the torque non-linearity. Nevertheless, this control structure allows a much smoother torque production than with the constant winding current control. The torque control method is generally not useful for high-speed applications, however, because the torque ripple increases rapidly with degraded ability to arbitrarily regulate the motor current.

4.4 The PWM Strategies

The selection of Pulse Width Modulation strategy is an important issue in SR motor control because it dictates how the motor can be controlled. The PWM strategy is also directly related to the power driver topology. Assuming that each phase of the SR motor can be independently driven there are three PWM strategies.

- *The single pulse operation*
  The flux in the Switched Reluctance motor is not constant and so it must be established from zero every stroke. Each phase must be energized at the turn-on angle and switched off at the turn-off angle. The difference between the turn-off and the turn-on angle is called the dwell angle. In *single pulse operation* the power supply is kept switched on during the dwell angle and is switched off at the phase commutation angle. As there is no control of the current and as there is a sharp increase in the rate of change of current, this PWM strategy is used when the amount of time available to get the desired current is short. Typically, *single pulse operation* is used at high mechanical speed with respect to the turn-on angle determined as a function of speed.

- *The chopping voltage strategy*
  On the other hand, the *chopping voltage strategy* is useful for controlling the current at low speeds. This PWM strategy works with a fixed chopping frequency. Where, in the *single pulse operation,* the supply voltage was kept switched on during the dwell angle, the supply voltage in the *chopping voltage strategy* is chopped at a fixed frequency with a duty cycle depending on the current error. Thus both the current and the rate of change of current can be controlled.
  The *chopping voltage strategy* can be separated into two modes: the hard chopping and the soft chopping strategies. In the hard chopping strategy both phase transistors are driven by the same pulsed signal: the two transistors are switched on and switched off at the same time. The power electronics board is then easier to design and is relatively cheap as it handles only three pulsed signals.
  A disadvantage of the hard chopping operation is that it increases the current ripple by a large factor. The soft chopping strategy allows not only control of the current but a minimization of the current ripple as well. In this soft chopping mode the low side transistor is left on during the dwell angle and the high side transistor switches according to the pulsed signal. In this case, the power electronics board has to handle six PWM signals.

- *The chopping current strategy*
  The *chopping current strategy* is a Hysteresis type current regulator in which the power transistors are switched off and on according to whether the current is greater or less than a reference current. The error is used directly to control the states of the power transistors. The hysteresis controller is used to limit the phase current within a preset hysteresis band. As the supply voltage is fixed, the result is that the switching frequency varies as the current error varies. The current chopping operation is thus not a fixed chopping frequency PWM strategy. This PWM method is more commonly implemented in

drives where motor speed and load do not vary too much, so that the variation in switching frequency is small. Here again both hard and soft chopping schemes are possible.

This *chopping current strategy* allows a very precise current control – made possible because the tolerance band width is a design parameter, but acoustic and electromagnetic noise are difficult to filter because of the varying switching frequency.

4.5 What Defines the Control Fitted to the Application

The choice of the right control is a critical matter for a system design. If the control strategy is defined properly it provides a better motor performance, lower energy usage, quieter operation, greater reliability, fewer system components and a better dimensioning of the power elements.

Here are some helpful variables to describe the system characteristics:

- Motor type (e.g. 4 rotor poles 3 phase Switched Reluctance motor)
- Speed range in rpm
- Speed accuracy range including tolerance
- Sensors or sensorless
- Torque range in Nm
- Efficiency for low and high speed
- Control parameters (e.g. speed or position)
- Drive control type (e.g. PID speed closed loop, real time torque control)
- Operating point for low and high speed in amperes
- Maximum power in W
- Driver type e.g. 3 independent phase inverter)
- Maximal phase voltage
- PWM carrier frequency in Hz
- Motor driving strategy
- Protection devices

5. Power Electronics Topologies and Position Sensors

The inverter is an important part of a drive system. In this section, two standard inverters for SR-motors will be proposed and discussed. The proposed inverters are the Miller and the asymmetric half bridges. The complexity of each inverter type depends on the number of stator phases.

5.1 Asymmetric Half Bridge Inverter

The asymmetric half bridge inverter is the most used inverter. Each machine phase is connected to an asymmetric half bridge consisting of two power switches and two diodes. The figure below illustrates the circuit for a 6/8 SR-motor.

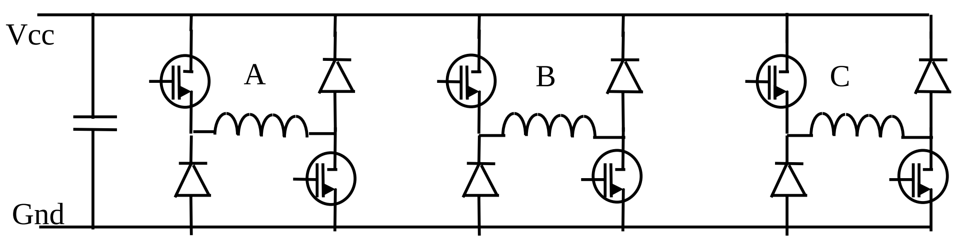

Figure 10: Three Phase SR Motor Asymmetric Half Bridge Inverter

The complete DC voltage can be used to energize and de-energize a machine phase in hard chopping mode. When a pair of switches are closed a phase will be energized from the positive DC voltage supply. When both switches are opened, the current commutates from the switches to the diodes. The voltage across the phase is now the negative DC voltage. These asymmetric half bridges permit soft switching operation as well, thus obtaining a zero voltage freewheeling state: the phase is energized from the positive DC voltage and de-energized at zero voltage. No restriction exists to prevent energizing two phases at the same time, thus achieving a higher torque.

The disadvantage of this inverter is the high number of power semiconductor elements as each half bridge needs two switches and two diodes.

5.2 Miller Inverter

The Miller inverter optimizes the number of power devices, using only one main power switch and one main diode for all phases together plus one more switch-diode pair per phase. The scheme of the Miller inverter shows Figure 11

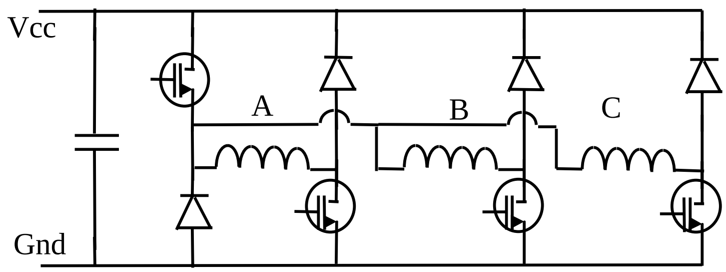

Figure 11: Three Phase SR Motor Miller Inverter

The features of the Miller inverter are:

- Hard and Soft chopping operation are possible.
- The number of power semiconductor devices is minimized. For a three phase SR-motor only four switches and four diodes are necessary. However the power specification of the main switch and main diode is much more higher than the phase switches or diodes and so is the cost.

The main disadvantage of the Miller inverter is that the phases can't be energized independently.

5.3 Shaft Position Sensors

The position information is used to generate precise firing commands for the power converter, ensuring drive stability and fast dynamic response. In servo applications, position feedback is also used in the position feedback loop. Velocity feedback can be derived from the position data, thus eliminating a separate velocity transducer for the speed control loop. Two common types of position sensors are used: the incremental sensors and Hall effect sensor.

- The *incremental sensors* use optically coded disks with either single track or quadrature resolution to produce a series of square wave pulses. Position is determined by counting the number of pulses from a known reference position. Quadrature encoders are direction sensitive and so do not produce false data due to any vibration when the shaft begins rotation. The Quadrature Encoder Pulse unit of the TMS320C24x DSP handles encoders output lines and can provide 1,2 or 4 times the encoder resolution. Speed information is available by counting the number of pulses within a fixed time period.
- The *Hall effect sensors* provide non-overlapping signals giving a 15° (6/8 Switched Reluctance motor configuration) or 30° (6/4 SR motor configuration) wide position range. The signals can be wired to the C24x DSP Input Capture pins, thus speed information is available by measuring the time interval between two Input Captures. The time interval is automatically stored by the TMS320C24x in a specific register at each Input Capture. From speed information it is numerically possible to get the precise position information needed for sharp firing commands.

6. Enhanced Motor Control

In the above classical Switched Reluctance Motor operation, torque is developed by the tendency of the magnetic circuit to adopt a configuration of minimum reluctance. The conduction angle for a phase is controlled and synchronized with rotor position, which is usually provided by a direct sensor. In the following chapters several methods are presented to improve the SR motor control quality and to reduce the overall drive cost by suppressing the position sensor.

6.1 Control Strategies Based on Sensing Inductance

As the direct rotor position sensors do not provide any information on the electrical characteristics of the machine, because position sensors are insensitive to inductance profile variation with rotor angle, and as the torque production is not dependent on the instantaneous rotor position but on the rate of change of co-energy with rotor position ($T = \frac{1}{2} i^2 \frac{dL}{d\theta}$) it appears that a desired instantaneous torque can be obtained from instantaneous inductance information rather than rotor position. The figure below depicts the use of inductance for direct commutation.

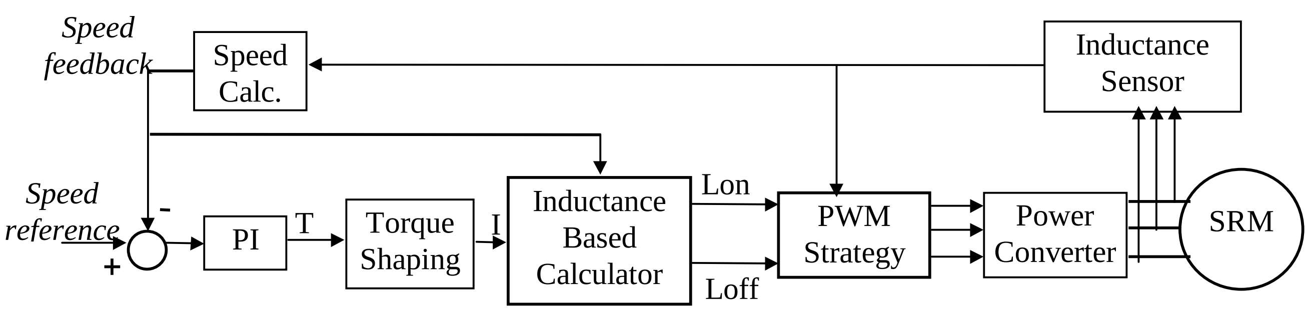

Figure 12: Use of Inductance for Direct Commutation

Since there is at least one idle phase in a SRM the inductance of that phase can be sensed for the purpose of commutation control. The phase inductance of the idle phase is estimated from the measurements of the motor terminal voltages and currents. The commutation instants of the active coil are expressed in terms of the phase inductance value of the idle phase: Lon and Loff. The commutator compares the instantaneous supplied coil inductance L with the values Lon and Loff and commutates the corresponding coil current.

6.2 Methods of Sensing Inductance

The fundamental types of inductance sensors are based on the following principles.

- *Phase pulsing*: a voltage pulse V is applied to an unenergized SRM phase by the drive converter for a period of time ΔT and the change in coil current ΔI is measured. The inductance is obtained from $L = V\frac{\Delta T}{\Delta I}$.
- *Frequency modulation*: inductance information is encoded in a frequency-modulated signal using a low voltage analog circuit.
- *Phase modulation*: a low alternating voltage is applied to an unenergized phase of the SRM and the phase angle difference between the input voltage and the resulting current is detected. The inductance is given by $L = \frac{R\tan\phi}{\omega}$ where ϕ is the phase angle.
- *Amplitude modulation*: a low level alternating voltage is applied to an unenergized phase and the amplitude of the resulting current is mapped to the coil inductance. The inductance can be expressed as $L = \frac{1}{\omega}\sqrt{\frac{V_m^2}{I_m^2} - R^2}$ where Vm is the voltage amplitude of the input alternating voltage, Im is the current amplitude and R is the resistance in the circuit.
- *Self voltage technique*: the inductance of the active phase is estimated in real time from measurements of the active phase current and phase flux. If I_0 is the current in the active phase linking a flux Ψ_0 then the phase inductance is given by $L_0 = \frac{\Psi_0}{I_0}$.

6.3 SRM Sensorless Operation Based on Flux/Current Characteristics

The rotor position can be calculated from the magnetic characteristics provided that ψ (or L) and I can be measured. Some flux/current based sensorless methods are given below.

- *The Waveform detection technique* relies on monitoring the phase current rise and fall times due to change in the incremental phase inductance which varies as a function of current and rotor position.
- *The State Observer* method based on terminal measurements of voltage and currents used as inputs of a digitized electromagnetic model of the SR machine.

7. An Example Studied

An example is given below of the implementation and realization of a Switched Reluctance motor controlled in speed and connected to an alternating supply voltage. Few results are given.

7.1 Power Electronics

Below is a complete drive system including the load that may be non-linear.

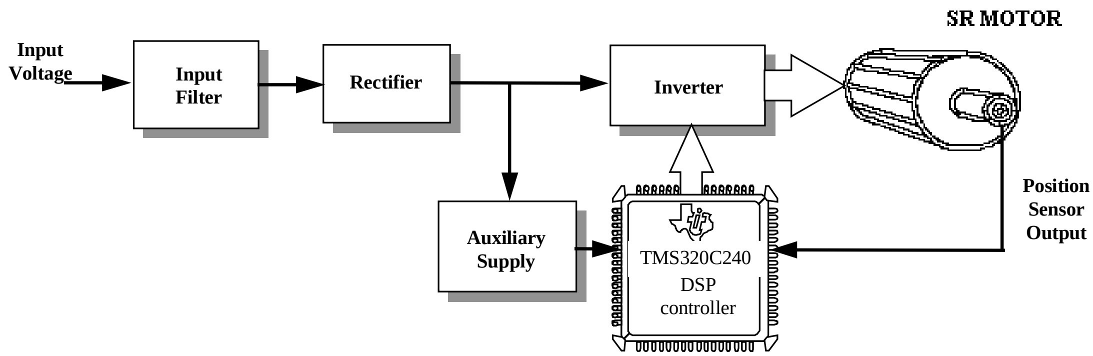

Figure 13: Three Phase Switched Reluctance Motor Driver

The input filter provides several functions, protection of the hardware (by fuse and voltage transient suppresser) and, to match the EMC standards, an EMI filter and a power factor correction (PFC) are implemented. The PFC may be active or passive; in the active case it is entirely handled by the DSP. This block is directly connected to the voltage supply.

To achieve a continuous voltage from the alternating 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 to supply the 3 SR motor phase signals to the motor, a 3-phase inverter is used, based on MOSFET technology.

The system is controlled by the TMS320C240 DSP. The inputs are three Hall effect sensors to detect the shaft position, and a resistor sensor on the line (I_{BUS}) to measure the phase currents. The controller uses a serial link to communicate. The auxiliary supply feeds the inverter driver and the logic circuitry.

7.2 The Control Strategy

The control uses a fixed frequency (set on 20kHz) symmetrical Pulse Width Modulation. The power electronics board is designed to support voltage chopping in hard-chopping mode. The motor design and the control electronics support the switching of the phase inductance value in order to achieve torque regulation in high speed operation. The chosen control strategy is current control with commutation angle information given by a position sensor. The speed and current controllers are all implemented using a standard PI regulator block. The braking action is done by delaying the phase winding firing angle. The rotor position is given by three Hall effect sensors wired on the Input Capture and the phase current information is given by three current/voltage transformers.

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 synchronized by the DSP PWM Timer that generates interrupts on its Period Signal. These interrupts start current conversion on the line determined in the Capture interrupts. The current conversion result is put into the current loop to generate new pulsed signals. The current loop frequency thus equals the PWM timer frequency, that is to say, 20 kHz. The Capture Interrupts synchronize the supplied phase with the rotor position. The speed is controlled once every few current control cycles and is computed from the time interval between two interrupts coming from the position sensor.

Phase current measurements need sampling of the inverter DC current during the 20 kHz PWM period. This is performed by driving the A/D conversion through another interrupt (PWM period interrupt) and the result is received through an end-of-conversion interrupt.

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