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Digital Signal Processing Solutions for Motor Control Using the TMS320F240 DSP-Controller

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ABSTRACT

This paper presents a Digital Signal Processing (DSP)solutions in digital motor control applications. Digital Signal Processing (DSP) technology is enabling cost effective and energy efficient control system design. The performance of a DSP architecture allows an intelligent approach to reduce the complete system costs of digital motion control applications using cheaper electrical motors, fewer sensors and smaller size of EMI filters.

INTRODUCTION

The requirements of electrical drive systems increase by the request of better performance, higher integration, easier to program and lower cost. To optimize the drive system several ways can be chosen. One is to stay with standard control concept and its sensors and try to reduce the sensor elements using sensorless control techniques, which normally requires more computation performance. Combining both ways leads normally to a system cost optimized solution.

Based on these trends, TM developed a new controller concept which integrates a Digital Signal Processor (DSP) core with intelligent peripherals to achieve a single chip solution also for sensorless controlled drive systems. The new controller family is named "DSP-Controller". The DSP-Controller TMS320F420 will be described in detail.

Out of the feature list of the DSP-Controllers an overview of sensorless control techniques will be given, whereby the target drives are based on 3 phase permanent magnet synchronous motors (PMSM) and 3 phase induction cage motors. For the induction cage motor a practical implementation will be presented. In the case of the induction motor, Kalman Observer is used to eliminate any speed and rotor position sensor. The main problems to implement a complex Kalman Observer on a 16Bit Fixed Point DSP core is included into scaling task. The practical realization and its results confirm that it is possible. Most of other publications are using Floating Point arithmetic in their implementation, which is not acceptable in mass production out of cost reasons. This paper commences with a brief overview of the different types of DSPs and their application fields followed by the introduction of the new DSP family, the DSP-Controller TMS320F420. Several practical motor applications and their implementation will be discussed.

METHODOLOGY

The Different DSP Architectures and their Digital Motor Control Target Applications

The DSP family is subdivided into three different types : the combination of an integration of a 32Bit RISC processor and several advanced DSPs like the TMS320C8x family, the

32Bit Floating Point Devices e.g. TMS320C3x and the 16Bit Fixed Point DSPs. Regarding the TMS3208x and its 2 BOBS (Billion Operation Per Second) the digital motor control application field is very small. One typical application is the control of magnet bearings, normally used in turbines to reduce the friction to a minimum. The application fields for 32 Floatinf Point DSPs are Computer Numerical Controlled (CNC) machines, high precision linear motors with a resolution down to a range of 100nm, used in the field of research and pre-development. The use of good high level language support like "C" and its efficient conversion is very much important in this applications. The 16 Fixed Point DSP can be used in all types of BLDC, PMSM, Switched Reluctance motors, as well squirrel cage induction motors. Main application are industrial power converters and white goods, with the aim to reduce the sensor elements, to increase the efficiency (the important green aspect), to reduce the noises as well as to decrease the system costs. The Fixed Point DSPs with its performance range of 6.5 to 100MPS are able to control a complete enhanced motor management system including a sensorless approach, power factor correction, security and service features, human machine interface, as well as the digital motor control itself.

Architecture of the DSP-Contoller TMS320F420

The DSP-Controller F240 in an integration of a digital signal processor core with the peripherals of a Microcontroller. The performance as well as the intelligent peripherals meet the requirements of an enhanced motor management system which is capable of executing of 20 million instruction per second. This high performance allows the execution of manifold tasks and of complex control like sensorless controlled drives (Kalman Filter Observers) in real time. Minimizing the control loop delays or control cycles time that improves the dynamic behavior and results in a better disturbance behavior.

The DSP-Controller F240 has been optimized for digital control system applications and has all the architectural features necessary for high-speed signal processing. The device processes all the peripherals,needed to provide a single chip stand-alone DSP-Controller. These peripherals include:bit selectable I/O ports, a high speed seriel port, 12 high precision pulse width modulation outputs, four capture inputs, 4 independent timers, and 2 10bit AD converter with 16 input channels. The "DSP-Contoller F240" architecture is also optimized for processing control signals. A 16 bit world length is used along with 32 bit registers for storing intermediate results, and two hardware shifters are available to scale numbers independent of the CPU. This combination minimizes quantization and truncation errors, and increases processing power for additional functions. A diagram of the DSP-Controller F240 is given in Figure 1.

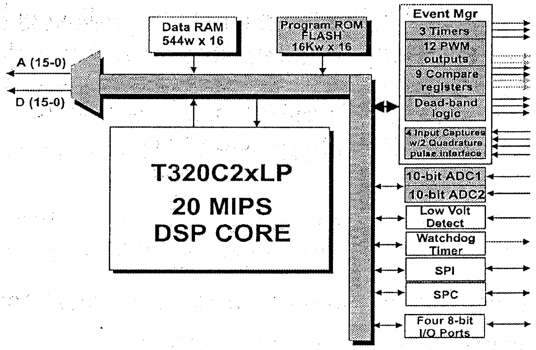

Figure 1 : Structure of the DSP-Controller TMS320F240.

The DSP-Controller F240 core architecture is based on the TMS320C5x, which utilizes a modified Harvard architecture for speed and flexibility. The main characteristic of the 2xLP core is the static design of the C5x generation with its 4 level pipeline architecture combined with the instruction set of the 2nd generation of DSPs. In strict Harvard architecture, program and data memory lie in two separate spaces, permitting a full overlap of instruction fetch and execution. This processor addresses three memory spaces: program memory space for instructions; data memory space for data variables; and Input/Output port space for accessing peripheral registers and data.

The processor can address up to 64Kx16 words of program memory, 64Kx16 words of local data memory and 64Kx16 words of I/O ports. Already integrated are 544x16 words of Dual Access RAM and 16Kx16 words of FLASH program memory. The flash version is named F240 and the ROM version with C240. The intelligent peripherals consist out of the Event Manager (EV) block, the communication unit (SPI and SCI), test and program interface (JTAG), the AD converters, and for system protection a Watchdog timer and a Low Voltage Detection (LVD) unit.

The event manager with its 3 16bit timer supports up to 12 pulse width modulated outputs for motor control, Power Factor Correction (PFC), as well as Digital Analog Converters. 6 of the 12 PWM channels are dedicated for the control of 3 phase drives like AC motors or Switched Reluctance machines. The pulse pattern generator supports different kinds of PWM modes e.g asymmetric, symmetric and space vector modulation. In the case of Space Vector PWM (SVPWM) the DSP-Controller generates automatically the linear combination of the basic space vectors and reduces so 50% of the software overhead.Further feature is to start the AD converter from the Event Manager without any load of the DSP core. This trigger signal is free programmable using one of the timer compare registers. This feature will be used to synchronize the PWM outputs with the measurement of state variables of the system. Additionally the event manager includes 4 capture inputs to measure for example the commutation signals of a brushless motor, an interface for an optical encoder with quadrature interpretation and a programmable dead time unit to protect the power switches.

The AD converter block includes, 2 10bit AD converters with 2 Samples & Hold circuits and each of the ADC has 8 input channels. The conversion time is less than 10ìs. In summary the on-chip peripherals of the DSP-Controller make it the ideal solution for digital control.

Sensorless Control Algorithms.

The sensorless controller aims to control the motor without the use of a position sensor to give the rotor's position and speed. To a degree the term sensorless is a misnomer as the system still uses current and/or voltage sensors. It is from these current and voltage measurements that the controller must estimate the rotor's speed and position. A short overview of sensorless control algorithms will be given for 3 phase PMSM drives and Induction Motor. The class of trapezoidal Brushless DC Motor will be not covered in this paper.

Several sensorless control strategies have been investigated using MATLAB/ SIMULINK. In the case of PMSM drives, following methods have been simulated and improved :

- open flux integration
- open flux integration with auto offset compensation
- INFORM – develop by Dr. Schroedl

The open flux integration methods base on the stator voltage equation of a PMSM drive. Problems still exist at the beginning with the integration constant and its identification. To eliminate this problem an auto offset compensation algorithm was developed.

The INFORM method is able to detect the rotor position at standstill in Permanent Magnet based motors and is patented. The INFORM algorithm is based upon detecting the changes in the individual stator coil inductance due to the orientation of the rotor flux generated by its Permanent Magnet. The stator inductance is defined to be the rate of change of the stator flux. This stator flux is composed of two components, the rotor flux and the flux generated by the current is flowing through the coil. It is also possible to transfer the INFORM method to induction motors. In comparison the sliding mode observer has some advantages in comparison to the other methods. Out of the sliding approach this control scheme showed a very robust behavior and is simple to implement. These are the main reasons why we have chosen to transfer the simulation to a practical implementation. Practical implementation on the DSP-Controller will be given in this section. The first one is a Kalman Observer application using an induction cage motor and the second is a sensorless controlled PMSM drive using a sliding mode observer approach.

Kalman Observer Of An Induction Motor.

The first practical example, which requests a DSP-Controller, is a Kalman Observer to receive in a sensorless way the actual values of the rotor position, the rotor velocity and the rotor flux. In many cases it is impossible to use sensors for velocity or position measurement, either because it is technically impossible, or too expensive. The Kalman observer has a good dynamic behavior, disturbance resistance and it can work even in standstill. This practical example is based on a field orientated control method, whereby the necessary control variable 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 involves many matrix multiplications and one matrix inversion. These requirements can be fulfilled by a processor with high calculation performance. The DSP-Controller is especially well suited for this purpose, because of its good calculation-performance/price ratio.

To give an impression of the complexity of a Kalman observer of an induction motor the theoretical background will be derived. The Kalman filter provides a solution that directly cares for the effects of the disturbance noises. The errors in the parameters will normally also be handled as noise. The system is describable with the following equations.

$$\underline{x} = \underline{Ax} + \underline{Bu} + \underline{r} \qquad \text{(System)} \qquad (1)$$

$$\underline{y} = \underline{Cx} + \underline{p} \qquad \text{(Measurement)} \qquad (2)$$

Where r and p are the system and the measurement noise. The assumptions regarding the noises are, that these noises are stationary, white, uncorrelated and Gaussian noises and their expectation is 0. The definition of the covariance matrices of these noises is :

$$\mathrm{Cov}(r) = E\{\underline{rr}^T\} = Q \qquad (3)$$

$$\mathrm{Cov}(p) = E\{\underline{pp}^T\} = R \qquad (4)$$

Where E{.} denotes expected value. The overall structure of the Kalman observer leads to the system equations :

$$\underline{\hat{x}} = (\underline{A} - \underline{KC})\,\hat{x}\,\underline{Bu} + \underline{Ky}. \qquad (5)$$

Where K denotes the matrix of the Kalman filter. The setting of the matrix K will be done based on the covariance of the noises. The quality of measurement of the goodness of the observation is a cost function given by:

$$J = \sum_{i=1}^{n} E\{\tilde{x}_i^2\} \qquad (6)$$

This depends on the choice of K. K has to be chosen to make J minimal, is given by:

$$\underline{K} = \underline{PC}^T\underline{R}^{-1} \qquad (7)$$

where P can be calculated from the solution of the following equation :

$$\underline{PC}^T\,\underline{R}^{-1}\,\underline{CP} - \underline{AP} - \underline{PA}^T - \underline{Q} = \underline{0} \qquad (8)$$

Q and R have to be set up based on the stochastic properties of the corresponding noises. Since these are usually not known, they are used as weight matrices in most cases. In a recursive algorithm is presented for the discrete time case to provide the solution for this equation. This algorithm is in fact the EKF (extended Kalman Filter) algorithm, because the matrix of the Kalman observer K, will be online calculated. The EKF is also capable of handling nonlinear systems, such as the induction motor.

Let us now see the recursive form of the EKF. All symbols in the following formulas denote matrices or vectors. They are not denoted with a special notation, because there is no possibility of mixing them up with scalars.

$$x_{k|k} = x_{k|k-1} + K_k\,(y_k - h(x_{k|k-1}, k)) \qquad (9)$$

$$P_{k|k} = P_{k|k-1} - K_k \frac{\partial h}{\partial x}\Big|_{x=xk|k-1} P_{k|k-1} \qquad (10)$$

$$K_k = P_{k|k-1}\frac{\partial h^T}{\partial x}\Big|_{x=xk|k-1}\left(\frac{\partial h}{\partial x}\Big|_{x=xk|k-1} P_{k|k-1}\frac{\partial h^T}{\partial x}\Big|_{x=xk|k-1} + R\right)^{-1} \qquad (11)$$

$$x_{k+1|k} = \Phi(k+1, k, x_{k|k-1}, u_k) \qquad (12)$$

$$P_{k+1|k} = \frac{\partial \Phi}{\partial x}\Big|_{x=xk|k} P_{k|k}\frac{\partial \Phi^T}{\partial x}\Big| + \Gamma_k Q \Gamma^T{}_k \qquad (13)$$

where

$$\Phi(k+1, k, x_{k|k-1}, U_k) = A_k\,(x_{k|k} + B_k(x_{k|k})U_k \qquad (14)$$

$$h(x_{k|k-1}, k) = C_k(x_{k|k-1})x_{k|k-1} \qquad (15)$$

These are the system vector and the output vector. These vectors can be explicitly calculated. The matrix K is the feedback matrix of the EKF. This matrix determines how the state vector of the EKF is modified after the output of the model is compared to the real output of the system. At this point it is important to mention, that this system of equations contains many matrix operations, which mean a problem to implement in real time.

To implement this recursive algorithm of course we will need the model of the motor, which means that the matrices A, B and C, from which we have to calculate the matrices Ö and h. This discrete model of the induction motor is given in Equation 16 and 17 using the sample time T :

In summary the DSP-Controller must first calculate Ö and h matrix using afterwards the calculation of the Kalman matrix K with the matrix inversion operation. This must be done in real time, because the system matrix A includes also state variables like the velocity ù.

Realization With The Dsp-Controller F240.

Figure 2 presents a complete system schematics. The DSP-Controller measures only 2 of the 3 stator phase currents. No additional measurements are necessary. The load and its behavior must be not nearer defined. This is application specific.

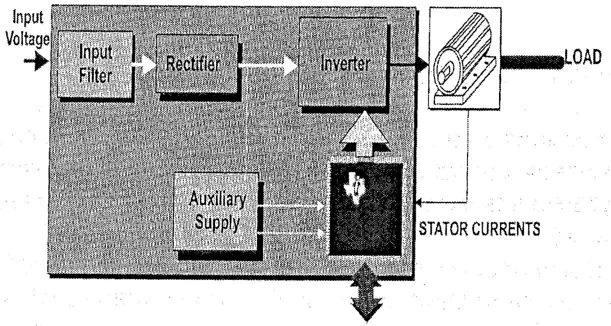

Figure 2 : System Concept of Kalman Observer of Induction Motor Control using the C240.

Practical Results Of The Kalman Observer.

The Kalman observer matrix K must be calculated in real time. Figure 3, shows the result of a speed reversal of plus/minus 1000 rpm electrically without any position/velocity sensor.

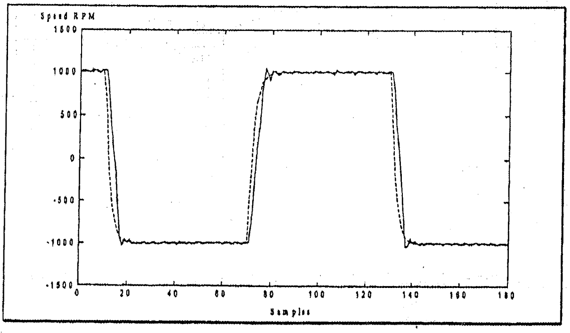

Figure 3 : Speed Reversal with Kalman Filter.

The program needs relatively little memory; the following table summarizes the needs :

Table 1 : Memory Requirements of Kalman Filter.

Program Part	**Program Size (Words)**	**DataSize (Words)**
Control + Kalman Filter	3641	631
Monitor Program	1577	603
Libraries	1605	309
Stack	0	1024
Σ Memory requirement	6823	2564

The DSP-Controller has a computing power of 20 MIPS at 20MHz, which means a cycle time of 50ns. The computation of the control happens in a 500ìs cycle, so the processor has 10,000 cycles available. The processor is using currently about 4400-4700 cycles and this means that it has time to perform foreground tasks, such as Monitor programs or other communications. The processor computing capacity is used to about 50%, but the cycle times could also be reduced.

Sensorless Controlled PMSM Drive.

As already discussed in the section, *Architecture of the DSP-Controller TMS320F240*, one possible sensorless control method is a sliding mode observer. Out of these requirement sliding mode observer strategy has the several advantages like its robustness, easy implementation etc.

Using a sinusoidal permanent magnet synchronous motor (PMSM) the standard control scheme is a vector control method, whereby the state variables will be transformed to a coordinate system rotating synchronous with the rotor. In rotor frame coordinates the PMSM behaves like a separately exited DC motor. The exact value of the rotor position is mandatory to control the speed, to transform the state variables, and to achieve a high efficiency. The control scheme is illustrated in Figure 4.

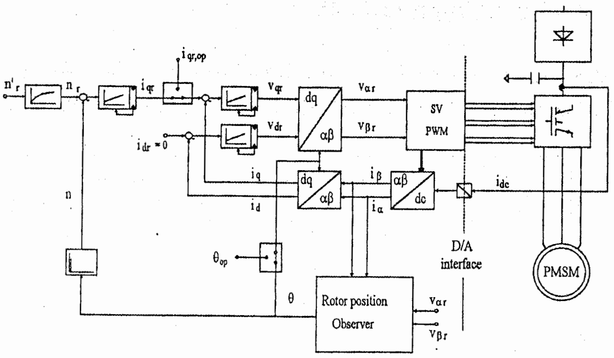

Figure 4 : Sensorless Vector Control Scheme of a PMSM Drive.

The principle and its theoretical background are given in Figure 5. The sign function (sliding mode) of ÄI will be multiplied with a constant factor K and afterwards transferred into a continuos system using a adaptive digital filter to compensate the phase shift influence of the digital filter. The result of the procedure is the already the sine and cosine function of the rotor position.

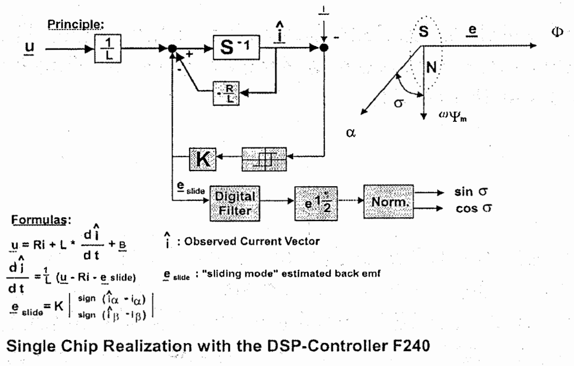

Figure 5 : Structure of a Sliding Mode Observer.

Single Chip Realization With The DSP-Controller F240.

Figure 6 presents a complete system structure of a sensorless controlled PMSM. The DSP-Controller measures only Ibus and Vbus. The stator phase currents will be estimated out of the switching positions of the power switches and the value of Ibus. For the current measurement is only 1 Shunt necessary and no galvanic or optical decoubling unit, because the DSP-Controller is related already to power ground. The same current measurement technique can be implemented for the Kalman observer application. The load and its behavior must be not nearer defined. This is normally application specific.

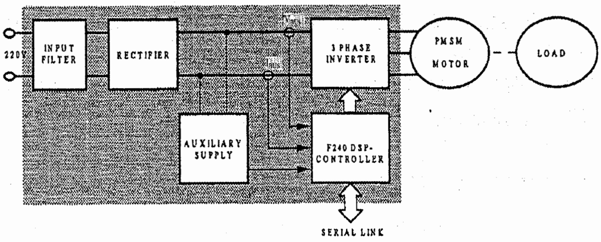

Figure 6 : Single Chip Realization of a Sensorless PMSM Drive.

PRACTICAL RESULTS.

The proposed control scheme has been implemented on the DSP-Controller. All the control routines are implemented using assembler language with fixed precision numerical representation. The calculation time of the whole control algorithm is less than 60ìs. The inverter switching frequency is 16 kHz. The speed control takes 2 ìs and is calculated every 28 cycles, then 1.75 ms. Phase currents estimation needs sampling of the inverter

DC current during the PWM period at instants that vary as a function of the actual PWM pattern. The memory space needed for is less than 1.2K word of ROM and 100 word of

RAM and use 70% (14 MIPS) of the DSP-Controller performance. The achieved electronic efficiency is in a range of 95% and the total efficiency >85%. The speed error was under worst case conditions less than 1.5%.

CONCLUSION.

This paper presents new controller architecture the DSP-Controller and its single chip solutions for sensorless controlled drive systems. The DSP-Controller TMS320F240 combines the performance of DSP architecture with the optimized peripherals of a Microcontroller. 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. The paper includes a short overview of sensorless control concepts focused for 3 phase PMSM an induction cage motors. For two sensorless control strategies practical examples of its implementation and its results were given.

REFERENCES.

1. Stephen J. Chapman, (1998). *Electric Machinery Fundamentals.* 3.ed. Mc Graw Hill
2. K.P.Basu, May13-15, (2002). *"A New Technique of Operation of Three Phase Induction Motor with Single Phasing Condition",* by Sixth IASTED International Conference on Power and Energy Systems, Marina del Rey, California, USA.
3. Allen V. Oppenheim & Ranald W. Schafer. *Discrete-Time Signal & Systems*. Prentice Hall.
4. Lonnie C. Ludeman, *Fundamentals of Digital Signal Processing*, John Wiley.