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DSP BASED ROBUST CONTROLLER OF BLDC SERVO MOTOR

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Abstract *This paper proposed a sliding mode fuzzy controller – SMFC, for a brushless DC motors used in motion control applications. The design procedure is based on a sliding mode controller with boundary layer (SMC-BL). The procedure presented, is focuses upon the development procedure for the sliding mode fuzzy controller. The fuzzy structure of controller (SMFC) was introduced in order to generate a non-linear transfer characteristic in contrast with that of SMC with BL. The motor controller drives the motor phase windings using field-orientation control. In such a way drives the motor is controlled at the maximum theoretical performance.*
Keywords: *brushless DC motor, field-oriented control, sliding mode fuzzy control, DSP controller.*

Introduction

Ideal sliding mode control (SMC) can guarantee asymptotic tracking with zero steady-state error for a wide class of non-linear systems. Sliding mode control with boundary layer (SMC-BL) can offer a number of attractive properties for industrial applications such as insensitivity to the parameter variations and external disturbances. The system dynamics are determined by the choice of sliding hyper-planes and are independent of uncertainties and external disturbances. In order to improve the system response for the SMC-BL, we have replaced the control term with a *fuzzy term*. This new *sliding mode fuzzy controller* (SMFC) offers a non-linear transfer characteristic in contrast to that of the SMC–BL. The system can compensate any output error caused either by variation of motor parameters or by the torque load variations or disturbances.
Electrical motor drives can be either voltage or current controlled. In the motion control applications these are typically current controlled so that the drive system behaves like an ideal torque generator. The brushless DC motor (BLCD) have been used widely as the actuators for motion control in robotics and automations applications, since it offer a good torque/weight ratio, a better heat dissipation and a freedom maintenance of switches. The current control loop is a sinusoidal current-controlled pulse width modulated (PWM) voltage-source inverter (VSI), which is widely applied in high-performance drives. The outer loop is designed to achieve a fast and accurate servo-tracking response under disturbance and plant parameter variations. Such requirements are usually difficult to achieve by using a simple linear controller. For this reason we

SMFC design

Sliding mode controller is a kind of robust controller resistible to system modeling uncertainties, time varying parameter fluctuations and external disturbances. Much improvement has been made in order to overcome the disadvantage of chattering. One is introducing a boundary layer neighboring the switching surface to smooth out the control discontinuity. Another kind controller has been also designed by integrating FLC into SMC, which is called fuzzy sliding mode control. FSMC is an extension of sliding mode control with boundary layer, to get chattering free and better performance controller. For a class of *2nd* order single input single output (SISO) nonlinear system in a continuous time domain the dynamic equation can be expressed as:

$$\ddot{x}(t) = f(\mathbf{x}(t),t) + b(\mathbf{x}(t),t)\cdot u(t) + \tilde{d}(t)$$
$$y(t) = x(t) \quad (1)$$

where $\mathbf{x}(t) = [x(t), \dot{x}(t)]^T \in \mathbf{R}^2$ is the state vector, $u(t)$ is the system input and $y(t)$ is the scalar output of the system. The objective of the controller design is to determine a control law $u(t)$ to track the desire trajectory $y_d(t)$ with small tracking error under the condition of modeling uncertainly. For the above system, the sliding line is $s(t) = \lambda\cdot e + \dot{e}$ and the control term $\hat{u}$ becomes $\hat{u} = \ddot{x}_d - \lambda\cdot\dot{e}$. Than the control law, for traditional sliding-mode control with boundary layer (SMC-BL), takes the following form:

$$u = \hat{b}^{-1}\cdot\left(-\hat{f} + G\cdot\hat{u} + G\cdot\boldsymbol{K}(\mathbf{x},t)\cdot sat(s/\Phi)\right), \quad (2)$$

where Φ is called the thickness of the boundary layer (BL); $\boldsymbol{K}(\mathbf{x},t) > 0$; $\hat{f}$ and $\hat{b}$ are estimates of f and b, respectively. The multiplier term G is given by relation $G = \left(\beta^{\min}\cdot\beta^{\max}\right)^{-1/2}$, and the following bounds $0 \le \beta^{\min} \le b\cdot\hat{b}^{-1} \le \beta^{\max}$ are defined. The BL corresponds to substituting of the function *sgn*(*s*) by a saturation function - *sat*(*s*). The above control law consists of 4 terms which they are: *compensation term* - $u_{comp} = -\hat{b}^{-1}\hat{f}$; *filter term* - $u_{filt} = -\hat{b}^{-1}G\cdot\lambda\dot{e}$; *feed-forward term* - $u_{ff} = -\hat{b}^{-1}G\cdot\ddot{y}_d$; *control term* - $u_{comp} = -\hat{b}^{-1}\cdot G\cdot\boldsymbol{K}(\mathbf{x},t)\cdot sat(s/\Phi)$. In the control term, the part $u_{diag} = \boldsymbol{K}(\mathbf{x},t)\cdot sat(s/\Phi)$ is of diagonal form with the "*diagonal*"- $s = 0$. Considering that $\boldsymbol{K}(\mathbf{x},t) = const$ and the state vector ***e*** to be located inside of BL we have that

$$u_{diag} = -\frac{\boldsymbol{K}(\mathbf{x},t)}{\Phi}\cdot s = \frac{\boldsymbol{K}(\mathbf{x},t)\cdot|s|}{\Phi}\mathrm{sgn}(s)\cdot \quad (3)$$

The magnitude of the fuzzy value for the controller output $u(t)$ depends on the distance of fuzzy region from the diagonal. But the diagonal form of fuzzy logic provides a mapping from crisp states $e(t)$ and $\dot{e}(t)$ to the crisp controller $u(t)$. Therefore, the analytical formulation of control law for the diagonal fuzzy logic controller – FLC, is

$$u_{fuzz} = -K_{fuzz}(e,\dot{e},\lambda)\cdot\mathrm{sgn}(s). \quad (4)$$

A comparison between of the relations (3) and (4) shows the close relationship between the SMC-BL and diagonal FLC. The transfer characteristic $u_{fuzz} = f(s)$ of the diagonal form FLC is non-linear in contrast to that of the SMC-BL. Also, for the FLC the state vector ***e*** is restricted by bounds on the fuzzy state space. The diagonal form FLC changes the magnitude of u depending on the distance $|s|$ between the state vector ***e*** and the diagonal $s = 0$. Therefore, the corresponding control law is $u_{fuzz} = -\boldsymbol{K}(\mathbf{x},t)\cdot|s|\cdot\mathrm{sgn}(s)$. The advantage of a Sliding Mode Fuzzy Controller (SMFC) over a FLC is that the number of fuzzy rules is reduced considerably. The above control law (2) is modified into a fuzzy control law

$$u = -\hat{b}^{-1}\hat{f} + \hat{b}^{-1}\cdot G\cdot\hat{u} - \hat{b}^{-1}\cdot G\cdot u_{fuzz}, \quad (5)$$

where u_{fuzz} was introduced instead of u_{diag}.

The design controller is specified as:

$$u(t) = \begin{cases} u^-(t), & if\ s(t) < 0 \\ u^+(t) & if\ s(t) > 0 \end{cases} \quad (6)$$

According with the fuzzy inference rule base is established as:

R[1]: If $s(t) < 0$ then $u^1(t) = u^-(t)$

R[1]: If $s(t) < 0$ then $u^2(t) = u^-(t)$

The states located on a diagonal play an important role, since the controller output u changes its sign. An important step in design of SMFC is to choice of the number of fuzzy value for the controller inputs and outputs respectively, and also the form and location of the corresponding membership functions. The number of operating points determines the number of discontinuities of transfer characteristic. Normally these points are depending on how many discontinuities are allowed.

Brushless DC motor

Generally, a small horsepower BLDC motor used for a speed or position control is the same as a permanent magnet synchronous machine. The stator is made by a three-phase Y-connection without the neutral and the rotor is a permanent magnet. The system equations in a *d-q* model can be expressed as follow:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} i_{sd\theta} \\ i_{sq\theta} \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{L_{sd}} & \omega\frac{L_{sq}}{L_{sd}} \\ -\omega\frac{L_{sd}}{L_{sq}} & -\frac{R_S}{L_{sq}} \end{bmatrix} \cdot \begin{bmatrix} i_{sd\theta} \\ i_{sq\theta} \end{bmatrix} +$$

$$+\begin{bmatrix} \frac{1}{L_{sd}} & 0 & 0 \\ 0 & \frac{1}{L_{sq}} & -\frac{\omega}{L_{sq}} \end{bmatrix} \begin{bmatrix} u_{sd\theta} \\ u_{sq\theta} \\ \Psi_M \end{bmatrix}; \qquad (7)$$

$$T_e = \frac{3}{2}\frac{p}{J}\left[\Psi_M i_{sq\theta} + \left(L_{sd} - L_{sq}\right) i_{sd\theta} i_{sq\theta}\right] =$$

$$= J\left(\frac{2}{p}\right)\frac{d\omega}{dt} + B\left(\frac{2}{p}\right)\omega + T_L . \qquad (8)$$

The analysis and control of such a plant appears complicated because of the coupling of all the control inputs. The problem can be overcome by applying the field-oriented control which reduces the control of the AC motor to that of a separated DC motor. The vector controlled scheme employs a rotor flux model based upon eq. (7) and (8), which means that $i_{sd\theta}=0$ and $i_{sq\theta} = i_s$. Therefore the system equations of BLDC motor model are described the following equations:

$$\dot{i}_{sq\theta} = -\frac{R_S}{L_{sq}} \cdot i_{sq\theta} + \frac{1}{L_{sq}} \cdot u_{sq\theta} - \frac{\omega}{L_{sq}} \cdot \Psi_M \qquad (9)$$

$$\dot{\omega} = \frac{3}{2}\frac{1}{J}\left(\frac{p}{2}\right)^2 \cdot \Psi_M \cdot i_{sq\theta} - \frac{B}{J}\omega - \left(\frac{p}{2J}\right)T_L \qquad 10)$$

The torque equation is given by

$$T_e = \frac{3}{2}\frac{p}{2} \cdot \Psi_M \cdot i_{sq\theta} = k_t \cdot i_{sq\theta} \qquad (11)$$

where $k_t = \frac{3}{2}\frac{p}{2} \cdot \Psi_M$.

Since the current control is employed in a speed control, the system model expressing the speed dynamics becomes eq. (10), and the rotor position dynamics becomes $\dot{\theta} = \omega$. For the implementation of the field orientation, each three-phase current control command is generated separately. A current controlled sinusoidal PWM inverter, like in Fig 2, is used to generate the three-phase current commands. The order of the model given by eq. (9), (10) can be reduced if the *d-q* currents are considered as reference inputs for the system drive. The command is carry out by converting the controller current from the rotor reference *d-q* frame to the stator reference frame - i_{sa}, i_{sb}, i_{sc}.

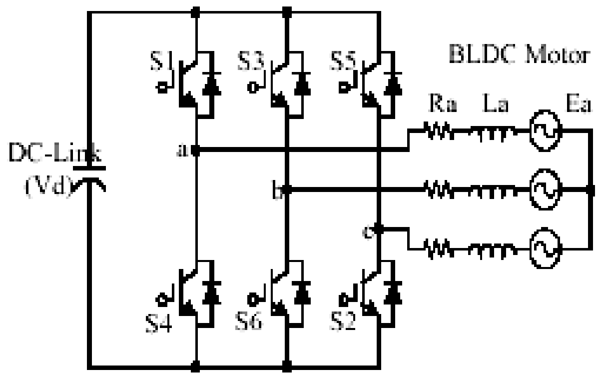

Figure 1. Current controlled PWM inverter

DSP Controller

The controller, presented in Fig. 2, based on a TMS320 F243 is utilized to implement a three-phase BLDC motor drive. The motion system includes basic motor control with closed loop position control. The overall system drive that we have used for the experimental results are composed by a Pittman BLDC 3400 series and a MCK240 Technosoft controller.

It last component integrates the power electronics peripherals – 12 PWM channels, three 16 bit multi-mode general purpose timers, 16 channel 10 bit ADC with simultaneous conversion capability, four capture pins, encoder interface capability, SCI, SPI, Watch Dog etc.

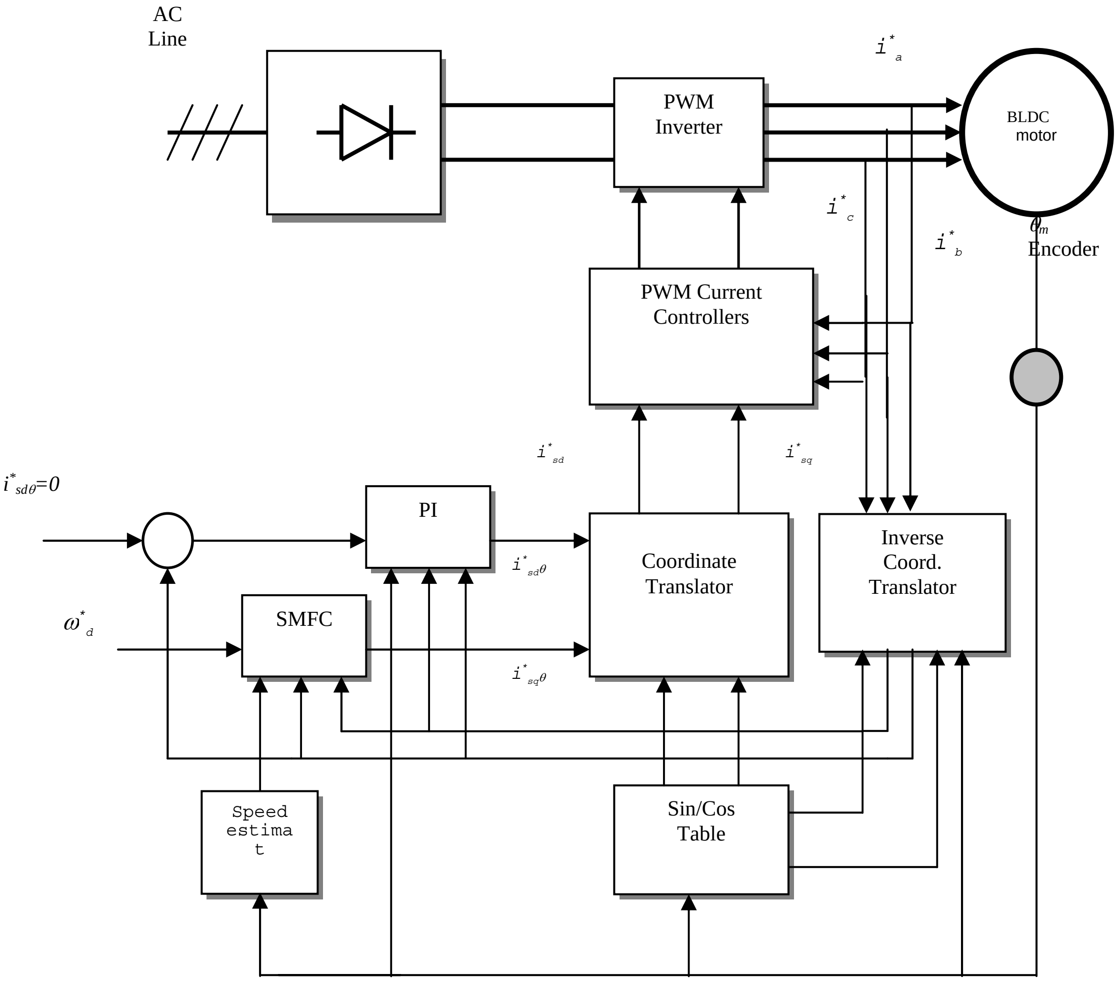

Figure 2. SMFC controller for BLDC motor drive

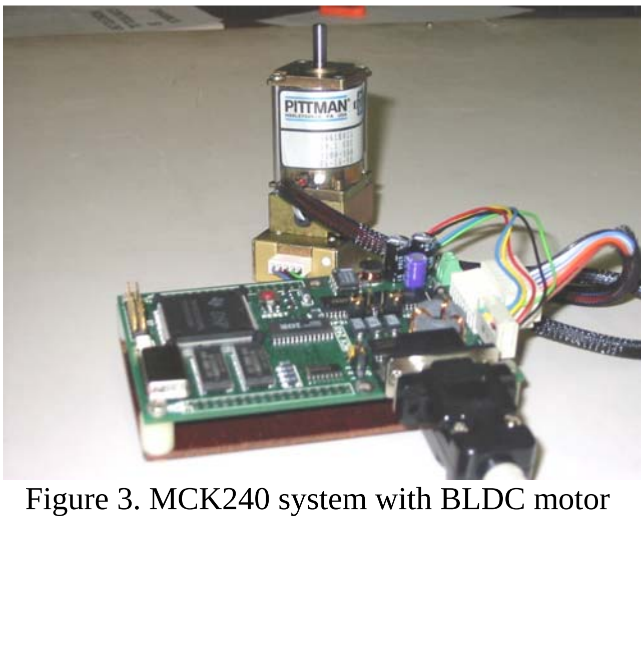

Figure 3. MCK240 system with BLDC motor

Six PWM channels (PWM1 through PWM6) control the three-phase voltage source inverter.

The entire application software is driven by an Interrupt service routine (ISR). The main code (i.e. background loop) consists simply of TMS320C243 peripheral initialization. The remainder of the code is taken up entirely by PWM_ISR. This ISR is invoked every 50uS (20KHz) by the Period event flag on Timer 1 of the Event manager.

The software was written in C and assembly and is less than 6KW of program space. The on chip flash of the controller stored the program. Experimental results are presented in Fig. 4.

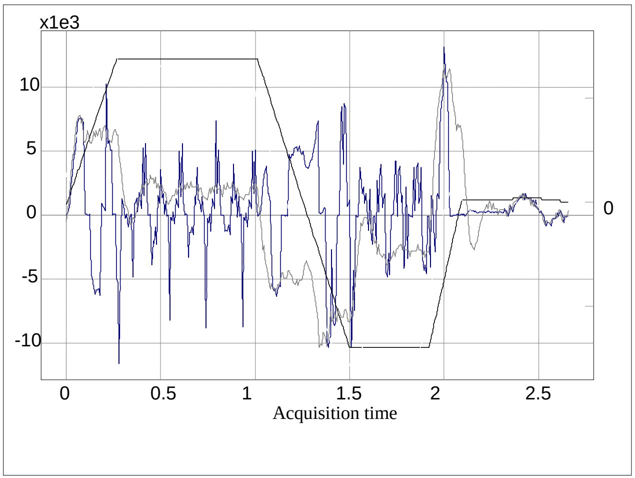

Figure 4. Speed ω and current $i_{sq\theta} = i_s$

Conclusions

In this work, we consider the design of robust sliding mode fuzzy control based on a DSP controller. Much effort was focused to carry out the firmware for such a controller. In order to get chattering free and better performances for the traditional SMC, we have implemented a sliding mode fuzzy controller. It results by integrating a fuzzy logic controller (FLC) into the classical SMC with BL. In spite that we finally got experimental results, we appreciate this controller as being too difficult to be implemented and very depending on the final application.

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