Fuzzy Sliding Mode Control of the Brushless DC Motor

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Abstract - **This paper presents a speed control system for the DC brushless motor applications. Sliding mode and fuzzy logic control can be combined in a very different of ways. However, all approaches tend to fall in one of two broad categories: fuzzy boundary layers or fuzzy Lyapunov function. Fuzzy logic is introduced in order to suppressing the chattering and enhancing the robustness of controlled system. In this paper a procedure based on the fuzzy boundary layer is developed since it can provide a smother transition to the equivalent control.**

I. INTRODUCTION

The brushless DC motor 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. Performance of many motion control systems is limited by variations of system parameters and disturbances such as payload changes. These requirements are usually difficult to achieve by using a simple linear controller. Sliding mode control 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 [4]. To eliminate the chattering, a boundary layer (BL) can be introduced around the sliding surface and the tracking performance is compromised [1]. Within the boundary layer, the control command is a linear function of the distance between the actual system state and the sliding surface. The distance is represented by a function called sliding function. The combination of fuzzy logic control and sliding mode control is still of research interest due to the fact that the stability of a general fuzzy logic controller is difficult to prove whereas the stability of a sliding mode controller is inherent. A direct benefit of combining fuzzy logic control and sliding mode control is that fuzzy logic can effectively eliminate chattering, which is a common problem in sliding mode control.

Fuzzy logic is being used to map the distance to the control command as a nonlinear Single-Input-Single-Output function. In the almost approaches developed, a simple FLC is used to fuzzify the relationship of the control command and the distance between the actual state and the sliding surface. This approach is called Fuzzy Sliding Mode Controller (FSMC) since fuzzy logic is used only to fuzzify a sliding surface. For the 2D case, the sliding line becomes a band of sliding area [1]. In essence, this is equal to introducing a boundary layer to control command changes nonlinearly inside the band. In the sections II and III this paper presents general sliding mode control theory, followed by the details of Fuzzy Sliding Mode Controllers (FSMC). Next sections deals with modeling and speed control for a BLDC motor application. Simulations and experimental results are presented.

II. SLIDING MODE CONTROLLER

A Sliding Mode Controller is a Variable Structure Controller (VSC). Basically, a VSC includes several different continuous functions that map plant state to a control surface, and the switching among different functions is determined by plant state that is represented by a switching function.

In present paper, it was considered the design of a sliding mode controller for a second order system:

$$\ddot{x} = f(x,\dot{x},t) + b \cdot u(t) \tag{1}$$

where we assume that $b > 0$. The control input for this system is $u(t)$. Next equation represents the structure for the sliding mode controller [5]:

$$u = u_{eq} - k\,\mathrm{sgn}(s), \tag{2}$$

where u_{eq} is called equivalent control which is used when the system state is in the sliding mode [4]. k is a constant, representing the maximum controller output. s is called switching function because the control action switches its sign on the two sides of the switching surface $s = 0$. s is defined as [2]:

$$s = \dot{e} + \lambda e, \tag{3}$$

where $e = x - x_d$ and x_d is the desired state. The definition of e requires that k from (2) to be positive and λ to be a constant.

The control strategy adopted will guarantee a trajectory for the system that move toward the sliding surface $s = 0$ and stay on from any initial condition if the following condition meets:

$$s\dot{s} \le -\eta|s| \tag{4}$$

where η is a positive constant that guarantees the system trajectories hit the sliding surface in finite time [5].

Using a *sign* function often it causes chattering in practice. One solution is to introduce a boundary layer around the switch surface [1]:

$$u = u_{eq} - k\,sat(\frac{s}{\phi}) \tag{5}$$

where constant factor ϕ defines the thickness of the boundary layer or the region in which the control law is linear.

This controller is actually a continuous approximation of the ideal relay control [1]. The system robustness is a function of the width of the boundary layer. It [12] is proven that if k is large enough, the sliding model controllers of (2) and (5) are guaranteed to be asymptotically stable.

III. FUZZY SLIDING MODE CONTROL (FSMC)

In the case of second order systems, the sliding surface is a line. Control action given by equation (2) will changed alternatively its sign and the system state switches from one side of the line to the other side of the line. A boundary layer can alleviate the chattering problem. Using the fuzzy logic it is possible to replace the signum function from (2) by a fuzzy map. A relatively simple input/output map, where the input is the current value of the sliding variable (3), and the output is the fuzzy approximation of the signum function. The input membership function is shown in Figure 1, while the output membership function is fuzzy singletons at -1 and +1, respectively.

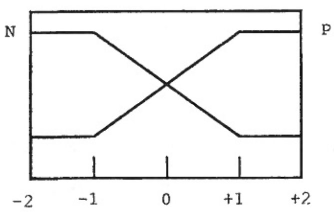

Figure 1. Input membership functions

Using the output membership function, the defuzzification may be computed by

$$s_Z = \frac{\mu_P(s) - \mu_N(s)}{\mu_P(s) + \mu_N(s)} \tag{6}$$

and the equation representing the input membership function P, can be written as

$$\mu_P(s) = \begin{cases} 0 & if \quad s < -1 \\ \frac{s+1}{2} & if \quad -1 \le s \le +1 \\ 1 & if \quad s > +1 \end{cases} . \tag{7}$$

From Figure 1, it is possible to write that

$$\mu_N(s) = 1 - \mu_P(s) \tag{8}$$

which means that s_z becomes

$$s_Z = \begin{cases} -1 & if \quad s < -1 \\ s & if \quad -1 \le s \le +1 \\ 1 & if \quad s > +1 \end{cases} . \tag{9}$$

Finally, we see that this fuzzy replacement for signum function from control law (3) is nothing more than the saturation function with $\phi = 1$.

IV. BRUSHLESS DC MOTOR MODEL

Brushless DC motor considered in this paper is a surface mounted, non-salient pole, permanent magnet (PM) synchronous machine with trapezoidal flux distribution in the air gap. This kind motor is very attractive in servo and/or variable speed application since it can produce a torque characteristic similar to that of a permanent magnet DC motor while avoiding the problems of failure of brushes and mechanical commutation.

Basic voltage current relations can be written as:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_a & L_{ba} & L_{ca} \\ L_{ba} & L_b & L_{cb} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{10}$$

where

R	Winding resistance per phase
L_a	Self inductance per phase a
L_{ba}	Mutual inductance between phases b and a
e_a	Per phase a EMF
V_a	Per phase a voltage

$$L_a = L_b = L_c = L \qquad L_{ab} = L_{bc} = L_{ca} = M \tag{11}$$

Due to symmetry in the isolated neutral configuration of stator windings of the motor we have that:

$$i_a + i_b + i_c = 0 \tag{12}$$

$$Mi_b + Mi_c = -Mi_a . \tag{13}$$

Using the above equations, the BLDC model can be reduced to the following state space form:

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_s} & 0 & 0 \\ 0 & -\frac{R}{L_s} & 0 \\ 0 & 0 & -\frac{R}{L_s} \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} -\frac{1}{L_s} & 0 & 0 \\ 0 & -\frac{1}{L_s} & 0 \\ 0 & 0 & -\frac{1}{L_s} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \frac{1}{L_s}\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (14)$$

where

$$L_s = L - M \, . \quad (15)$$

The torque and mechanical equations are

$$T_e = \left(\frac{P}{2}\right)\frac{e_a \cdot i_a + e_b \cdot i_b + e_c \cdot i_c}{\omega_r} \quad (16)$$

$$J\left(\frac{2}{P}\right)\cdot\frac{d\omega_r}{dt} + B\left(\frac{2}{P}\right)\omega_r = T_e - T_L \quad (17)$$

and

$$\omega_r = \omega_m\left(\frac{P}{2}\right), \quad (18)$$

respectively.

V. BRUSHLESS DC MOTOR CONTROL

A common way to control BLDC motor is through the use of a voltage source current-controlled PWM inverter. The inverter must supply a quasi-square current waveform, of which magnitude is proportional to the motor shaft torque [2]. Then, by controlling the phase currents, torque and speed can be adjusted. Fig. 2 shows the BLDC motor fed by the PWM inverter. It receives PWM signals from the drive circuit behind, based on the converted current feedback of Hall sensors and position encoders.

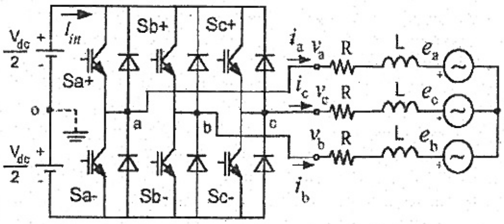

Figure 2. BLDC current controlled PWM inverter

The Hall sensors are placed on the stator of BLDC motor that give 120° phase shifted square waves in phase with respective phase voltages. These waves represent the rotor position. The decoder circuit converts these waves into the six-step command signals. Converted signals with appropriate polarities are than used to drive the gates of the MOSFETs (S_a+, S_a-,…,S_c+, S_c-) of the respective phases.

The actual phase currents of the rotor, track the command currents by hysteresis-band current control. At any instant time, only two of the phase currents are enabled, one with positive polarity and the other with negative polarity. When these currents (equal in magnitude) tend to exceed the hysteresis band, both the MOSFETs are turned off at the same instant to initiate current feedback through the free wheeling diodes. The currents i_a, i_b and i_c needed to produce a steady torque without torque pulsations and the back EMF's e_a, e_b, e_c are shown in Fig. 3.

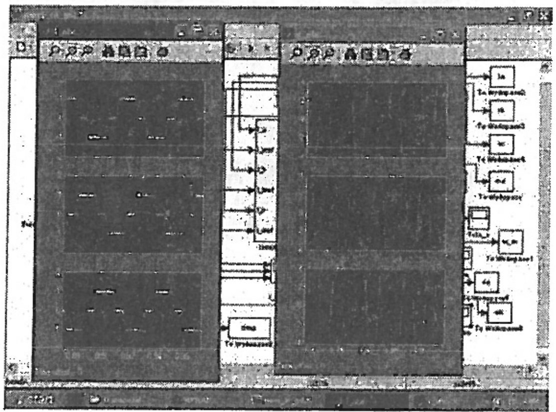

Figure 3. Currents and back EMF of the BLDC motor

The developed torque is directly proportional to the phase current. It means that the torque can be maintained constant by a stable supply current. In order to realize this state, one method is to keep the ratio of voltage to frequency a constant. This can be achieved by using a speed and current closed-loop control. Fig. 4 shows the overall block diagram of the developed model for BLDC drive system. The simulation is performed using the Matlab/Simulink software. The control structure has an inner current closed-loop and an outer-speed loop to govern the current. To control the rotor speed - ω_m, we have developed a fuzzy sliding mode controller, under the theoretical consideration presented in the sections II, III and IV. The controller regulates the rotor speed by varying the frequency of the pulse based on signal feedback from the Hall-ICs.

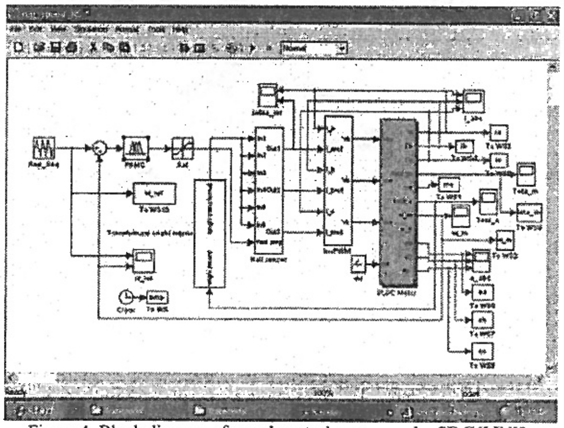

Figure 4. Block diagram of speed control system under SIMULINK

In Fig. 5 presents the simulation results for the current windings (i_a, i_b, i_c), back EMF's (e_a, e_b, e_c) and the rotor speed (ω_m), respectively.

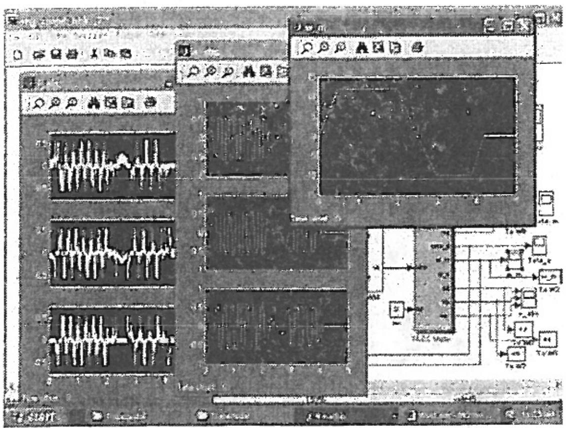

Figure 5. Current in BLDC phases, back EMF voltages and speed

The speed feedback loop compares the rotor speed ω_m with the desired rotor speed ω_{ref} to produce the command torque component current. If the speed is faster than desired speed it will reduce the frequency of the pulse to be injected by the inverter. Vice versa, if speed is slower frequency will be increased.

VI. DSP CONTROLLER

The system drive used in experimental test is a MCK240 Technosoft, composed by a Pittman BLDC 3400 and a DSP TMS320F243 based controller. Fig. 6 presents a picture of the system drive. The motion system includes basic motor control with closed loops for current and speed control. The system communicate with a master PC via a serial COM port and is enough flexible to be used for new developments.

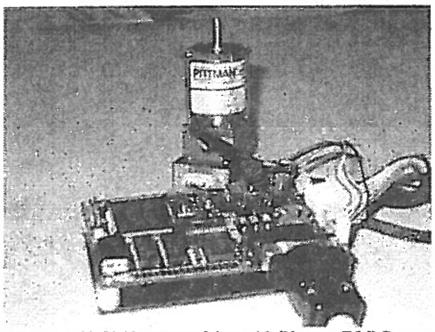

Figure 6. MCK240 system drive with Pittman BLDC motor

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

The entire application software for the DSP controller is driven by an Interrupt service routine – IRQ2. The main code (i.e. running in background loop) consists in TMS320C243 peripheral initialization (PWM channels, Timers, ADC converters, Watch Dog). 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 is written in C and assembly and is less than 6Kw of program space. The program is loaded via com2 port into the chip flash memory of the DSP. A data logger was used for the acquisition process. Experimental results for speed - ω_m and current -i_a, are shown in Fig. 7.

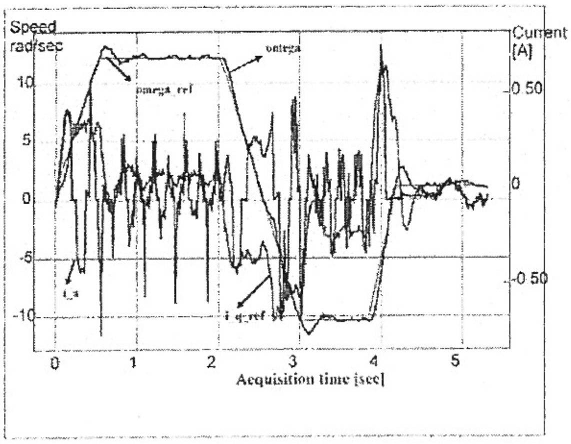

Figure 7. Speed ω_m and current winding i_a

VII. CONCLUSIONS

In this paper a speed control for the BLDC motor, based on a combination between SMC and fuzzy logic is presented. Fuzzy logic can be used to replace the signum function from the SMC control law by a fuzzy map. The results of simulation and experiment show that the performance of the system drive by using the proposed controller has some advantages than that by using a pure SMC. In addition, the control precision of the system by using FSMC is improved than that of using either pure SMC or pure FLC.

VIII. REFERENCES

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