A novel fuzzy logic direct torque controller for a permanent magnet synchronous motor with a field programmable gate array

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Abstract: A high-performance digital servo system built on the platform of a field programmable gate array (FPGA), a fully digitized hardware design scheme of a direct torque control (DTC) and a low speed permanent magnet synchronous motor (PMSM) is proposed. The DTC strategy of PMSM is described with Verilog hardware description language and is employed on-chip FPGA in accordance with the electronic design automation design methodology. Due to large torque ripples in low speed PMSM, the hysteresis controller in a conventional PMSM DTC was replaced by a fuzzy controller. This FPGA scheme integrates the direct torque controller strategy, the time speed measurement algorithm, the fuzzy regulating technique and the space vector pulse width modulation principle. Experimental results indicate the fuzzy controller can provide a controllable speed at 20 r min⁻¹ and torque at 330 N m with satisfactory dynamic and static performance. Furthermore, the results show that this new control strategy decreases the torque ripple drastically and enhances control performance.

Keywords: fuzzy control; direct torque control; field programmable gate array; permanent magnet synchronous motor

1 Introduction

Recent advances in high power semiconductor switching devices, magnetic materials and energy storage systems have generated considerable interest in electric drive systems for vehicle propulsion applications. They have no shafts and gearing, but promote vehicle stealth and flexibility. Meanwhile, in harsh environments presented in many electric drive applications, novel propulsion configurations and control strategies are pushing the need for high power density and high performance electric machines.

The permanent magnet synchronous motor (PMSM) offers several features which make it attractive for use in electric drive systems. For example, PMSMs only require torque control instead of a speed control system. In the 1980s, Takahashi proposed a direct torque control (DTC) for an induction machine drive [1]. Followed by its commercialization in induction machine drive products, the DTC concept has been extended to other AC machine drives. Furthermore, Zhong et al. discussed DTC application in PMSM for the first time [2].

Because of the complexity of servo control algorithms, we always implemented engineering practice with software based on Digital Signal Processing (DSP) [3]. This approach can provide flexibility, but it suffers from a long period of development and exhausts CPU (central processing unit) resources. In recent years, a novel methodology called FPGA (field programmable gate array)-based hardware implementation technology arose [4-5]. Compared with DSP, FPGA only collects standard cells, which have no...
specific functions. But owing to its field programmable characteristics and reuse of the intelligence property (IP) cores, users can design their own application specific integrated circuit (ASIC) according to their schemes with professional placement and routing tools in the shortest time without participation of semiconductor manufacturers. In addition, FPGA can carry out parallel processing by a hardware mode, which places no demands on the CPU. The system therefore can achieve very low speeds as well as significant torque [6].

Although the DTC scheme is an attractive proposition in its own right, it has some drawbacks, such as the high torque and flux ripples, and estimation error in torque and flux linkage. Based on a detailed analysis of PMSM DTC theory, we present a simple method to solve the contradiction between steady state and transient performance. An FPGA embedded with the software of torque control, DTC scheme and torque control has been developed for high performance position control of PMSM drives. With excellent characteristics, the proposed system makes the drive of PMSM more programmable, robust, and easily implemented. Details of the hardware and software implementation are provided, and performance tradeoffs and implementation issues addressed.

2 PMSM model and DTC fundamentals

2.1 Machine equations

The PMSM machine under investigation can be modeled in the rotor reference frame as:

\[
\begin{bmatrix}
    v_d \\
    v_q
\end{bmatrix} =
\begin{bmatrix}
    R_s + pL_d & -\omega L_q \\
    \omega L_d & R_s + pL_q
\end{bmatrix}
\begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} +
\begin{bmatrix}
    0 \\
    \omega \lambda_d
\end{bmatrix},
\]

(1)

\[
T_m = \frac{3p}{2} [\lambda_d i_q + (L_d - L_q) i_q i_d],
\]

(2)

\[
T_m = \frac{J}{p} \frac{d}{dt} \omega + \frac{D}{p} \omega + T_l,
\]

(3)

where \(v, i\) respectively represent the stator voltage and the current; \(p\) is the number of pole pair; \(L_d, L_q\) are the \(d\) and the \(q\) axis inductances; \(R_s\) is the stator armature resistance; \(\omega\) is the electric angle speed of revolving rotor; \(\lambda_d\) is the rotor’s magnetic linkage of permanent magnet; \(T_m\) is the electromagnetic torque; \(T_l\) is the load torque; \(J\) is the moment of inertia; \(D\) is the electric dipole moment.

For the DTC of the PMSM machine, the estimation of flux linkage and torque were carried out in the stationary reference frame as follows:

\[
\lambda = \int (U_{DC} - R_s i) dt ,
\]

\[
\dot{\lambda}_d = \int (v_d - R_s i_d) dt ,
\]

\[
\dot{\lambda}_q = \int (v_q - R_s i_q) dt ,
\]

\[
T_m = \frac{3}{2} p(\lambda i) = \frac{3}{2} p(\dot{\lambda}_d i_q - \dot{\lambda}_q i_d),
\]

(6)

where \(\lambda\) is the inductance; \(\dot{\lambda}_d, \dot{\lambda}_q\) are \(\alpha\) and \(\beta\) axis inductances; \(i_d, i_q\) are \(\alpha\) and \(\beta\) axis current; \(v_d\) and \(v_q\) are \(\alpha\) and \(\beta\) axis voltages.

2.2 The structure of the PMSM DTC system

The PMSM DTC system includes flux and torque estimators, flux and torque hysteresis controllers and a switch table (Fig. 1). In addition, we needed a DC bus voltage sensor and two output current sensors for flux and torque estimation.

2.3 The strategy of the fuzzy DTC system

A fuzzy controller is composed of following three parts: fuzzification, fuzzy inference and defuzzification. The output of the controller is added to a vector table. The corresponding voltage vector subsequently can be obtained [7].
In a DTC system, the whole voltage vector plane is divided into six regions: I, II, III, IV, V, VI (Fig. 1). When the flux linkage is in a proper voltage vector region, it can be kept revolving and the track is a circle. Because the function of each space voltage vector (Fig. 1) was symmetric in each sextant region, we could derive fuzzy reasoning rules for the entire DTC system based on only one sextant region. The whole 360 plane can be mapped onto one sextant region \( \left( -\frac{6}{\pi}, +\frac{6}{\pi} \right) \) to reduce the number of fuzzy reasoning rules by

\[
\theta_m = \theta - \frac{\pi}{3} \text{Int} \left( \frac{\theta + \frac{\pi}{6}}{\frac{\pi}{3}} \right),
\]

where \( \theta_m \) is the real flux linkage angle input of the fuzzy controller after mapping; and \( \theta \) is the real stator flux linkage angle [8].

The fuzzification was performed by a membership function whose shape affected the function of each fuzzy rule. In the PMSM DTC system, simultaneous control of the torque and the flux linkage was required. However, the simulation results show that none of the space voltage vectors in Fig. 1 could achieve accurate control on the torque and flux linkage at the same time. Because it was easier to control the flux linkage than the torque, we prioritized the requirement of torque first whenever there was a contradiction between these two control variables. We divided the membership function of the flux linkage error and the torque error into seven fuzzy subsets with these linguistic values: NL (negative large), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), PL (positive large) (Fig. 2). Meanwhile, according to the vector selection rules, the vector functions were classified into three types, namely increasing torque and increasing flux linkage, increasing torque and decreasing flux linkage, and decreasing torque and decreasing flux linkage. These three functions were fuzzified as the foregoing seven singleton fuzzy sets, whose output errors fell into three domains as shown in Fig. 3.

3 Design scheme for the FPGA based digital hardware

3.1 Design scheme for the digital hardware

The proposed FPGA-based platform for PMSM DTC consists of several function modules (Fig. 4), including a Clarke transformation module, a speed measurement module (detecting with time), a fuzzy regulator module, a hysteresis controller module, a space vector pulse width modulation (SVPWM) module, a DC-link voltage compensation module, a scaling module and so on. Only the main modules are discussed herein [9].

![Image](image-url)
We can express the digitized speed as

\[ n = \frac{60f}{2mP_N} \text{ (r min}^{-1}) \tag{8} \]

where \( P_N \) is the equivalent pulse per revolution.

### 3.3 Fuzzy regulator module

In the fuzzy logic, the error \( (e) \) and error change rate \( (\Delta e) \) of the system output are the two main input variables used in the fuzzy system. The control rule of the fuzzy regulator module is basically composed of many IF-THEN statements shown as follows:

\[ \text{IF } e \text{ is } A_i \text{ and } \Delta e \text{ is } B_j \text{ THEN } u \text{ is } u_{ij}, \tag{9} \]

where \( i \) and \( j \) are the number indexes of the control rules; \( u \) is the output of fuzzy controller.

### 3.4 SVPWM module

Compared with typical Sinusoidal Pulse Width Modulation (SPWM), the SVPWM technique has the merits of lower total harmonic distortion (THD), lower switching loss, lower torque ripple, better DC link voltage utilization and easier realization in digital hardware. Incorporated with vector control, it has conquered the world of motor drive control [10-11].

There are six active vectors \((V_{s0}-V_{s6})\) and two zero vectors \((V_{s7}, V_{s8})\). The vector modulation technique is based on the zero-state vector and splitting duty ratios of each vector, which can be expressed as:

\[ V_{\text{ref}} = V_{s7} + V_{s8} = V_{s0} = \sqrt{3} \frac{V_{\text{DC}}}{2} \left[ V_{s0} \sin \left( \frac{k\pi}{3} \right) - V_{s6} \cos \left( \frac{k\pi}{3} \right) \right]. \tag{10} \]

where \( V_{\text{ref}} \) is the complex reference vector produced by a zero-state vector and the two adjacent switching-states; \( V_{s0}, V_{s6} \) are the switching-state vectors; \( f \) is the sample time; \( l_k, l_{k+1} \) are the time for each one which is inactive, respectively, and

\[
\begin{align*}
  l_k &= \frac{k\pi}{3} - \frac{1}{2} - \frac{1}{3} l_{k+1}, \\
  l_{k+1} &= \frac{k\pi}{3} - \frac{1}{2} + \frac{1}{3} l_k.
\end{align*}
\]

Then we can generate the wave of SVPWM using the above equations.

### 3.5 Communication module

The system carries out the communication between the information system (main control or supplemental control) and the PC by RS232 interface and uses MAX232 to act as a corresponding driver. MAX232 is the interface manufactured by the Maxim Company. It uses a single electrical source (+5) to supply power and contains a charger converter. Having two drives and two receivers, only the RS-232 interface can download control program conveniently.

### 4 FPGA implementation and experimental results

Each module of the DTC is described by Verilog hardware description language (VHDL) and synthesized by Symply software. The experimental hardware set-up, which is the fuzzy logic PMSM DTC system, includes a digitally controlled insulated gate bipolar transistor (IGBT) voltage sourced inverter (VSI) with the IGBT driver supplied by Semikron and an EPIC20F400 FPGA from Altera. The hardware is
coupled to a separately excited DC machine by means of a torque meter, allowing the measurement of motor shaft torque. We conducted various tests to verify the proposed fuzzy logic DTC scheme. The parameters of the PMSM machine are given in Table 1 and experimental results are illustrated in Figs. 6 to 8.

Table 1 Parameters of the permanent magnet synchronous motor machine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated output power/W</td>
<td>7 500</td>
</tr>
<tr>
<td>Rated phase voltage/V</td>
<td>300</td>
</tr>
<tr>
<td>Magnetic flux linkage/Wb</td>
<td>0.867</td>
</tr>
<tr>
<td>Poles</td>
<td>24</td>
</tr>
<tr>
<td>Rated torque/(N m)</td>
<td>500</td>
</tr>
<tr>
<td>Base speed/(rev/min)</td>
<td>100</td>
</tr>
<tr>
<td>Stator resistance/Ω</td>
<td>2.2</td>
</tr>
<tr>
<td>$d$-Axis inductance/H</td>
<td>0.044 8</td>
</tr>
<tr>
<td>$q$-Axis inductance/H</td>
<td>0.102 7</td>
</tr>
</tbody>
</table>

It can be seen from Fig. 6 that there are improvements due to use the time method of low speed measurement [12].

The dynamic performance of the speed control loop of DTC systems (Fig. 7) shows that the dynamic speed response is very fast and it quickly reaches 20 r min$^{-1}$.

From the rotor position response of PMSM DTC System (Fig. 8), it can be concluded that ripples of the flux linkage, the torque, and the speed in the fuzzy logic DTC are smaller than that in a conventional DTC system.

The measured shaft torque $T_s$ of the test motor (Fig. 9) shows that the torque, flux linkage and the speed ripple under the modified DTC are greatly reduced. The drive can work successfully with full load at 20 r min$^{-1}$ (Fig. 6).

5 Conclusion

We presented a specific speed servo controller based on FPGA implementation. The proposed DTC scheme integrated vector transformation, T speed measurement, fuzzy regulation, SVPWM and other function modules. A fuzzy logic controller was designed and implemented with a suitable shape of membership function. Experiment results show that in torque step command response and frequency command response, the rotor position of PMSM can fast track the prescribed dynamic response well.
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References


