VECTOR CONTROL DRIVE OF PERMANENT MAGNET SYNCHRONOUS MOTOR BASED dSPACE DS1103 IMPLEMENTATION

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Abstract—This paper presented a vector controlled drives of permanent Magnet Synchronous Motor (PMSM) by using Proportional-Integral (PI) Speed controller based dSPACE implementation. The concept of vector control is applied to PMSM to obtain linear dynamics similar to that of a DC motor. The model consist of two control loops, hysteresis current controller is used for inner loop current control and PI controller for outer loop speed control. PI speed controller selected due to simplicity compare to fuzzy, neutral etc. to make sure dSPACE DS1103 successfully implemented. The PMSM vector control algorithm for a theoretical basic has been verified by experimental results and created a rapid control prototype environment by using MATLAB/ Simulink and the DS1103 DSP of dSPACE.

Index Terms—PMSM, Vector Control, Simulink, DS1103, Proportional-Integral

I. INTRODUCTION

In recent years, with the rapid development of electric power electronic Permanent magnet synchronous motors are progressively replacing dc motors in high-performance applications like aerospace actuators, robotics and industrial applications because of precision, efficient, larger torque inertia ratio and power density when compared to the induction motor for the same output capacity. The PMSM is smaller in size and lower in weight that makes it preferable for certain high performance applications [1]. Vector control is normally used in ac machines to convert them, performance wise, into equivalent separately excited dc machines.

The PMSM is a rotating electric machine where the stator is a classic three phase stator like that of an induction motor and the rotor has surface-mounted permanent magnets. In this respect, the PMSM is equivalent to an induction motor where the air gap magnetic field is produced by a permanent magnet. The use of a permanent magnet to generate a substantial air gap magnetic flux makes it possible to design highly efficient PMSM. Many intelligent control techniques, such as fuzzy control, neural networks control, adaptive fuzzy control, etc., have been developed and applied to the precision position

control of servo motor drives to obtain high operating performance. A high performance motor control system should have a fast dynamic response in adjusting its control parameters so that the motor outputs affected by the disturbances can recover to their original status as soon as possible [2].

In [2], with the rapid development in microprocessor, the high performance DSP chip becomes a popular research on digital control for ac drives due to their high-speed performance, simple circuitry, on-chip peripherals of a micro-controller into a single chip solution. The experimental results demonstrate that in step command response and frequency command response, the rotor position of PMSM can fast track the prescribed dynamic response well. However, the whole system required a complicated operation of the proposed control algorithm, programming and difficulty on control design modification.

In [3], a vector control implemented on PMSM in real time with ADMC-401 motor control DSP. The time varying abc currents are made stationary using Reverse Park Transformation, to simplify the calculation of PI controller's constants. This method enables the operation of the drive at zero direct axis stator current. Therefore, with minimum armature current can obtain maximum torque per ampere and maximum efficiency. The performance of vector control is satisfactory for achieving fast reversal of PMSM even at very high speed ranges systems. However, the ADMC-401 motor control DSP required programming or debugging control languages to develop the control system and is not practical feasibility on robust control.

In [4], have shown the practical feasibility of the proposed approach that allows robust control of the induction. The control algorithm is build within Simulink environment combined with the Real- Time Interface (RTI) provided by dSPACE and is implemented by the main processor of the DS-1103 board in real-time. The combination of dSPACE DS1103 DSP and MATLAB/Simulink effectively created a rapid control prototype environment, in which the designer focused on control design rather than programming details or debugging control languages.

Therefore, in this paper, a DS1103DSP embedded with the Real-Time Interface (RTI) provided by dSPACE, hysteresis current controller scheme and PI control has been developed for a high performance control for PMSM drives. With the excellent characteristics of the proposed system, it created a

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II. PMSM Dynamics

The machine model for the PMSM on the synchronously rotating d-q reference frame can be represented as [5]:

$$V_{qs} = r_s i_{qs} + p \Psi_{qs} + \omega_r \Psi_{ds} \qquad (1)$$

$$V_{ds} = r_s i_{ds} + p \Psi_{ds} - \omega_r \Psi_{qs} \qquad (2)$$

$$\Psi_{qs} = L_{qs} i_{qs} \qquad (3)$$

$$\Psi_{ds} = L_{ds} i_{ds} + \Psi_f \qquad (4)$$

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left[\Psi_f i_{qs} + \left(L_{ds} - L_{qs}\right)i_{ds} i_{qs}\right] \qquad (5)$$

$$T_e = Jp\,\omega_r + B\omega_r + T_L \qquad (6)$$

Where:

i_{ds}, i_{qs}	: d-q axis stator currents
L_{ds}, L_{qs}	: d-q-axis inductances
r_s	: stator resistance
Ψ_f	: constant magnet flux linkage
ω_r	: motor speed
p	: number of pole
T_L	: load torque
B	: damping co-efficient
J	: rotor inertia
T_e	: electromagnetic torque

Vector control actually is control of phase and amplitude for at motor stator voltage or current vector at the same time. There are two types of permanent magnet synchronous motor : the surface and inside buried. For surface PMSM, the straight axis and cross axis for the main inductance is equal ($L_d = L_q$) and for the inside buried, the cross axis of main inductance is not equal ($L_d \neq L_q$). From the equation (5) show the torque depend on the inductances (L_d, L_q), type of rotor, magnet flux on the permanent magnet mount on the rotor and number of pole. With $L_d = L_q$, the electromagnetic torque can be expressed as

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left[\Psi_f i_{qs}\right] \qquad (7)$$

An optimal efficiency PMSM is to ensures that stator current phasor contains only a quadrature axis component i_q. This is analogous to the separately excited DC machine, where this is achieved by consecutive switching of the armature coil through the commutator [6].
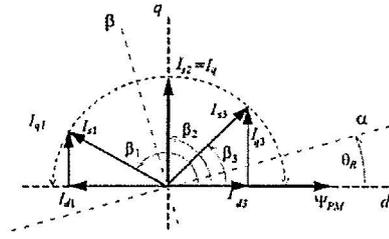
Fig. 1. Different locations of the stator current vector.

General expression of the torque can be written as

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\Psi_f |i_s| \sin\beta \qquad (8)$$

In the Fig. 1 shown how the I_q is changing with the change of I_s position, which results in a change in angle β. To achieved maximum torque can be obtained with an angle $\beta = 90°$, this mode of operation gives the maximum torque per ampere of stator current and a high efficiency[6].

III. System Description

A speed control system of the vector controlled PMSM drive is illustrated as Fig. 2. The control system is combination of two major elements: the Simulink/dSPACE and Hardware interface. Data of the motor used are given in Table I. The rotor speed, ω_r is compared with ω_r* from resolver digital converter (RDC) and the resulted error is processed in the PI controller. The output of controller is reference torque, T* which is then has been limited by a limiter in order to generate the q-axis reference current, i_{qs}*. (Refer to Fig. 3). Meanwhile, d-axis reference current, i_{ds}* is set to zero. Both d-axis and q-axis stator currents generate three phase reference currents (i_a*, i_b* and i_c*) through Park's Transformation which are compared with sensed winding currents (i_a, i_b and i_c) of the PMSM. The current errors are fed to hysteresis current controllers which generate switching signals (S_{abc}*) for the voltage source inverter. Optocouplers used as isolator to protect the dSPACE from overvoltage damage at inverter. Thus, by obtaining winding currents of the system, the speed response is obtained.
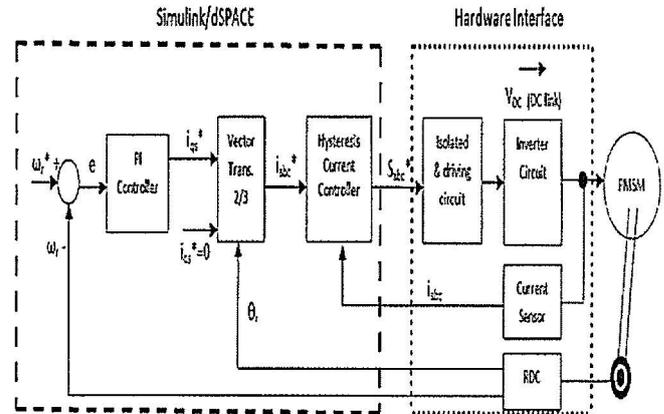
Fig. 2. Configuration of vector controlled PMSM drive
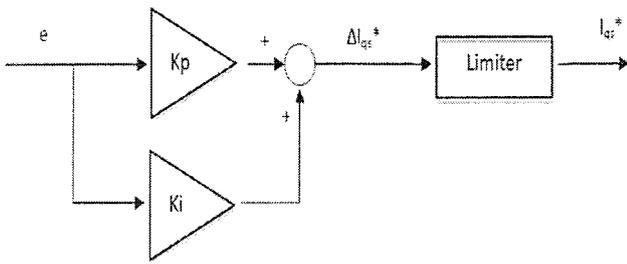
Fig. 3. PI Controller with Limiter

The transformation of synchronous machine from the a-b-c phase variables to the d-q variables transforms all are sinusoidal varying inductances in the a-b-c frame into constants in the d-q frame. Park transformation used to convert stator winding quantities such as current, voltage and flux linkage to the d-q references frame that is attached to the machine rotor [7,8].

$$
\begin{bmatrix} U_o \\ U_{ds} \\ U_{qs} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \tag{9}
$$

As references frame is selected firmly attached to the rotor, only the stator equations need to be transformed from the stationary references frame to the rotating references frame. The two-axis d-q current references are transformed into three-phase stator current references. The correlation between d-q axis current references and stator phase current is given as below:

$$
\begin{bmatrix} i_a{}^* \\ i_b{}^* \\ i_c{}^* \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta - \frac{4\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_o \end{bmatrix} \tag{10}
$$
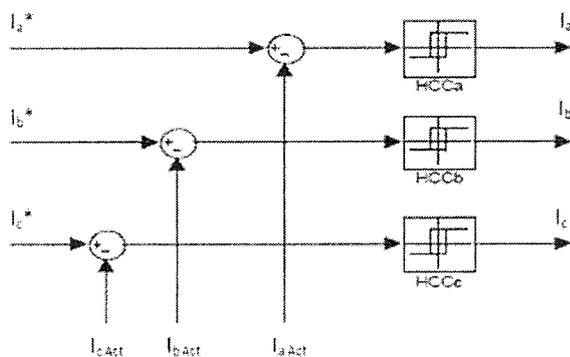
Fig. 4. Hysteresis Current Control

In the Fig. 4 show the block diagram for hysteresis controller in order to produce the output signal. The actual

phase currents (i_a, i_b, i_c) are compared with reference phase current ($i_a{}^*$, $i_b{}^*$, $i_c{}^*$) using three independent comparator in hysteresis controller. The logic condition for six inverter switches is chosen by the output of the comparator [9]. When the phase "a" current is smaller than (i*-Δi), where Δi is the hysteresis band, the output of the comparator is "1", the "a" phase will be connected with the positive track of DC link. In contrast, if the phase "a" current is bigger than (i*- Δi), the output of the comparator will become "0", and the "a" phase will connected to the negative track of DC bus. A similar procedure exists in the other legs. The reason that this is called a hysteresis controller is that the leg voltage switches to keep the phase current within the hysteresis band. The phase currents are, therefore, approximately sinusoidal in steady state. The smaller the hysteresis band, the more closely do the phase currents represent sine wave. Small hysteresis band, however, imply a high switching frequency, which is a practical limitation of the power device. Increased switching frequency also implies increased inverter losses.

TABLE I.   PMSM TEST MOTOR

Parameter	Value
Maximum torque	10.8 Nm
Rated torque	3.6 Nm
Rated current	6.29 A
Maximum current	16 A
Rated speed	418 rad/s (4000rpm)
Inertia	0.000553 kgm^2
Stator winding resistance	2.2 Ω
Inductance	8.2 mH
Voltage Constant	57.5 Vpk/krpm
Pole pairs	2
V_{DC}	300 V

IV. SIMULATION AND EXPERIMENTAL RESULTS

The control system for PMSM includes dSPACE DS1103 DSP-board, PMSM coupled with DC generator as a dynamic load, isolate and driving circuit, personal computer (PC), current sensor, RDC and an inverter circuit. The dSPACE DS-1103 DSP board [10] forms the core of the closed loop system. Aside from the duties of controlling the operator interface, it perform the acquisition of the feedback signal, computes a speed signal, delivers the speed signal to the control algorithm, and executes the control algorithm to determine a control signal. A variable DC power supply is used as DC link and a DC power supply is used to supply the isolator and driving circuit with 15V DC. The isolate and driving circuit was combination of 6 units optocoupler HCPL3020 with high speed response 0.7us to protect damage on DS1103 DSP and six units of SKHI22A with 100KHz switching frequency used as driver of the IGBT module for inverter. The PC is a Pentium (R) Dual CPU 1.19GHz with Windows XP. Fig. 5 showed the experimental rig.

Fig. 5. The experimental rig

Fig. 6. The schematic diagram of experimental rig.

Fig. 7. Real-Time control prototyping

Control Desk is a user interface that allows the user to run simulations on different platforms such as the real-time DS1103 Controller Board, fig. 8 expanded layout window in ControlDesk[10].

Fig. 8 Expanded layout window in Control Desk

The motor is 4000 r/min three-phase. It is equipped with resolver. The RDC use to convert resolver signal to the speed and angle from PMSM as feedback signal. The motor is also coupled with a DC Generator as a dynamic load. A variable resistive load is connected to the terminals of the DC generator. To achieve sudden disturbances, the dSPACE send a signal to trigger and activate a relay to switch resistive load turned ON and OFF.

The control algorithm is build within Simulink environment combined with the Real-Time Interface (RTI) provided by dSPACE and is implemented by the main processor of the DS-1103 board in real-time fig. 7.

In the experiment, the sampling time is 10 µs. A low pass third order Butterworth filter is used for noise elimination and the passband edge is 100 rad/s. With P is 1.8 and I is 0.1, no load start with speed command is 500rpm at t = 1s, t = 6s when the step down command to 400rpm. Waveforms as follows:

Fig. 9. Speed response curves
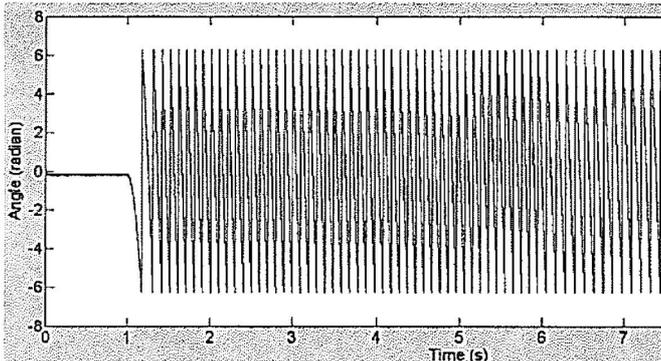
Fig. 10. Rotor position waveform
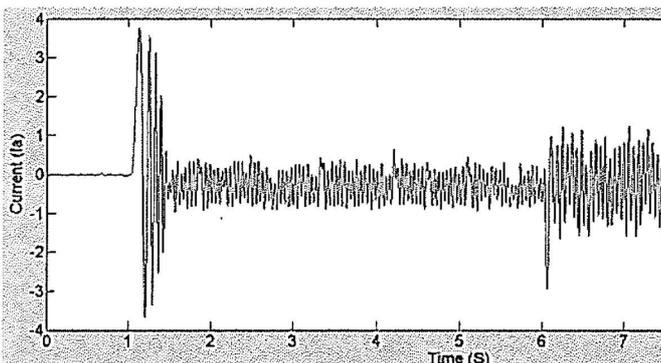
Fig. 11. Ia current waveform
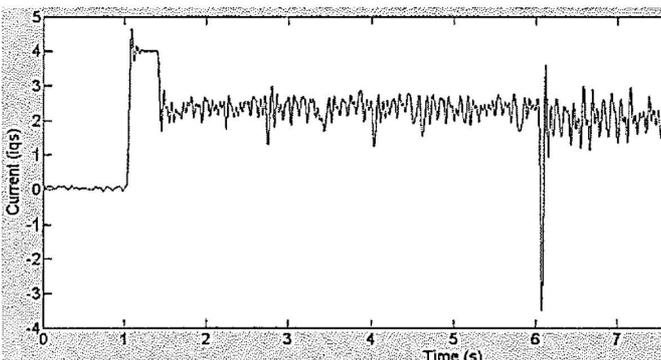
Fig. 12. q axis current waveform

When applied load disturbances on the PMSM, the DC generator have high inertia and caused PI controller need to retuning on PI value to make sure PMSM operate at optimum performance. In this case, P is 15 and I is 0.395, the system is

loaded with 0.85Nm at instant time, $t = 1$s and the results are showed in Fig.13.
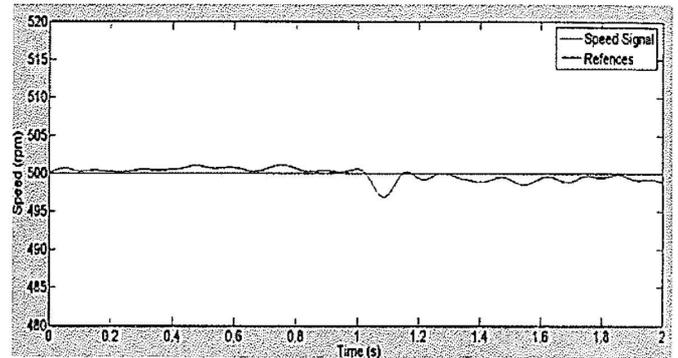
Fig. 13. Load disturbance waveform

The speed controller reject load disturbance rapidly without overshoot and almost zero steady state error at speed command 500rpm.

V. CONCLUSION

From the experimental results have shown the practical feasibility of the proposed approach that allows robust control of the PMSM. The system can run smoothly, has good static and dynamic characteristics. Experiment and validate id = 0 is a good control algorithm. It provides a guideline of designing and debugging for practical PMSM system in real time. The combination of dSPACE DS1103 DSP and MATLAB/Simulink effectively created a rapid control prototype environment with good dynamic performances of the developed drive systems and show the validity of simple.

VI. REFERENCES

[1] P. Pillay and R. Krishnan. Modeling, simulation, and analysis of permanent-magnet motor drives, part 1: The permanent-magnet synchronous motor drive. *IEEE Trans. Ind. Appl., 25(2), 1989.*

[2] Ying-Shieh Kung and Pin-Ging Huang, "High Performance Position Controller for PMSM Drives Based on TMS320F2812 DSP", *in Proc International Conference on Control Applications, Sept 2-4, 2004, pp. 290 - 295 Vol.1.*

[3] R.K. Sharma, V. Sanadhya, L. Behera and S. Bhattacharya, "Vector control of a permanent magnet synchronous motor", *in Proc. INDICON, Dec 1-13, 2008, pp. 81 - 86.*

[4] S. Amamra, L. Barazane, M.S. Boucherit and A. Cherifi, "Inverse fuzzy model control for a speed control induction motor based dSPACE implementation", *in Proc. MEPS, Sept 20-22, 2010, pp. 1 - 5.*

[5] J. Zare, and M. Askari, "Vector Control of permanent magnet synchronus motor with surface magnet using genetic algorithm fuzzy logic controller" *in 45th Intl. UPEC, Aug 31 - Sept 3 2010, pp. 1-4.*

[6] S. Marek, H. Valeria and F. Marek, "Permanent magnets synchronous motor control theory," *in Journal of ELECTRICAL ENGINEERING, VOL. 58, NO. 2, 2007, pp. 79-84*

[7] Peter Vas, "Sensorless Vector and Direct Torque Control", pp 46, 1998

[8] P. Pillay and V. Levin, "Mathematical models for induction machines", *in Proc. Industry Applications Conference, Oct 8-12, 1995, pp.606 - 616 Vol.1*

[9] Z. Li and S. Fengchun, "Torque control of dual induction motors independent drive for tracked vehicle," *in 2008 10th Intl. Conf. on Control, Automation, Robotics and Vision, 2009, pp. 68-72.*

[10] dSPACE User's Guide, Digital Signal Processing and Control Engineering, dSPACE, Paderborn, Germany, 2003.