Design and Simulation Vector Control of Permanent Magnet Synchronous Motor

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Abstract— Motor drives are essential in many industrial applications such automotive, robotics, power and energy industry. The motor drives need the information of rotor speed to achieve speed control. Rotor speed can be measured by sensors attached to rotor shaft which sends the motor speed to the motor drive. However, using sensors in the rotating shaft is not always practical.. The entire PMSM control system is divided into several independent functional modules such as PMSM body module, inverter module and coordinate transformation module and Sinusoidal pulse width modulation (SPWM) production module and so on. we can analyzed a variety of simulation waveforms and it provide an effective means for the analysis and design of the PMSM control system PMSM (Permanent Magnetic Synchronous Motor) has been increasingly used in many high performance application due to its advantages of high power density, high power factor and efficiency. Firstly, a SVPWM scheme, vector control method and fuzzy controller are derived and applied in the speed control IC of PMSM drive.

Key words: Vector Control Permanent Magnet Synchronous Motor (PMSM); PI Controller and Limiter

I. Introduction

The quality of permanent magnet (PM) material has improved and attracted considerably contribution in the development of permanent magnet AC (PMAC) motors [1]. PMAC motor with sinusoidal back emf known as permanent magnet synchronous motor (PMSM) is commonly applied in industrial application. It can be further categorized into surface mounted rotor magnet (SPMSM), inset rotor magnet, and interior PMSM (IPMSM). Due to its simple structures, high efficiency, low inertia, and high power density, PMSM is implemented as adjustablespeed drives in automotive industry and several application such as robotics and aircrafts. But, to attain the optimal drive performance, the design of PMSM requires matched drive that leads to become attractive topic to the researchers [2]. The nonlinearity coupling among its winding current and rotor speed [3] complicates the design of motor drive. Generally, control techniques for PMSM especially in adjustable-speed drives of the automotive application can be divided into scalar control which adjusts only magnitude and vector control which adjusts both magnitude and instantaneous position. The differential quadrature dq-axis current control are the important parameters in vector control technique [4]. Field oriented control (FOC) is the vector control technique that employs the coordinate transformation of motor equation in dq-axis frame which synchronously rotates with PM flux [5]. It controls motor stator currents in the form of space vector [6]. Due to its fast dynamic response, simple control structure, and energy efficient operation FOC is one of the best vector control technique for PMSM [7]. Speed control system for the manufactured and measured inset rotor PMSM parameters in [8,9] integrates DCDC boost converter, inverter, and sinusoidal pulse width modulation (SPWM). Since the battery voltage in DC source of the speed control system is below the operating voltage of inset rotor PMSM, the converter boosts the battery output voltage feeding the inverter with rated DC bus voltage. The interleaved DC-DC boost converter topology avoids the system suffering from heat and large inductor size [10]. Precise rotor position information Green Process, Material, and Energy: provided by sensors and sine wave generated by SPWM determine the switching of the inverter for driving the motor [11]. Both converter and inverter are controlled by proportional integral (PI) controller due to its simplicity, functional structure, and robust performance [12]. The controller is designed by defining the constant gain which performs correction to parameter error and disturbance of large load. However, tuning the PI constant needs high accuracy since the motor performance will be degraded due to time varying parameters [1]. This paper investigates the effectiveness of the proposed speed control method for driving inset rotor PMSM using FOC and PI controller. Computer simulation is conducted to simulate the designed speed control. The motor control performances are observed in operating condition with disturbance in the form of sudden change of load torque.

II. Previous work

The electric motors are electromechanical machines, which are used for the conversion of electrical energy into mechanical energy. The foremost categories of AC motors are Asynchronous and Synchronous motors. The Asynchronous motors are called singly excited machines i.e. the stator windings are connected to AC supply whereas the rotor has no connection from the stator or to any other source of supply. The power is transferred from the stator to the rotor only by mutual induction, owing to which the asynchronous motors are called as induction machines.

The demo circuit in Simulink for Permanent magnet synchronous motor fed by PWM inverter had a three-phase motor rated 1.1 kW, 220 V, 3000 rpm in The MathWorks Incorporation (2010). The PWM inverter was built entirely with standard Simulink blocks. Its output went through Controlled Voltage Source blocks before being applied to the PMSM block's stator windings. Two control loops were used. The inner loop regulated the motor's stator currents. The outer loop controlled the motor's speed. Line to line voltages, three phase currents, speed and torque were available at the output of the scope blocks. 42 The active filter design to reduce or compensate harmonics in the supply side by injecting harmonics into the line current has been proposed by Fujita et al (2000), Rivas et al (2003), Detjen et al (2001) and Gulez et al (2008), which has no effect on the current supplying the load. Moreover, they are complicated in design, and online filter tuning causes more complexity and hardware implementation is relatively expensive. Islam et al (2009) proposes Skewing designs for the reduction of torque ripples and cogging torque reduction in permanent magnet synchronous motor drive with surface mounted permanent magnets. The effects of the slot/pole combinations and various magnet shapes on the harmonic content of the output torque responses are estimated. It has been found that the torque ripple reduction in the PMSM drive using improved step skewed magnet is a good method but this technique requires adequate attention in the selection of the shape of the magnets. Torque ripple reduction using skewing is more effective in machines as it has a higher optimum skew angle, such as in 9-slot/6-pole and 12-slot/8-pole machines. Another major disadvantage found in these designs is that torque ripple in some motors will increase even after magnet skew, if the magnet shape is not designed carefully. Finite Element Analysis shows that the skewing with steps does not necessarily reduce the torque ripple but may cause it to increase for certain magnet designs and configurations. A H model matching two-degree-of-freedom control with adaptive torque ripple cancellation for direct-drive systems under parameter and load uncertainties for PMSM is investigated by Bogosyan et al (2007) but this hardware implementation is relatively expensive and complicated design. The main causes of torque pulsations are due to the introduction of cogging torque and the non-sinusoidal flux density distribution in the air gap. 43 The main cause for the non-sinusoidal flux density distribution is that the rotor permanent magnet field is variable under the condition of demagnetization, induces this effect of distribution. The torque ripples fluctuate from time to time with the position of the rotor and are redirected by speed pulsations, which influence the PMSM drive efficiency and performance. To estimate flux magnitude, an extended Kalman filter is built by using the state variables, such as stator current and PM flux. This extended Kalman filter method can be used to accurately track the flux linkage of the motor. Xi Xiao & Changming Chen (2010) proposed a current compensation method to moderate the negative influence caused by demagnetization of the permanent magnets. The compensated currents are derived from the estimated flux linkage. The proposed method has been applied to reduce the torque ripple of synchronous reluctance with permanent magnet motor and it could reduce the 6th and 12th flux linkage harmonics. Ma & Li (2011) proposed open type and closed type PID type iterative learning control for linear systems and proved that it can speed up the convergence of the tracking error and the controller parameters the PIDtype learning algorithm. Hao Zhu et al (2012) proposed a control scheme for minimizing the non-sinusoidal flux density distribution in the PMSM motor drives. The DTC scheme of permanent-magnet synchronous motors receives growing attention due to its merits in reducing the current controllers and quicker dynamic response output than the other motor control algorithm schemes. This means that large stator voltage and current harmonic contents exist in the PM motors. Since the variation of motor electromagnetic torque is related to the voltages that are applied to the motor by analysing the relationships between the stator flux, torque, and voltages such a scheme is proposed. A torque dynamic equation is developed for the analysis of torque real time behaviour. 44 The prediction scheme uses incremental changes in the stator flux and the stator current, together with voltage vectors to achieve accurate torque control. Instead of using the increment of stator flux magnitude that might introduce deviation to the calculation, voltage vector is directly handled in the prediction of voltage control angle. The control voltage is accurately oriented according to the rotor flux vector. This scheme simplifies the calculation and improves the accuracy of calculation. Combined with flux control criteria that follows the principle of DTC, the voltage vector control angle is carefully selected to deliver high control performance of both the torque and the stator flux. Jezernik et al (2013) proposed a field-programmable gate array implementation of a variable structure system predictive sequential switching control strategy, as applied to a permanent magnet synchronous machine. In the case of AC motor drives, in contrast to the conventional vector control where the inverter is not taken into consideration by the controller, the proposed control integrates the inverter model and the inverter states. It allows obtaining faster torque dynamics than the vector control algorithms. The main design specifications are a reduced switching frequency and simple hardware implementation. A predictive sliding mode controller has been developed, designed as finite-state machine, and implemented with a FPGA. This new logic FPGA torque and speed controller has been developed, analysed, and experimentally verified. The predictive current VSS control strategy introduced is very simple and powerful, and advantageously considers the discrete nature of power inverters, and the digital controller. Flieller et al (2014) proposed a self- learning solution for minimizing the torque ripples which are caused due to the non-sinusoidal flux density distribution of the permanent magnets based on Artificial Neural Network framework. To calculate the optimal currents are introduced from 45 geometrical considerations which are based on Lagrange optimization. These currents are obtained from the two hyper planes enclosed which depend on the structure of the machine. The author has tried to reduce the presence of harmonics in the cogging torque and the back EMF through Adeline neural structure algorithm. Here in this scheme, the two signals speed and torque are given to the two neural blocks, where one is for optimal current calculation and the other is for the generation of these currents via a VSI. The main disadvantage found in this method is the use of Adaline neural algorithm which makes the training process complex.

III. VECTOR CONTROL

Vector control is also known as decoupling or field orientated control. Vector control decouples three phase stator current into two phase d-q axis current, one producing flux and other producing torque. This allows direct control of flux and torque. So by using vector control, the PMSM is equivalent into a separately excited dc machine. The model of PMSM is nonlinear. So by using vector control, the model of PMSM is linear. The scheme of vector control is based on coordinate transformation and motor torque equation by means of controlling stator current to improve the performances of motor, and is widely used in the field of PMSM servo system. In the control of a threephase PMSM system, modulated current is supplied to the A-B-C stator windings to build rotated magnetic field and drive the rotator. The vector control strategy is formulated in the synchronously rotating reference frame. By Clarke–Park transformations and inverse transformations the equivalent relations of currents are built among a.b,c stator coordinates, stationary α, β axis coordinates and rotating d, q axis coordinates. Fig.2. shows a vector diagram of the PMSM. Phase a is assumed to be the reference. The instantaneous position of the rotor (and hence rotor flux) is at θr from phase a. The application of vector control, so as to make it similar to a DC machine, demands that the quadrature axis current iq be in quadrature to the rotor flux. Consequently id has to be along the rotor flux since in the reference used id lags iq by 90º. If id is in the same direction as the rotor flux, the d axis stator flux adds to the rotor flux that leads to increase in the net air gap flux. On the other hand if id is negative then the stator d-axis flux is in opposite to that of the rotor flux resulting in a decrease in air gap

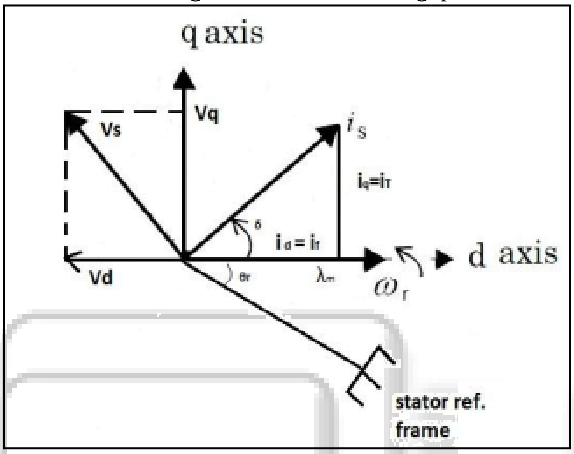


Fig. 2: Phasor diagram of PMSM

The PMSMs are designed such that the rotor magnet alone is capable of producing the required air gap flux up to the rated speed. Hence id is normally zero in the constant torque mode of operation. Consider three phase currents are:

$$ia = is\ \sin(\omega r\ t + \delta)$$

$$ib = is\ \sin(\omega r\ t + \delta - 2\pi\ 3\ )$$

$$ic = is\ \sin(\omega r\ t + \delta + 2\pi\ 3\ ) \quad (11)$$

iq = Torque-producing component of stator current = It

id = Flux-producing component of stator current = if we make

id = 0 by δ = 90º then the electric torque equation (9) becomes:

$$Te = (3/2)(P/2)\ \lambda m\ iq$$

Hence the electric torque depends only on the quadrature axis current and a constant torque is obtainable by ensuring that iq is constant. The constant air gap flux required up to rated speed. Vector control is therefore only possible when precise knowledge of the instantaneous rotor flux is available. Hence it is inherently easier in the PMSM than in the induction motor because the position of the rotor flux is uniquely determined by that of the rotor position in the PMSM. Hence with the application of vector control, independent control of the torque (iq) and flux (id) producing currents are possible.

A. PMSM Equation

A Non-linear differential equations formulated in the magnetic field-fixed d,q co-ordinate system describe the permanent magnet synchronous motor and form the basis of the control system development.

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_d} & p\omega_r\frac{L_q}{L_d} \\ -p\omega_r\frac{L_d}{L_q} & \frac{-R_s}{L_q} \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} - \frac{p\omega_r}{L_q}\begin{bmatrix} 0 \\ \Phi_{PM} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix}\begin{bmatrix} u_d \\ u_q \end{bmatrix}$$

IV. PROPOSED WORK

In order to achieve better dynamic performance, a more complex control scheme needs to be applied to control the PM motor. With the mathematical processing power offered by the microcontrollers, advanced control strategies can be implemented, which uses mathematical transformations in order to decouple the torque generation and the magnetization functions in the PM motors. Such decoupled torque and magnetization control is commonly called rotor flux oriented control, or simply FOC. Independent Control of Torque and Speed can be achieved by using the Field Oriented Control where two currents responsible for Torque and Field are separately resolved and Controlled (q axis current and d axis current). in MATLAB Vector control techniques have made possible the application of PMSM motors for high performance applications where traditionally only dc drives were applied. The vector control scheme enables the control of the PMSM in the same way as a separately excited DC motor operated with a current regulated armature supply where then the torque is proportional to the product of armature current and the excitation flux. Similarly, torque control of the PMSM is achieved by controlling the torque current component and flux current component independently.

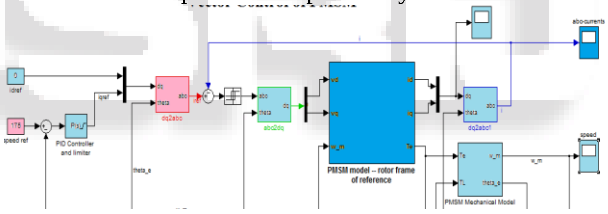


Fig. 2 Simulation model

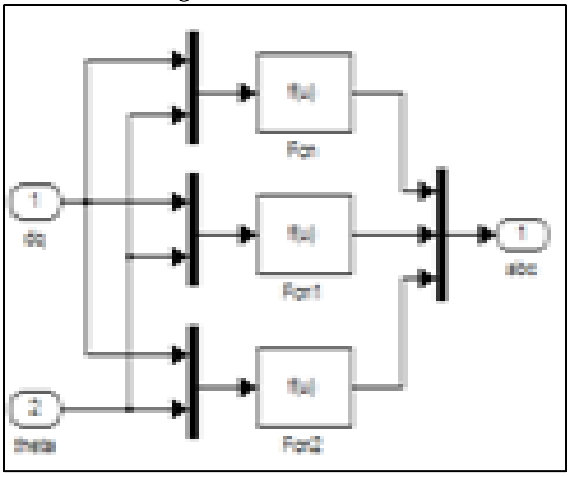


Fig. 3: Pmsc-sub model -1

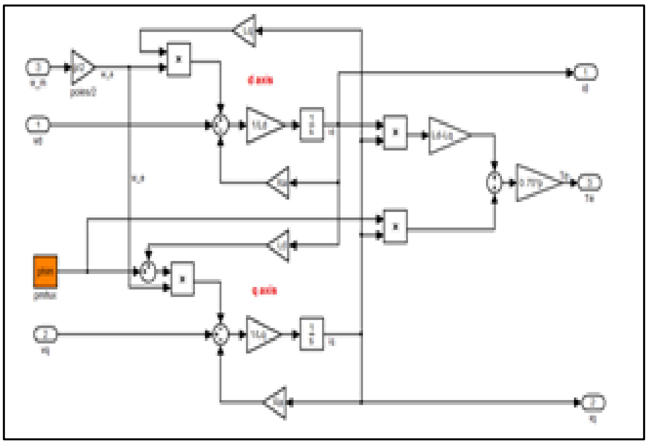


Fig. 3: PMSC-sub model

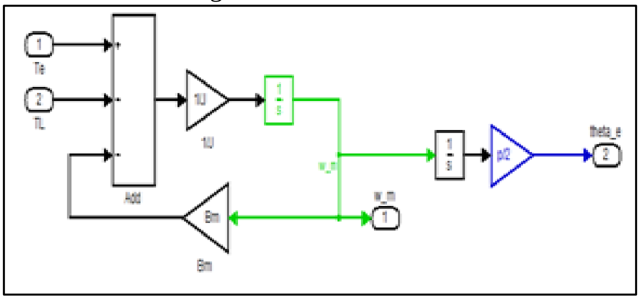


Fig. 1: PMSC-sub model -1

V. Simulation and Result

MATLAB Software is used to perform the simulation during this work. Different models have been developed for different speed control scheme in accordance. All the simulations are performed in discrete environment with sampling time in the order of microseconds. Numerical algorithm is used for the last one. The machine parameters throughout simulation are particular in the sudden change in the load torque TL of the inset PMSM is applied. The load torque is initially at TL 5Nm, then it is changed at t 0.5s to TL 35Nm as can be seen in Fig 7. It can be seen that the electromagnetic torque can tag along the load torque even there are oscillation at the motor starting phase and at the unexpected load torque change. The interleaved DC boost converter output is desired to be 170V to fulfil the inset rotor PMSM motor voltage. Fig 8 shows the performance of boost converter, the reference voltage Vref _ boost 170V need to be kept constant at all time. However, because of high power consumption, an oscillation occurred at the motor starting phase. Also when the load torque change suddenly at t 0.5s, the boost converter output voltage experiences a second oscillation. On the other hand, the performance of speed controller behaves different. At the starting phase, the response to a step response is very good since there is no overshoot and oscillation. But, when the sudden load torque change as the disturbance is given, there is an oscillation and the steady state error still remains till the end as can be seen in Fig 10.

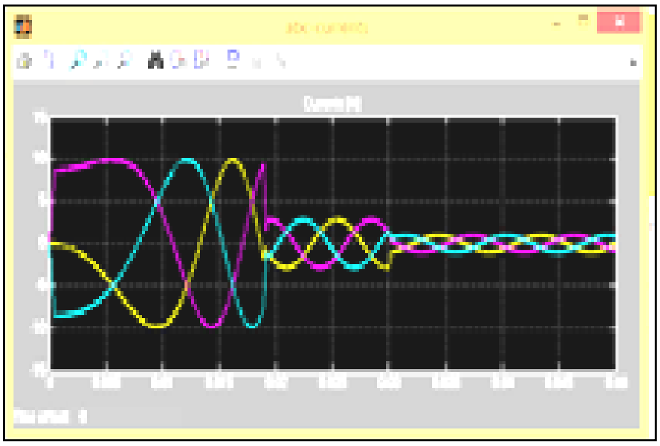


Fig. 6: Current response curve

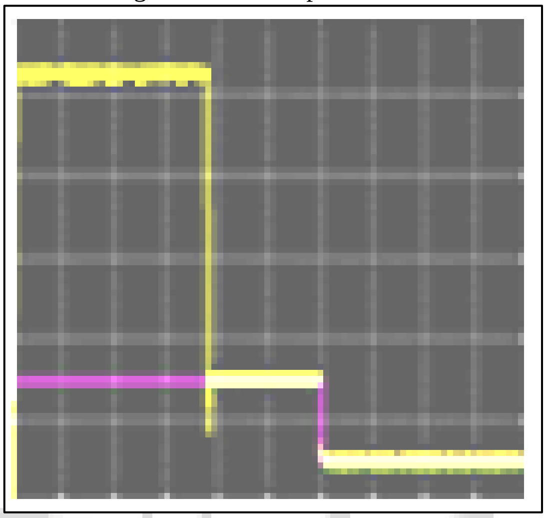
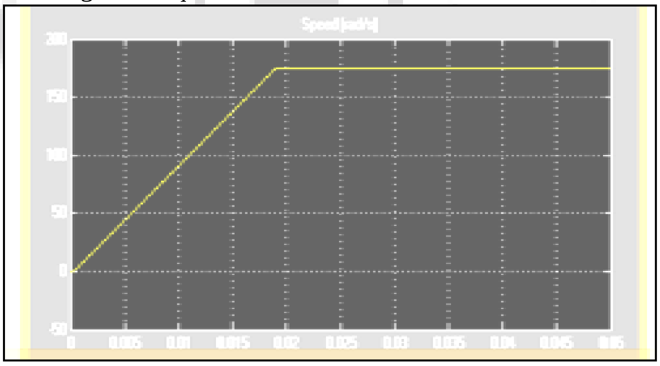


Fig. 7: Torque Vs Time Plot Under load condition



VI. Conclusion

This paper vector control has been described in adequate detail and has been implemented on PMSM in real time. to simplify the calculation of PID controller's constants. This method enables the operation of the drive at zero direct axis stator current. Therefore, it permits the operation at minimum armature current. In this situation, we obtain maximum torque per ampere as well as maximum efficiency. The motor needs much smaller voltage compared to the conventional synchronous motor. This leads to designing a voltage source inverter with lower voltage and current ratings. This voltage source inverter, together with its small size, will reflect a total low cost. The performance of vector control is quite satisfactory for achieving fast reversal of PMSM even at very high speed ranges. The main advantage is that Independently Control of Torque and

Speed can be achieved by using the Vector Control where two currents responsible for Torque and Field are separately resolved and controlled. Thus the Proposed method was designed and was found to be more efficient than the Existing method in terms of the control strategies used

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