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Research paper

Implementation of Field Oriented Control on Permanent Magnet Synchronous Motor

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Abstract

This paper proposes the control of a Permanent Magnet Synchronous Motor through Field Oriented Control algorithm coded on an FPGA controller which can be used in electric vehicles. Field Oriented Control method was chosen as it was found to be useful for electric vehicles for speed control. The paper details the implementation of Field Oriented Control on PMSM using MATLAB and Xilinx. The Hardware setup is 2 level IGBT inverter, FPGA controller and Permanent Magnet Synchronous Motor. Results obtained from practical implementation show that Field Oriented Control was successfully implemented. The speed control of PMSM was achieved and also the objectives of simulating the above scenario and observing power losses was accomplished. The FOC simulation of MATLAB shows system behaving similarly to the set point reference inputs given by the user.

Keywords:*Electric Vehicles; Field Oriented Control; Matlab Simulink; Permanent Magnet Synchronous Motor; Xilinx.*

1. Introduction

In the recent times we have seen a steep increase in the interest growing within the vehicular industry in Electric Vehicles. With the awareness of global warming, more and more people want to take steps in creating a greener tomorrow. The advances in Renewable energy only adds to the benefits of owning an Electric Vehicle. In 2017, renewable energy sources accounted for just 24.38% of the total energy produced. Coming to the efficiency of combustion cars which is about 30 to 40% while the efficiency of an electric vehicle is around 90%.With the dawn of global warming, we as humans have produced a massive amount of carbon dioxide and other greenhouse gases. With the advancements in renewable energy from solar, wind and hydro-power systems, electric vehicles offer a solution to this crisis of carbon dioxide emissions. As electrical engineers, we strive to design the most efficient systems of power conversions. One such domain is that of the Electric vehicles which have zero direct emissions at the point of usage. Coming to motors, the ideal motor is that which has high efficiency, high torque to weight and power to weight ratio. Tesla the leading electric car company uses its own Induction Motor. While Mitsubishi and Nissan use PMSM. The Field oriented control finds its application in industries where constant speed or torque is required.

2. Permanent Magnet Synchronous Motor (PMSM)

The PMSM is a synchronous AC motor, normally with a three phase stator winding similar to induction motors. Depending on the armature winding distribution the PMSM can be divided into two types, Brushless DC (BLDC) or Permanent Magnet AC (PMAC) motors. The PMSM is normally controlled with a frequency converter that supplies the motor with the correct frequency and voltage/current values. Here we will be considering the FOC Vector control method as the control algorithm for the PMSM [1]. The equivalent circuits show the d-axis and q-axis circuits and the Kirchhoff's, Flux linkage and Torque equations are given below:

$$V_d = R*i_d + p*\lambda_d - K\,\omega\lambda_q \qquad (1)$$

$$V_q = R*i_d + p*\lambda_d + K\,\omega\lambda_d \qquad (2)$$

$$\lambda_d = L_d * i_d \qquad (3)$$

$$\lambda_q = L_q * i_q + \lambda_{af} \qquad (4)$$

V_d and V_q represent the direct and the quadrature axis voltages respectively.
R and L_d/L_q are the series resistance and reactance respectively of the direct and the quadrature axis.
λ_d and λ_q are the flux linkages.
L_{md} and L_{mq} represent the mutual inductances of the d-axis and q-axis circuits respectively. In order to maximize the torque production for a given value, the strategy is to set i_d to 0.The electrical torque Te is given by:

$$T_e = (3/2) *p/2 *(\lambda_{af} * i_q + (L_d-L_q) *i_d *i_q) \qquad (5)$$

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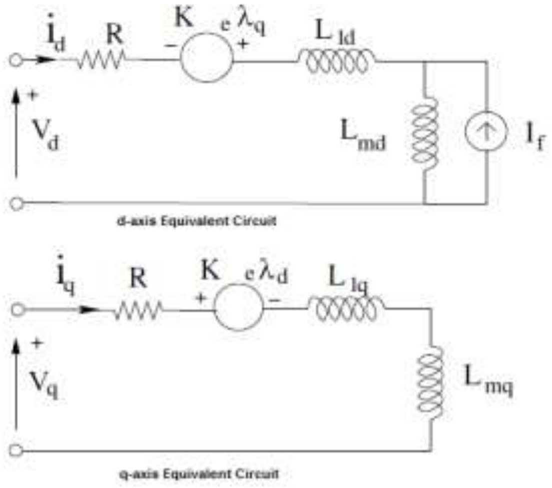

Fig. 1: Direct and Quadrature axis equivalent circuits

3. Field Oriented Control (FOC)

Field Oriented Control is a type of vector control which provides closed loop control of PMSM. Having closed loop control provides great control over the motor. Scalar control is an open loop control which wouldn't be desired. Sensor-less Vector control adds another task of estimating the rotor position and speed, which increase complexity and calculations. Thus we choose Field oriented control which takes feedback of the rotor position and speed via an encoder. The goal of the Field Oriented Control is to perform real-time control of torque variations demand, to control the rotor mechanical speed and to regulate phase currents in order to avoid current spikes during transient phases. To perform these controls, the electrical equations are projected from a 3 phase non-rotating frame into a two co-ordinate rotating frame. This mathematical projection (Clarke & Park) greatly simplifies the expression of the electrical equations and remove their time and position dependencies [2] [3]. This transformation takes the rotating rotor as the reference frame. So the signal value is now a DC value which is much easier to understand and control compared to the 3 phase AC counterpart. It's done using the following equation:

$$V_{\alpha} = V_a \quad (6)$$

$$V_{\beta} = (2V_b + V_a) = p/\sqrt{(3)} \quad (7)$$

$$V_d = V_{\alpha} \cos(\theta) + V_{\beta} * \sin(\theta) \quad (8)$$

$$V_q = V_{\beta} \cos(\theta) - V_{\alpha} * \sin(\theta) \quad (9)$$

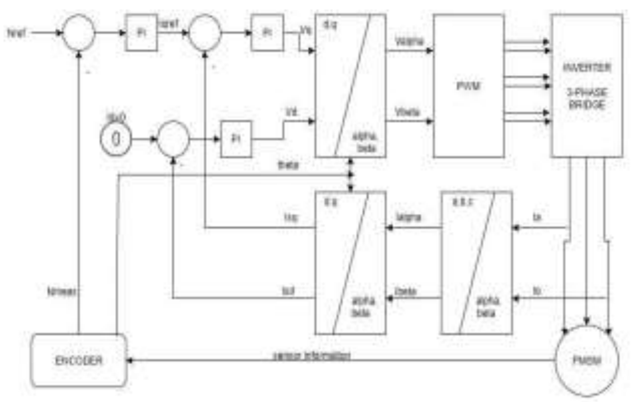

Fig. 2: FOC Block Diagram

4. Methodology and Implementation

The block diagram shows the closed loop FOC technique. The whole system is generated using Xilinx block sets in MATLAB which then is converted into a BIN file and downloaded onto a FPGA controller and will be used to the run the hardware setup comprising of the Rectifier-Inverter setup and the Motor. The encoder provides the angular speed and the angle θ as a feedback from the motor.

4.1. Hardware Implementation

The hardware includes a Baldor PMSM motor with two encoders, a Rectifier-Inverter setup whose voltage is fed through an Auto-transformer, a FPGA based controller and a PC for monitoring and control. Our work majorly involves Logic designing of the Field Oriented Control on MATLAB platform.

4.2. Software Implementation

With the Help of Matlab Simulink and Xilinx System generator the Field Oriented Control algorithm was designed. At first, three sine waves were generated with the help of ROM block (look-up table) of 325V amplitude and 120 phase shift. Next, the carrier wave was generated by first creating a saw-tooth wave which was converted into a triangle wave by using an absolute block which is used as a carrier signal. Comparing each of these three phase sine wave with the carrier wave we get three signals. This signal plus the invert of this signal makes the gating signal for that branch of 2-level inverter. This gives us a total of 6 gating signals. An enable is used to control all the switches. After this we created the model for the field oriented control (FOC) that would be downloaded onto the hardware. This required signal conditioning from signals coming from the absolute encoder, incremental encoder and the sensed current signals [4].

4.3.1 Working of Encoders

The absolute encoder provides a 3 bit signal specifying the rotor position with a resolution of 60° which is too low to be used directly as θ for the Parks/Inverse Parks transformations. The incremental encoder provides 2500ppr (pulses per revolution) that means for a revolution, it provides 2500 pulses. Therefore the resolution is much higher than that of absolute. Therefore we integrated both the absolute encoder and incremental encoder together by writing a MATLAB code that would give an output for θ. This code would not know where the rotor lies at the start when the motor is stationary, therefore we run the motor with the logic of a Brush-less DC motor that doesn't require the θ value for 120° (2 absolute encoder cycles). Then as soon as the position of the rotor is known, we integrate it with the incremental encoder's logic to increase the resolution to 2500ppr which becomes our θ. Now to realize the speed we take a sample of the incremental encoder and count the pulses for a particular duration then we get the speed of the rotor. The sensed current is subjected to multiple amplifications and filters for the FPGA controller to analyze and perform the operation according to the algorithm logic.

4.3.2 PI controllers

Since we are using three PI controllers, two in the inner loop operating as current controllers and one in the outer loop operating as a speed controller, we faced the problem for incorporating the integral function in the controller. Hence the Integral operation is done as follows:

$$Y(n) = Y(n-1) + x(n) \quad (10)$$

The integrator comprises of an accumulator block to continuously accumulate the error and integrate it. All the three PI controller blocks in system are enabled by a common enable signal. This enable signal also resets the accumulator as soon as enable is high, thus removing all the previously accumulated errors in the integrator.

5. Result Analysis

The following results were obtained when the PI controllers were tuned and the voltage levels were kept at the rated value to obtain a user set speed of 1700 rpm. The speed observed with the help of encoders and tachometer was in the range of 1700 ± 10% tolerance with the set speed. Fig. 3 shows the absolute encoder signal that has a 3 bit output (two are scoped). Fig. 4 is the output from the incremental encoder which is in form of pulses of 2500ppr. At inverter side, the peak current was observed to be at 0.26A and the line voltage had a peak of 68.5V when the input voltage was 70V. Fig. 5 shows the three phase voltage measured at the inverter output. Fig 6. Shows the plotting of θ vs Time. Now since the encoder sends back 2500 (PPR), it can be seen in the graph that value of θ varies from 0 to 1249 and then resets i.e. half of 2500 (PPR) as explained in the methodology.

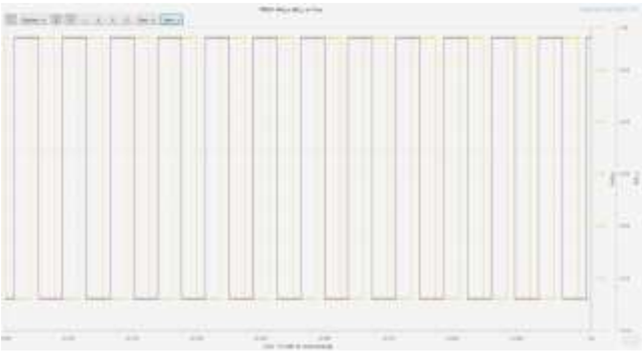

Fig. 3: Absolute Encoder (Hall V & Hall W) pulses.

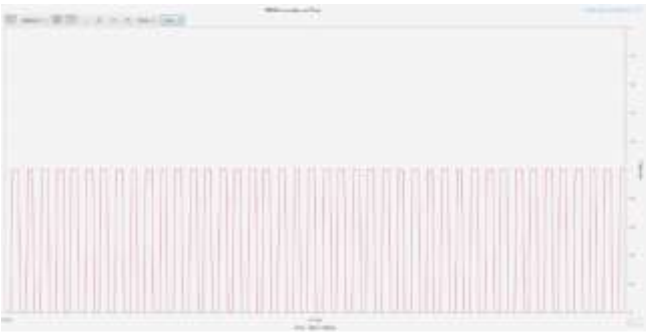

Fig. 4: Incremental Encoder Pulses.

6. Conclusion

The implementation of FOC was achieved using the algorithm designed by us which involved both MATLAB and Xilinx block-sets. The real time and simulations results clearly depict that we were successful in achieving Speed Control on the PMSM. The PI controller parameters vary in the above mentioned range. The data coming from the encoders was analyzed and calculation was done, to observe the real time speed and theta (angular rotation). We were successful in implementing Parks-Clarke's Transform and Inverse Parks-Clarke's Transform. The whole system was tested and iterations were run. The future work for this project is to implement Torque control. Also increase the overall range of operating values for the model such that it can be used on an electric vehicle.

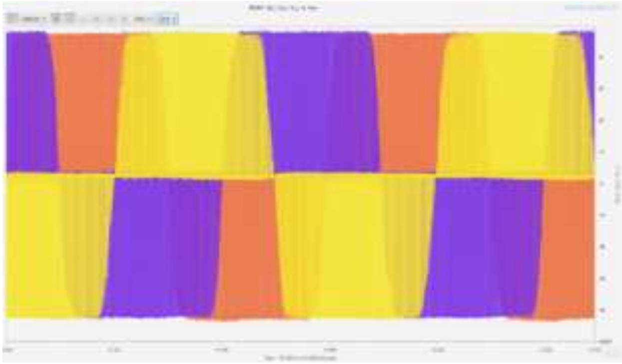

Fig. 5: Three Phase Sinusoidal Output Voltages

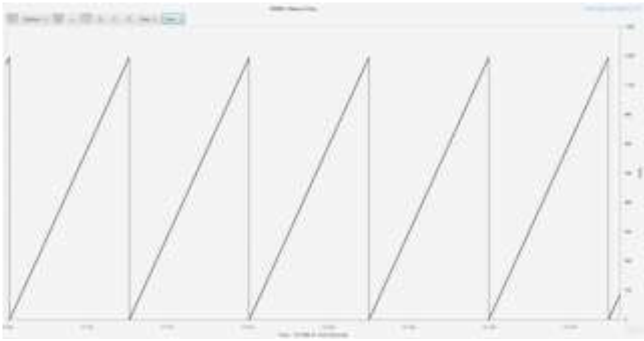

Fig. 6: θ vs Time

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