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Modeling and Simulation of Two phase Synchronous motor using four-leg Inverter

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***Abstract-* In this paper modeling and simulation of two phase permanent magnet synchronous motor is studied using four-leg inverter. Permanent magnet synchronous motor is proposed which reduces field winding losses and complexities of using slip-rings, brushes and commutators. Four-leg inverter gives most appropriate results as compared to two-leg or three-leg inverter. Unipolar pulse width modulation scheme is implemented for getting more reliable results. Essential equations for modeling of synchronous motor are presented here. The performance of two phase synchronous motor is evaluated and detailed analysis is done using matlab simulation.**

***Index Terms-* Two phase permanent magnet synchronous motor, four-leg inverter, unipolar PWM.**

I. INTRODUCTION

Synchronous motors are widely used in constant speed drives at line frequency as well as in variable speed drive with inverter-fed variable frequency supplies [1]-[3]. For such vehicles high torque densities and efficiencies of the electric drive are needed. The total losses of the electric drive shall be as low as possible. Nowadays, three types of electric machines are commonly used in electric vehicles [4]:

- induction machine with squirrel cage structure
- electrically excited synchronous machine
- permanent magnet (PM) synchronous machine

Typically, asynchronous induction machines are very reliable due to its robust design. However, it needs a magnetizing current component to excite the magnetic field. Electrically excited synchronous machine has a separate field winding in the rotor which is usually supplied through slip rings. For induction and electrically excited synchronous machines, additional copper losses takes place due to the currents required for exciting magnetic field. In permanent magnet synchronous machines, the magnetic field is mainly provided by the permanent magnets. Rare earth magnet has a high energy density and shows a very high torque and power density.

A two-phase synchronous motor presents attractive features such as simple and robust structure, high torque density, and high efficiency [5], [6]. Line-start, two-phase synchronous motors [7] are of special interest because they can operate either in constant speed mode while being supplied by a single phase grid or in variable speed mode while being supplied by a two-phase inverter [8].

The main advantages, as compared with induction motors, are the absence of rotor slip power loss and the natural ability to supply reactive current. Since the magnetic excitation may be provided from the rotor side instead of the stator, the machine can be built with a larger airgap without degraded performance. The ability to supply reactive current also permits the use of natural-commutated dc link converters [9]. These motors also have lower weight, volume, and inertia compared to dc motors for the same ratings.

In certain applications, the field excitation can be provided using permanent magnets, thus dispensing with brushes, slip rings and the dc field winding losses [10], [11]. Applications of these permanently excited synchronous motors are found in various industrial drive systems, such as aerospace, machine tools, robotics, precision textiles, etc. The brushless permanent magnet synchronous motors are simply known as permanent magnet ac motors. These motors are either linestart or inverter-fed types whose polyphase stator windings are simultaneously switched on via balanced polyphase supply voltages [12].

II. PERMANENT MAGNET SYNCHRONOUS MOTOR

In a PMSM, the dc field winding of the rotor is replaced by a permanent magnet material to produce the magnetic flux. Due to absence of components like brushes, slip rings and commutator, the motor becomes lighter, power to weight ratio increases and hence efficiency and reliability gets improved.

PM electric machines are classified into two types: PMDC machines and PMAC machines. PMDC machines are like the DC commutator machines; with the field winding being replaced by the permanent magnets. In PMAC the field is generated by the permanent magnets placed on the rotor. PMAC is simpler to use instead of PMDC. PMAC is divided into two types depending on the nature of the back electromotive force (EMF): Trapezoidal type and Sinusoidal type.

The trapezoidal PMAC machines are also called as Brushless DC motors and build up trapezoidal back EMF waveforms with following characteristics:

1. Rectangular distribution of magnet flux in the air gap
2. Rectangular current waveform
3. Concentrated stator windings.

The sinusoidal PMAC machines are also called as Permanent magnet synchronous machines (PMSM) and build up sinusoidal back EMF waveforms with following characteristics:

1. Sinusoidal current waveforms
2. Sinusoidal distribution of stator conductors.
3. Sinusoidal distribution of magnet flux in the air gap

Based on the rotor design the PM synchronous machine can be classified as:

(a) Surface mounted magnet type (SPMSM):

In this case the magnets are mounted on the surface of the rotor. The magnets can be considered as air because the permeability of the magnets is nearly unity and there is no saliency because of same width of the magnets. Therefore the inductances expressed in the quadrature coordinates are equal (Ld = Lq).

(b) Interior magnet type (IPMSM):

In this case the magnets are place inside the rotor. In this configuration saliency is presented and the d-axis air-gap is greater compared with the q axis air gap for which the q axis inductance is greater in value than the d axis inductance.

The permanent magnet synchronous motor examined is the two phase permanent magnet synchronous motor. Thus armature has only two windings, d axis and q axis winding. If the direct (d) axis winding is ssumed to be centered magnetically in the center of the north pole. Then the quadrature(q) axis winding is 90 electrical degrees ahead of the d-axis. The selection of q-axis as leading to d-axis is purely arbitrary. Alternate option may also be chosen. The machine consists of two essential elements: the field and the armature. Field winding carries direct current and produces a magnetic field which induces alternating current voltages in the armature windings. The armature winding operates at voltage higher than that of the field and hence required more space for insulation. Normal practice is to have the armature on stator. The armature is subjected to a varying magnetic flux, the stator iron is built up of thin laminations to reduce eddy current losses. When carrying balanced two phase currents, the armature will produce a magnetic field in the air gap rotating at synchronous speed. The field produced by the permanent magnet on rotor, on the other hand revolves with the rotor. Here rotor used is of permanent magnet type hence no field windings are considered. For the production of a steady torque, the fields of stator and rotor must rotate at the same speed. Therefore the rotor must run at precisely the synchronous speed. The number of field poles is determined by the equation (1).

$$N_s = \frac{120f}{P} \qquad (1)$$

Where, f= frequency of armature windings and P= number of poles.

Some characteristic features of Synchronous motors are as follows:

- It runs at synchronous speed or not at all i. e. while running it maintains synchronous speed.
- It is capable of being operated under a wide range of power factors, both lagging and leading. Hence it can be used for power correction purpose, in addition to supplying torque to drive.
- As load on motor is increased, rotor progressively tends to fall back in phase but not in speed as in dc motors.
- Permanent magnet synchronous motor has sinusoidal back emf.
- High reliability even at very high achievable speeds due to its brushless structure.
- High efficiency.
- Driven by multi phase inverter controllers.
- Sensor-less speed control is possible.
- Appropriate for position control.

A. The Mathematical modeling of PMSM

The model of PMSM without having damper winding is developed on stator reference frame using the following assumptions:

- The induced EMF is sinusoidal.
- Eddy current and hysteresis losses are negligible.
- There are no field current dynamics, are assumed to be constant.
- The stator windings are balanced with sinusoidal;y distributed magneto-motive force.

The PMSM motor equations of stator fluxes, voltages and electromagnetic torque in stator frame of reference are as follows:

$$\lambda_{sd} = L_{sd} i_{sd} + \lambda_M \qquad (2)$$

$$\lambda_{sq} = L_{sq} i_{sq} \qquad (3)$$

$$v_{sd} = R_s i_{sd} + \frac{d}{dx}\lambda_{sd} - \omega_r \lambda_{sq} \quad (4)$$

$$v_{sq} = R_s i_{sq} + \frac{d}{dx}\lambda_{sq} + \omega_r \lambda_{sd} \quad (5)$$

$$T_e = P(\lambda_{sd} i_{sd} - \lambda_{sq} i_{sq}) \quad (6)$$

$$T_e - T_l = J\frac{d\omega_r}{dt} \quad (7)$$

Where as,
λ_{sd} = d-axis stator magnetic flux,
λ_{sq} = q-axis stator magnetic flux,
λ_M = rotor magnetic flux,
L_{sd} = d-axis stator leakage inductance,
L_{sq} = q-axis stator leakage inductance,
R_s = stator winding resistance,
T_e = electromagnetic torque,
T_l = motor load torque,
P = number of poles.

Equations (2) and (3) give d-axis and q-axis stator magnetic fluxes respectively. Equations (4) and (5) give direct and quadrature axes voltage equations. In which quadrature axis voltage leads the direct axis voltage by 90° electrical. Electromagnetic torque is calculated using equation (6). Synchronous speed of Synchronous motor is being calculated from Equation (7).

III. FOUR-LEG INVERTER

The operation of two leg inverter is weak, but because of minimum number of switches, it is low cost approach. In the applications in which the middle point of dc voltage is accessible, using a two-leg inverter is an acceptable approach. When the middle point of dc voltage is inaccessible, utilizing this scheme needs not only two capacitors with high capacitances but also a voltage equalizing circuit [5]. Voltage equalization can be done by using resistors in parallel to capacitors. This increases the volume of drive system and power loss [13].

Another approach is utilization of charge-balancing circuits [14] which makes the drive circuit complicated and costly. A noticeable limitation of three-leg inverters in controlling two phase motors is that the RMS value of common leg current is higher than those of other two legs [15], [13] that necessitates utilization of switches with higher current ratings in one leg. When integrated power modules are used, the entire module should be of higher current ratings. This makes the cost enhancement more noticeable. This additional cost as well as better performance of four-leg inverter makes the use of four-leg inverter justifiable in high performance applications [16].

Here four-leg inverter is implemented, containing two series connected Insulated Gate Bipolar Transistor's (IGBT) in one limb respectively. The circuit diagram of four-leg inverter is shown in Fig. 1. Between first two legs, d-axis winding of synchronous motor is connected and between last two legs, q-axis winding of synchronous motor is connected. IGBT's are preferred because it has low switching losses and require no snubber circuits for its operation. Gate signals of IGBT's are controlled using Unipolar Pulse Width Modulation (PWM). The advantages of Unipolar PWM are as follows:

- It has low switching losses.
- Total Harmonic Distortion (THD) of signals is low.
- It also reduces error band width of signals.

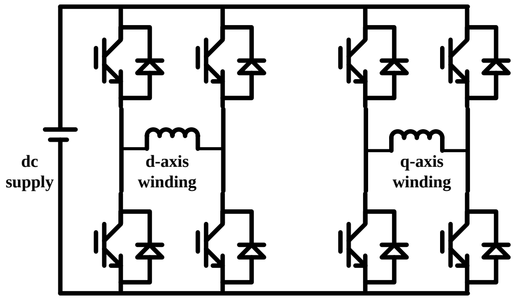


Fig. 1. Two phase two level four leg inverter

IV. IMPLEMENTING MODELLED EQUATION by SIMULINK

Using Equations (2)-(7) modeling of two phase permanent magnet synchronous motor is done. Firstly using Equations (4) and (5), d-axis and q-axis fluxes are calculated in subsystem one as shown in Fig. 2. After using this calculated fluxes and Equations (1) and (2), d-axis and q-axis currents are derived in subsystem two as shown in Fig. 2. Then using all these derived quantities and Equation (5) torque is obtained. From torque value and using speed Equation (7) synchronous speed is calculated. In this way two phase synchronous is modeled.

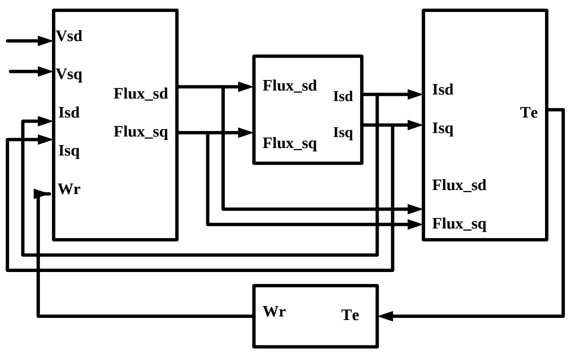


Fig. 2. Model of Two phase synchronous motor

V. RESULTS AND ANALYSIS

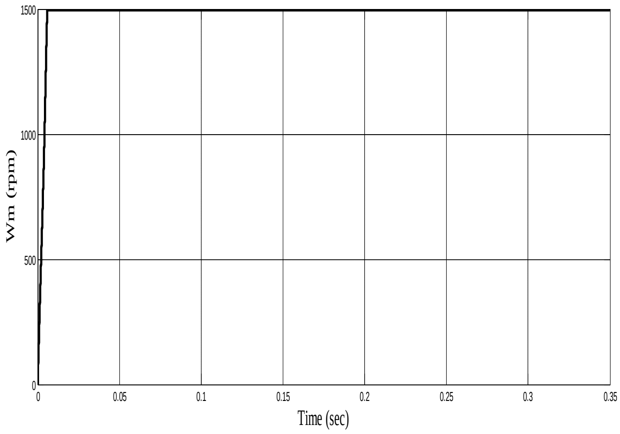
Parameters used for modeling of Synchronous Motor are given in Table I. Using these parameter two phase

Permanent magnet motor is modeled and derived results are given below. Speed of Synchronous motor is constant so kept at 1500 *rpm*. The speed is calculated as shown below. Fig. 3 (a) shows graph of synchronous speed of motor plotted against time. This shows the synchronous speed at 1500 *rpm*. Due to the constant speed, electrical torque required for driving synchronous motor is null. But when load increases, electrical torque tries to catch-up with the load torque so as to keep motor at synchronous speed. Fig. 3 (b) shows electrical torque of PMSM varying with time. Fig. 3 (c) shows direct axis and quadrature axis fluxes of PMSM. The quadrature axis flux leads the direct axis flux by 90 electrical degrees. Stator flux trajectory of direct axis and quadrature axis fluxes are shown in fig. 4. This trajectory is circular to represent the sinusoidal flux PMSM.

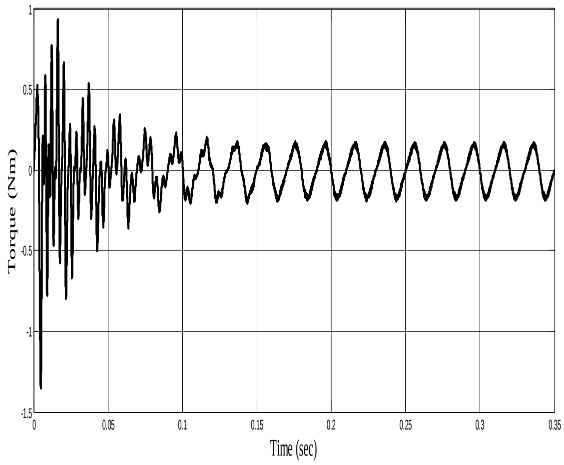
TABLE I
PARAMETERS OF TWO PHASE SYNCHRONOUS MOTOR

Stator Resistance	4.5Ω
d-axis inductance	323mH
q-axis inductance	110mH
Number of poles	4
Rotor flux	1

Frequency= 50 *Hz*
No. of poles= 4
From Equation (1), we get
Speed= 120*50/4
= 1500 *rpm*



(a)



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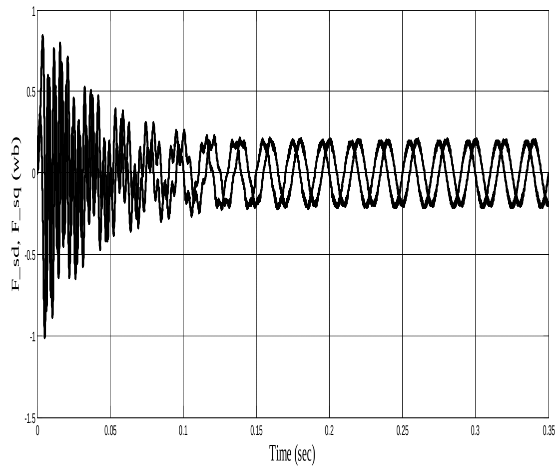

(c)

Fig. 3. Two phase SM's (a) synchronous speed, (b) electromagnetic torque, (c) d-axis and q-axis components of the stator flux.

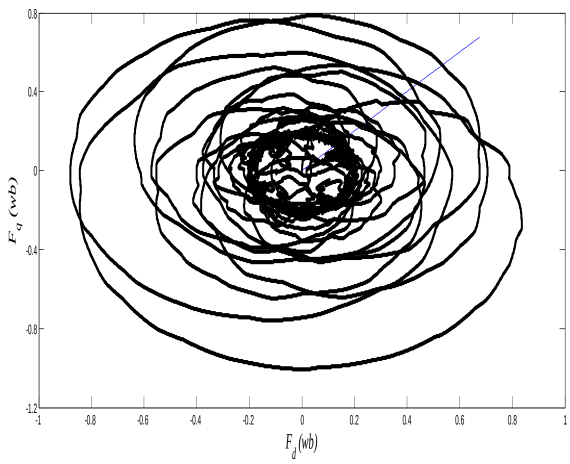

Fig. 4. Stator flux trajectory of two phase SM

VI. ONCLUSION

In this way modeling and simulation of Permanent Magnet Synchronous motor has been done. This shows that PMSM is most reliable in case of constant speed applications. Interior magnet PMSM provides very robust structure and hence can be used in high power and servo applications. PMSM can be used for wide range of varying power factors. PMSM is easy to maintain and hence more efficient than other motors.

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