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Literature Review of Permanent Magnet AC Motors Drive for Automotive Application

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Abstract

Permanent Magnet Synchronous Motor (PMSM's) is used in many applications that require rapid torque response and high – performance operation. New developed materials such as magnetic materials, conducting materials and insulating materials as well as several new applications have greatly contributed to development of small and special purpose machines. Using such materials, the size of the motor would considerably reduce and high performance motors can be built. Due to several new applications, these motors are quite popular & use in a developing country such as India for Automotive application. In a permanent magnet synchronous motor, the dc field winding of the rotor is replaced by a permanent magnet. The advantages are elimination of field copper loss, higher power density, lower rotor inertia and more robust construction of the rotor. The demerits are loss of flexibility of field flux control and possible demagnetization effect. The PMSM has higher efficiency than an induction motor, but generally its cost is higher, which makes the life cycle cost of the drive somewhat lower. PMSM particularly at low power range are widely used in industry. Recently, the interest in their application is growing, particularly up to 100 KW, only reluctance motor are simpler in construction and in assembly procedure than PMSM, but reluctance motor generally developed less torque per unit of current and per unit of weight. Therefore, on a basis of power output per unit weight (and general, per unit volume), the PMSM is superior to all other brushless synchronous motor, especially with the commercial feasibility of rare earth magnets. Section 1 describes the introduction, section 2 describes Classification of permanent magnet AC motor, and section 3 describes the conclusion.

Keywords: *permanent magnet synchronous machine, permanent magnet material, induction machines, variable reluctance machines, sinusoïdal surface magnet machine (SPM), sinusoidal interior magnet machine (IPM), trapezoidal surface magnet machine.*

1. Introduction

The electrical machine, that converts electrical energy into mechanical energy and vice versa, is the workhorse in a drive system. Drive systems are widely used in applications such as fiber spinning mills, rolling mills, MAGLEV - linear synchronous motor propulsion, aircraft engines, paper and textile mills, electric vehicle and subway transportation, home appliances, wind generation systems, servos and robotics, computer peripherals, steel and cement mills, ship propulsion, etc. A machine is a complex structure electrically, mechanically, and thermally. Although machines were introduced more than one hundred years ago, the research and development (R&D) in this area appears to be never-ending. However, the evolution of machines has been slow compared to power semiconductor devices and power electronic converters. An engineer designing a high-performance drive system must have the knowledge about machine performance, the dynamic model, and parameter variations. Industrial drive applications are generally classified into constant-speed and variable-speed drives. Traditionally, ac machines with a constant frequency sinusoidal power supply have been used in constant-speed applications, whereas dc machines were preferred for variable-speed drives. Dc machines have the disadvantages of higher cost, higher rotor inertia, and maintenance problems with commutator and brushes. Commutator and brushes, in addition, limit the machine speed and peak current, cause EMI problems, and do not permit a machine to operate in dirty

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and explosive environments. However, dc machine drive converters and controls are simple, and the machine torque response is very fast.

2. Classification of Permanent Magnet AC motor

Ac machines can generally be classified as follows:

- Induction machines.
- Synchronous machines.
- Variable reluctance machines.

A synchronous machine, as the name indicates, must rotate at synchronous speed; that is the speed is uniquely related to supply frequency. Each machine has got its own advantages and disadvantages.

In a permanent magnet synchronous machine, the dc field winding of the rotor is replaced by a permanent magnet. The advantages are elimination of field copper loss, higher power density, lower rotor inertia and more robust construction of the rotor. The demerits are loss of flexibility of field flux control and possible demagnetization effect. The machine has higher efficiency than an induction motor, but generally its cost is higher, which makes the life cycle cost of the drive somewhat lower. PM machines, particularly at low power range, are widely used in industry. Recently, the interest in their application is growing, particularly up to 100 KW.

Variable speed drive with AC motors is superior to DC drive systems in many ways, important amongst them are as follows:

- Very high speed of operation.
- Rugged design.
- Less maintenance.
- Most suitable for explosive, hazardous and dusty areas or areas where maintenance is both difficult and dangerous.
- Possibility of gearless drive system.
- Possible to operate the motor directly from the mains by using bypass switch as a standard arrangement.
- Reduction in starting current (Large torque per ampere during starting).
- Low electrical noise. (No brushes).
- Low cost of machine installation.
- Every saving: An average plant can save as much as 20% of its total energy.

2.1. Three phase synchronous motor

Three phase synchronous motor consists of an armature winding and a magnetic field provided by field winding. Armature winding mounted on stator and field winding on rotor. The stator consists of cost iron frame and supports the armature core having slots on its inner periphery for housing the armature conductors. The rotor is like flywheel having Alternate N&S poles fixed to its outer rim. The magnetic poles are excited from DC supply.
Some characteristics feature of a 3 phase synchronous motor:

- It runs either at synchronous speed or not at all i.e. while running it maintains a constant speed. The only way to change its speed is to very the supply frequency because NS = 120 f/p.
- It is not inherently self-starting. It has to run unto synchronous or near to synchronous speed by some means before it can be synchronized to the supply.
- It is capable of being operated under wide range of power factors. Hence, it can be used for power factor correction purpose in addition to supplying torque to drive loads.

Applications

i) Power factor correction:
Over excited synchronous motor having leading p.f. widely used for improving p.f. of those systems which employ a large number of induction motors and other devices having lagging p.f. such as welders and fluorescent lights etc.

ii) Constant Speed, Constant Load Drives:
Because of their high efficiency and high speed, synchronous motor are well suited for loads where constant speed is required such as belt driven reciprocating compressors,

blowers, line shafts, rubber and paper mills etc. Low speed synchronous motors (below 600 r.p.m.) are used for drives such as centrifugal and screw type pumps, ball and tube mills, vacuum pumps and rolling mills.

iii) For Voltage Regulation:
The voltage at the end of a long transmission line varies greatly, especially when large inductive loads are present. When an inductive load is suddenly disconnected, voltage tends to rise considerably above its normal value because of the line capacitance. By installing a synchronous motor with a field regulator (for varying its excitation) this voltage rise can be controlled.

2.2. Permanent Magnet Synchronous Motor

The vast array of synchronous motor configuration in the medium and low power ranges can generally be classified into two groups: Conventional & Brushless. PM motors fall into the latter group. PM synchronous motors generally have the same operating and performance characteristics as synchronous motor in general operation at synchronous speed. A single or poly phase source of alternating current supply the armature windings. If the operation of the PMSM at synchronous speed is done above the power limit, this gives unstable performance, reversible power flow. A PMSM can have a configuration almost identical to the conventional synchronous motor with the absence of slip rings and a field winding. The absence, of course, is responsible for the one major difference between PMSM and a conventional synchronous motor: lack of power factor or reactive power control and its association with terminal voltage regulation.

Permanent Magnet Synchronous Motors are:

a) Single phase synchronous motor:
1. Reluctance type
2. Hysterisis motor
3. Permanent magnet Synchronous motor
   i. Permanent magnet synchronous motor.
   ii. Induction type permanent magnet synchronous motor.

1. Reluctance Type

Stator is permanent split phase capacitor run. The squirrel cage rotor is unsymmetrical magnetic construction. This type of unsymmetrical magnetic construction can be achieved by removing some of the teeth of a symmetrical squirrel cage rotor punching. In this way, it offers variable magnetic reluctance to the stator flux, reluctance vary with the position of rotor.

It is used in the application such as signalling devices recording instruments, clocks and all types of filming devices, teleprinter, sound recording and sound producing apparatus, etc.

2. Hysterisis Motor

Stator winding may be split or capacitor type shaded pole motor. The rotor is formed by smooth chrome-steel cylinder which has high retentivity so that hysterisis loss is high. Because of high retentivity of rotor material, it is very difficult to change the magnetic polarities, once they are included in rotor by revolving flux. The rotor poles magnetically lock with the revolving stator poles of opposite polarity.

It is used in the applications like quite operation, absence of mechanical and magnetic vibrations such as sound recording and sound producing equipment etc.

3. Permanent Magnet Motor

Ceramic magnet material has been developed over the last few years. It has made possible the development of synchronous motor which has magnetic salient poles but not physical salient poles. It is the extremely high coercivity of the ceramic materials that has made this development possible. According to construction of rotor poles, the single phase PM motor consists of two types as follows:

i) Permanent Magnet Synchronous Motor

In typical construction of the rotor of permanent magnet synchronous motor, it consists of a hollow cylinder of a very high coercivity ceramic material. The cylinder has been pre-magnetized to set up permanent magnetic poles, alternatively North and South. With such rotor, stator can be a wide variety of constructions and designs and can be wound for single phase or poly phase excitation. The stator has to be wound for some number of poles as rotor.

ii) Induction Permanent Magnet Synchronous Motor

The fractional HP motors use permanent magnet excitation instead of DC excitation. They have interesting characteristics that they will run only at synchronous speed or not at all. They do not operate at sub-synchronous speeds as reluctance and hysterisis motors do. Two rotors are mounted on the same shaft. All the teeth of one rotor are the same magnetic polarity, and all the teeth of second rotor are the opposite magnetic polarity. In this speed variable technique, induction type permanent magnet synchronous motor is used.

Single phase PMSM mainly used in constant speed application such as coil winding machines, digitally controlled paint spraying machines and packaging machines, etc.

b) Three Phase Permanent Magnet Synchronous Motors are:

1) Sinusoidal surface magnet machine (SPM)
2) Sinusoidal interior magnet machine (IPM)
3) Trapezoidal surface magnet machine

1) Sinusoidal surface magnet machine(SPM)

In this machine, the stator has a phase sinusoidal winding as before, which creates a synchronously rotating air gap flux. The PMs are glued on the rotor surface using epoxy adhesive. The rotor has an iron core, which may be solid or made of punched laminations for simplicity of manufacture. Line-start 60 Hz PM machines may have a squirrel cage winding to start as an induction motor. For variable – speed operation, PM machines may or may not have a cage or damper winding, which has an additional loss due to harmonics. If the machine is rotated by a prime mover, the stator windings generate balanced three-phase sinusoidal voltages. Since the relative permeability of a PM is very close to one ($\mu_r > 1$), and magnets are mounted on the rotor surface, the effective air gap of the machine is large and the machine is a nonsalient pole ($L_{dm} = L_{qm}$). This contributes to a low armature reaction effect due to low magnetizing inductance.

2) Sinusoidal Interior Magnet Machine (IPM)

Unlike an SPM, in an interior or busied magnet synchronous machine (IPM) the magnets are mounted inside the rotor. Although a number of geometries are possible, a typical configuration is shown in Figure 1. The stator has the usual three phase sinusoidal winding. The difference in the geometry gives the following characteristics to the IPM machine

i. The machine is more robust, permitting a much higher speed of operation.
ii. The effective air gap in the d^e axis is larger than that in the q^e axis, which manes the machine salient pole with Ldm < lqm (unlike a standard wound field synchronous machine) and
iii. With the effective air gap being low, the armature reaction effect becomes dominant.

The steady state analysis of a sinusoidal PM machine with an equivalent circuit and phasor diagram remains the same as a wound field machine except that equivalent field current, it should be considered constant, that is the flow linkage $\psi f = Lm, I_f =$ constant. The synchronously rotating frame transient equivalent circuit is also hold true here, expect the machine may not have any damper windings.

3) Trapezoidal Surface Magnet Machine:

A trapezoidal SPM machine is a non-salient pole, surface-mounted PM machine similar to a sinusoidal SPM machine, except its three phases stator winding (normally wye-connected) has concentrated full-pitch distribution instead of sinusoidal winding distribution. It has three phases stator windings. The two-pole machine with a gap to reduce the flux fringing effect, and the stator is shown with four slots per pole per phase. As the machine rotates, most of the time flux linkage in a phase winding varies linearly, except when the magnet gap passes through the phase axis. If the machine is rotated by a prime mover, the stator phase voltage will have symmetrical trapezoidal wave shape. An electronic inverter is required in the front end to establish a six-step current wave at the center of each half-cycle to develop torque. Since converter use is mandatory, it is often defined as an electronic motor. With the help of an inverter and an absolute-position sensor mounted on the shaft, both sinusoidal and trapezoidal SPM machines can be controlled to have “brushless dc motor” (BLDM) performance. However, a trapezoidal machine gives closer to dc machine-like performance. The machine is simple, inexpensive, and has somewhat higher power density than the sinusoidal machine. Low-power (up to a few kW) drives, using this machine, are commonly used in servo and appliance drives where commutators and brushes of dc motor are not desirable.

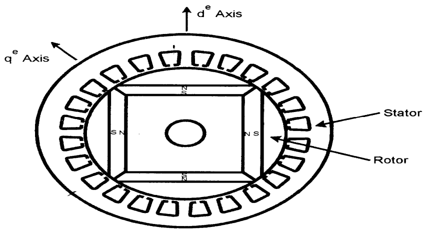

Figure 1. Cross Section of Interior Permanent Magnet Sinusoidal Machine (IPM)

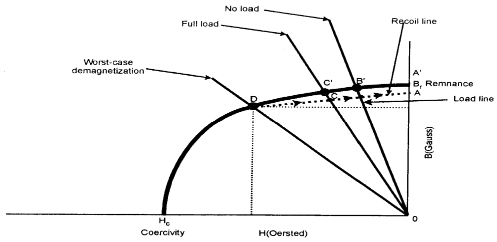

Figure 2. Permanent Magnet Machine Operating points on B-H curve.

2.3 Permanent Magnet Materials

The property of a permanent magnet of the selection of the proper materials is very important in the design of permanent magnet synchronous machine.

Figure 2 shows the demagnetization segment of the B-H curve where the permanent magnet is usually designed to operate. The maximum flux density Br corresponding to point A' will be available initially if the magnet is short circuited with steel keepers (no air gap). When the magnet is installed in the machine, the air gap will have some demagnetization effect and the operating point B' will corresponds to the no load line shown in the Figure 2. The slope of the no load line (w.r.t. H axis) will be smaller with higher air gap. With current flowing in the stator winding, the magnetic axis (d^e) armature reaction effect can have a further demagnetization effect, which will further reduce the air gap flow density. A load line corresponding to worst case demagnetization, which may be due to a starting, transient, or machine fault condition is also shown in Figure 2. Once the operating point reaches D and the demagnetization effect is removed, the magnet will recover along the recoil line, which has approximately the same slop as the original B-H curve near H=0. In a subsequent operation, the stable operating point will be determined by the intersection of the load line and the recoil line. The magnet is, therefore, permanently demagnetized at low load operation. Corresponding to the vertical distance between A and A'. The worst case demagnetization point is, therefore, vitally important for machine performance and should be closely controlled. Alternatively, if the material of the permanent magnet is selected to have a straight line demagnetization curve, the recoil line will coincide with the demagnetization line irrespective of the worst case demagnetization point. (i.e. permanent demagnetization will be negligible).

Figure 3 shows the characteristics of several possible PM materials. A line has high service temperature good thermal stability and high flow density, but the disadvantage is low coercive force coupled with squarish B-H characteristics, which means the permanent demagnetization high so that it is practically unsuitable for a PM machine. Barium and strontium ferrites are widely used as permanent magnets. Ferrite has the advantages of low cost and plentiful supply of low material. They are also easy to produce and their process is suited for high volume, as well as moderately high service temperature (400^0C). The magnet has a practically linear demagnetization curve, but its remnance (Br) is low. Therefore, the volume and weight of the machine tends to be high. The cobalt samarium (COSM) magnet is made of iron, nickel, cobalt and rare Earth Samarium. It has the advantages of high remnance, high energy density defined by (BHmax) and linear demagnetization characteristics. The service temperature can be as high as 300^0C and the temperature stability (% changes in B/^{0}C) is very good (-0.03%). But the material is very expensive because of an inadequate supply of samarium. The Neodymium iron boron (Nd-fe-B) magnet has the highest energy density, high remnance and very good coercivity (HC). The disadvantages are low service temperature (150^0C) and susceptibility to oxidation unless protected by a coating. Besides, the temperature stability (-0.13%) is interior to that of a COSM magnet. The material is expensive compared to ferrite, because of higher energy density the machine weight is reduced. The application of Nd-fe-B magnets is growing in PM machines.

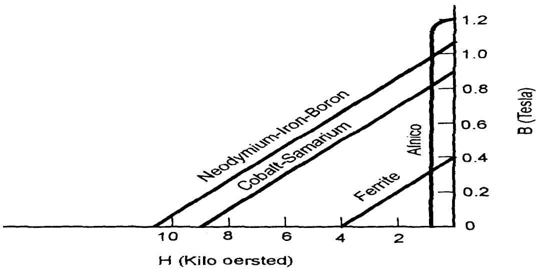

Figure 3 Permanent Magnet characteristics

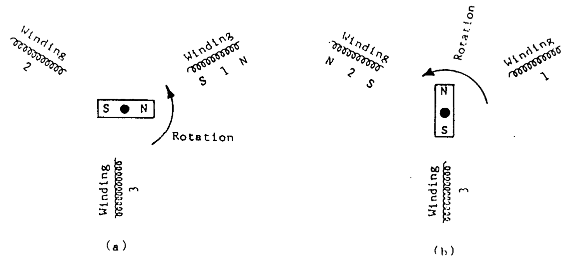

Figure 4 Basic Rotation of PMSM

2.4 Operating principle of PMSM

A cross section view of PMSM is shown in Figure 4. PMSM are similar to AC motors in that a moving magnet causes rotor movement of rotation. Both the motor types use stator winding have no brushes. Basic location of PMSM is shown in Figure 4 Permanent magnet generate one field the brushless motor, is in essence a hybrid, which combines the best attitude of both the AC & DC motors.

The configuration of the unlike an SPM in an interior or buried magnet synchronous machine the magnets are mounted inside the rotor. Although number of geometries is possible, a typical configuration is shown in figure 1.4. The stator has the usual three phase sinusoidal windings. The difference in geometry gives the following characteristics to the IPM machine:

i) The machine is more robust, permitting a much higher speed of operation.
ii) The effective air gap in the d^e – axis is larger than that in the q^e – axis, which makes the machine a salient pole with Ldm < Lqm. (Unlike a standard wound field synchronous machine).
iii) With the effective air gap being low, the armature reaction effect becomes dominant.

In these motor the rotor consist of permanent magnets and the stator consist of three phase windings. These windings are termed “Commutation” windings. By passing a current through winding, a magnetic field is setup with which permanent magnet on the rotor interact. This results in rotation of the rotor.

Figure 4 illustrates in simplified form how rotation occurs with a current passing through a windings. Figure 4 a) a south pole is set up with the permanent magnet will react and movement will begin. If, the appropriate time current is shut OFF in winding 1 and turn on in winding 2 (see in figure 4 b) then the rotor will continue to move. By continuation of this timing sequence, complete rotation will occurs as the rotor repeatedly tries to catch up the stator magnetic field and gets magnetically locked. In this example, the operation is simplified for explanation by exciting only one winding at a time. In practical situation, to and same times three windings are energized at a time. This procedure permits the development of higher torque. As indicated, if current is properly switched from winding to winding the rotor will continue to rotate.

Permanent magnet synchronous motor (PMSM) drive

The synchronous motor is becoming a strong competition with the induction motor in the variable speed drive domain. The main advantages as compared with induction motor are:

1. Elimination of rotor slips power loss.
2. Natural ability to supply reactive control.
3. Machine can be built with large airgap without degraded performance.
4. Torque is less sensitive to change in supply voltage.
5. It can be operated under wide range of power factor both lagging and leadings where as induction motor operates only with lagging P.f.
6. Synchronous motor can be used for supply mechanical load as well as for power factor improvement, whereas induction motor is used for supply mechanical load only.

In recent years, there has been an emerging growth of permanent magnet synchronous motor (PMSM). In the PMSM, the rotor field is supplied by permanent magnets. The main advantage, when compared with conventional synchronous machine, is the elimination of the field coils, dc supply & slip rings. Hence, lower loss and a less complexity etc. can be obtained. In PMSM, there is no provision for rotor side excitation control. The control of PMSM is entirely done through the stator excitation control.

The stator winding in the PMSM are either fed by rectangular current or sinusoidal current. The rectangular current fed motor has concentrated windings on the stator, and the induced voltage in the winding is square or trapezoidal. These machines are cheaper and normally used in low power drives. The sinusoidal current fed motors have distributed windings on the stator, provide smoother torque and are normally used in high power applications.

Synchronous motor variable speed drives

Synchronous speed is directly proportional to frequency. Motor speed can be controlled by varying the frequency. As in case of an induction motor constant flux operation below base speed is achieved by operating the motor with constant (v/f) ratio, which is increased at low speeds to compensate for the stator resistance drop. This gives motor operation with constant pull out torque. Rated voltage is reached at the base speed. For higher speeds, the machine is operated at a rate terminal voltage and variable frequency and the pull torque decreases with an increase in frequency.

In PMSM variable frequency control may employ any of the two modes:

a. True synchronous mode.
b. Self controlled mode.

a) True synchronous mode: Here, the stator supply frequency is controlled from an independent oscillator. Frequency from its initial to the desired value is changed gradually, so that the difference between the synchronous speed and rotor speed is always small. This allows rotor speed to track the changes in synchronous speed. When the desired synchronous speed (or frequency) is reached, the rotor pulls into step after hunting oscillation.
b) Self controlled mode: Here, the stator supply frequency is changed, so that synchronous speed is the same as rotor speed. This ensures that rotor runs at synchronous speed for all operating points. Constantly rotor cannot pull out of step and hunting oscillation is eliminated.

3. Conclusion

This paper gives the idea about permanent magnet Synchronous motor drive for automotive application. Although many areas have been covered by the papers, much is yet to be done in the area of machine & drive design.

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