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Application Characteristics of Permanent Magnet Synchronous Motors (Case Study)

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***Abstract*—This paper give the idea about Application Characteristics of Permanent magnet synchronous motor. Permanent magnet synchronous motor is being used in many low to medium power range applications in many places of the world due to their inherent advantages. This paper indicates, Due to good Application Characteristics of permanent magnet synchronous machines compare to other A.C Machines are used in automotive applications, vehicular electric drive motors; textile industries glass industries, computer and robotics applications. Also to improve the efficiency of submersible pumps, Permanent Magnet Synchronous Motor are 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 the 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 in a developing country such as India.**

***Keywords*—Interior permanent Magnet Synchronous Brushless DC Motor s**

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

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.

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 polyphase source of alternating current supplying 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 that of 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.

II. METHODOLGY

A. Characteristics of PMSM

The characteristics of the PMSM are determined with the aid of well known selection criteria. The criteria include the following.

1) Cost
2) Power density
3) Torque to inertia ratio
4) Speed range
5) Torque per unit current
6) Braking
7) Cogging and ripple torque
8) Parameter sensitivity
9)

1) COST

Ultimately, it is the cost that plays a crucial role in deciding on a particular drive. However, the cost is only fair comparison if the engineering performance of the drive under consideration is comparable. The cost of PMSM is slightly more than BDCM.

2) POWER DENSITY

In certain high performance application like robotics and aerospace actuators, it is preferable to have as low weight as possible for a given output power. The power density is limited by the dissipation capability of the machine, which in turn is determined by the stator surface area. In PM machines, most of the losses are developed in the stator in terms of copper, eddy current and hysteresis losses. Rotor losses are assumed negligible. Hence, for a given frame size, the motor that develops lower losses will be capable of a higher power density. The relative power densities would be determined by the copper losses.

In PMSM the rotor losses are assumed to be negligible, hence it has high power density.

3) TORQUE TO INERTIA RATIO

It is possible to obtain more power output of the PMSM also more electric torque hence, torque to inertia ratio is higher for the PMSM.It should be noted that the PMSM have a higher torque to inertia than the induction motor.

4) SPEED RANGE

Servo drives operate in the constant torque mode of operation from zero to rated speed and in the constant power mode of operation from rated to maximum speed. In the constant torque region, the air gap flux is held constant, where as in the constant power region, the air gap flux is weakened by applying a stator flux in opposition to the rotor magnet flux. This is also known as armature reaction and is shown in figure 1.5.

During constant flux operation i_s is maintained at 90^0 to the rotor flux as shown in figure 1.5. In the flux weakening mode, i_s is maintained at an angle grater than 90^0 from the rotor flux. This allows a component of stator current id to create a stator flux that opposes the rotor flux, and hence air gap flux weakening is obtained.

The magnitude of I_s, which is the vector sum of the direct and quadrature axis stator currents, has a fixed continuous rating during steady state operation. This can be exceeded for short periods of time during transients. If a higher speed range is required, a larger negative id is needed in order to reduce the air gap flux and iq should be lowered in order to ensure that the continuous rating of i_s is not exceeded. The speed capability of a permanent magnet motor drive when this method of flux weakening is used can be determined from the two axis equations as follows

$$(0.636V/Xq)^2 = iq^2 + (Xd(id + \omega e\ \lambda af/Xd)/Xq)^2 \text{ -----------------------(1)}$$

Where V is the DC bus voltage, Xd, Xq are the stator d, q axis reactance, id, iq are the stator d, q axis currents, ωe is the inverter frequency, and λ is the mutual flux linkage between the rotor and stator due to the magnet. By setting iq=0 and id equal to the continuous current rating of the machine, the inverter frequency and, hence, motor speed can be determined. Since the motor speed is given by ωe/P where P is the number of pole pairs. For typical PM motor parameters, it has been found that around 1.5 times rated speeds can be obtained.

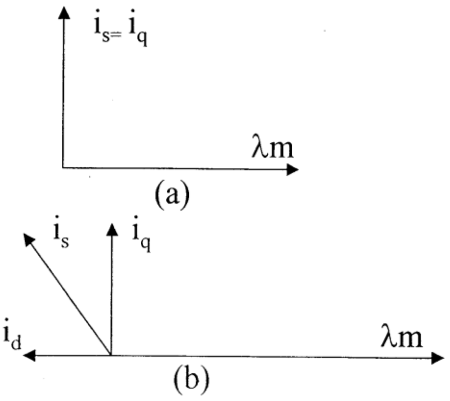

Fig. 1.1 Vector Diagram of PMSM During(a) Constant Flux & (b) Flux weakening operation

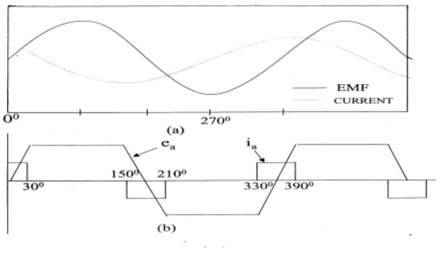

Fig. 1.2 (a) PMSM back emf and current wave forms

(b) Waveforms during flux-weakening operation.

The above discussion applies equally well to the PMSM and the BDCM (Brushless DC Motor). The practical limitation on the maximum speed is obtained when the back emf of each machine becomes equal to that of the DC bus. Because of the difference in the wave shape of the back emf of the PMSM and BDCM, the volt drop that is available to force to current flow is different in each machine in a given period as shown in fig 1.6. Figure 1.6 (a) shows the desired current relative to the back emf in order to obtained the maximum speed in the PMSM. At this operating point, the peak of the back emf is equal to that of the DC bus. In the BDCM, on the other hand, current can only be forced into the motor when the back emf is less then the DC bus voltage as shown in fig. 1.6 (b) assuming that the forced current is rectangular in shape, with a peak equal to the rated value of the BDCM, it is possible to find the fundamental component of this current, which becomes id in (3) with iq=0. Comparing a PMSM and BDCM with the same parameters, but taking into account the current waveforms shown in fig. 1.6 from (3), it can be shown that

$\omega ep/\omega eB = (\lambda af - Ld\ idB)/ (\lambda af - Ld\ idp) = 1.46$ ---------------------(2)

For the motor parameters ωep and ωeB are the maximum PMSM and synchronous speeds, where idp and idB are the direct axis currents of the PMSM and BDCM respectively. Therefore the speed range of a PMSM would be higher than that of a BDCM of the same parameters. The speed range of a permanent magnet machine therefore depends on the motor parameters, current rating, the back emf waveform, and the maximum output voltage from the inverter.

5) TORQUE PER UNIT CURRENT

Very often, servo motor drives are operated to produce the maximum torque per unit current out of the machine. This is done because by minimizing the input current of a given torque, the copper, inverter, and rectifier losses are minimized. In addition, lower current ratings of the inverter and rectifier are needed for a given output; this reduces the overall cost of the system.

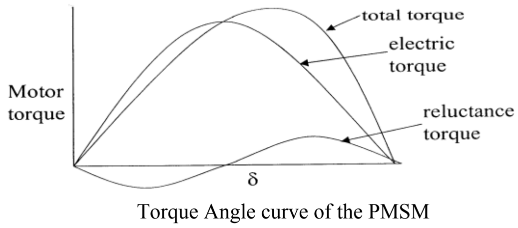

Fig1.3

Torque Angle curve of the PMSM

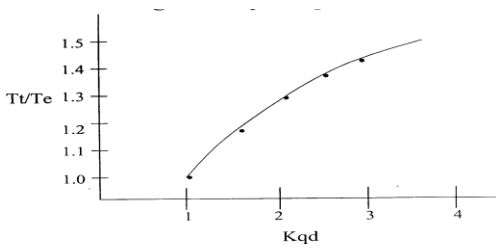

Fig.1.4

Ratio of total Torque over electric torque as a function of inductance ratio

The torque angle curve of a PM machine is shown in fig. The total motor torque consists of electric and reluctance torque components. The electric torque is produced as a result of the interaction of the stator current with the airgap flux while the reluctance torque is produced as a result of reluctance variation due to rotor saliency. As shown in the vector diagram of fig. 1.5, the d axis is chosen to be aligned along the magnet axis. The permeability of the magnet in the d axis is approximately that of air. If the length of the airgap on the quadrature axis is equal to that of the magnet plus airgap on the direct axis, then there is no appreciable reluctance difference between the d and q axes. Hence the reluctance torque is approximately zero, and the total motor torque is equal to the electric torque only, where the maximum is produced at a δ of 90^0, i.e., when i_s is perpendicular to the rotor flux. His is normally true of projecting surface mounted machines. In buried permanent magnet machines, however, the reluctance variation between the d and q axes can be significant, with the d axis reluctance normally being larger than that of the q axis. This is so because whereas in the magnetic circuit on the q axis there is only iron, a part of the magnetic circuit on the d axis consists of the magnet, which is a permeability approximately that of air. This increases d axis reluctance, hence, reducing its inductance. This tends to reluctance torque being of a negative sign to that of a wound rotor salient pole synchronous motor as shown in fig. 1.7. This means that maximum torque is produced at an angle greater than 90^0. If a δ of 90^0 is chosen for the buried or inset machines, the reluctance torque is forced to be zero, and maximum torque / amp operation would not be attained. Hence, a buried PMSM is capable of producing a higher output torque/ amp when compared with a surface mounted machine that has the same magnitude of electric torque. The buried permanent magnet motor is, however, more difficult and expensive to manufacture.

In order to determine the improvement in total torque capability of a PM machine by addition of the reluctance to the electric torque, the following procedure is adopted. The equation for the total torque produced by a PM machine is as follows;

$Tt = 3P (\lambda af\ I_s \sin\delta + (Ld - Lq)\ i_s^2 \sin 2\delta)/2)/2$ -------------------------(3)

The equation for the electric torque only, which is produced at an angle of 90^0, is

$Te = 3P (\lambda af\, I_s \sin\delta)/2$ ----------------(4)

Hence, the ratio of the total to the electric torque is

$Tt/Te = 1 + (Ld - Lq)\, i_s \sin 2\delta / (2\lambda af \sin\delta)$ - (5)

Since Ld is always less than or equal to Lq, this ratio is always greater than or equal to 1 if δ is greater than or equal to 90^0 and less than 180^0. Defining the ratio of the quadrature to direct axis inductances as Kqd, a graph of Tt/Te as a function of Kqd is given in fig. 1.8. Values of Kqd up to 2.5 have been practically realized in buried permanent magnet machines, whereas this value is approximately 1 for surface mounted machines. Hence, the range of Kqd considered is from 1 to 3. From the graph, it is clear that for a Kqd of 3, the total torque produces from the motor can be 40% larger than the electric torque alone. This value of Kqd would exist only in buried PM machines, whereas for inset PM surface mounted machines, the total to torque can be 10-15% larger than the electric torque. It should be remembered that this improvement in the torque is a result only of changing the location of the stator current vector from 90^0 to a value larger than 90^0 with the magnitude of the current vector remaining constant. The actual angle that provides this maximum torque can be obtained by finding the first derivative and setting it to zero to obtain.

$\cos\delta = -X - \sqrt{(X^2 + 0.5)}$

$X = \lambda af / (4(Ld - Lq)\, i_s)$ ---------(6)

Hence, for maximum torque per ampere rating, and given the quadrature to direct axis inductance ration, the torque enhancement and the angular position of the stator current vector can be determined from the above equations and graphs. Hence, the torque per unit current of PMSM is high.

6) BRAKING

Since PMSM have permanent magnet excitation, braking in inherently easier than with drives that face the possibility of loss of excitation due to a power supply failure. In PMSM as well as BDCM, braking can be achieved by adding a resistor in series with a transistor, which is connected just before the inverter power circuit. During motoring operation, this transistor is off, thus disconnecting the resistor from the supply. During braking, the rectifier is turned off, and the braking transistor is turned on in conjunction with the inverter power transistors. The trapped energy in the motor forces a current to flow through the motor coils and through the braking resistor. Braking is achieved by the dissipation of heat in the braking resistor.

7) COGGING AND RIPPLE TORQUES

Cogging and ripple torques is unwanted pulsating torques that is produced by essentially different phenomena. In a permanent magnet machine, the teeth are the stator can produce a reluctance torque variation as the rotor rotates. This reluctance torque that depends on the rotor position and exists in the absence of any armature current is cogging torque. Hence, cogging is space dependent. Ripple torque is a consequence of armature current communication and harmonics that do not produce constant torque. Hence, ripple torque is essentially independent of cogging, and either can exist in the absence of the other.

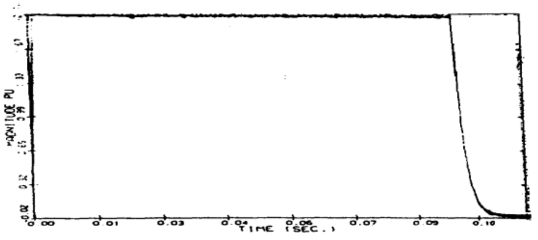

Fig. 1.5 Start- up Torque of a PMSM

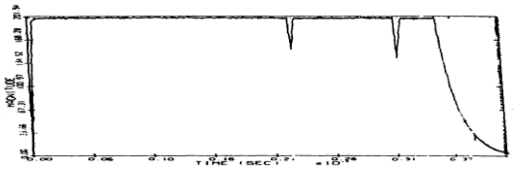

Fig 2.6 Start-up Torque of a BDC

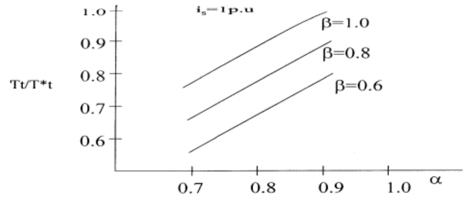

Fig. 1.7 Torque Reduction as a function of flux reduction coefficient

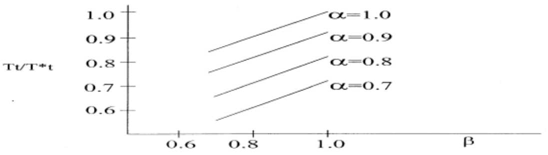

Fig. 1.8 Torque Reduction as a function of the saturation coefficient

A design criterion for the minimization of cogging torque has been established. If the reluctance as seen from the rotor is constant, the cogging torque would be negligible. It is well known that skewing of the stator slots or rotor magnet by one slot pitch reduces cogging to 1-2% (peak to average) of the rated torque. Hence, there is no significant difference between the cogging torque of the PMSM and the BDCM.

The phase current waveforms of the PMSM and the BDCM are intrinsically different, as was discussed previously. A sinusoidal current is needed for the PMSM, whereas a rectangular current is needed for the BDCM to produce constant torque. Although it is possible to source a sinusoidal current into the PMSM, it is impossible to source a rectangular current into the BDCM because the inductance of the BDCM resist rapid current transitions. Therefore, the input current into the BDCM is trapezoidal rather than rectangular due to the finite rise time. In addition, a finite time is needed for the actual current to reach zero from its maximum value in the BDCM. These forces the actual current to have a trapezoidal shape rather than the desired rectangular shape needed for constant torque. It is this deviation that causes the BDCM to exhibit communication torque ripples that are absent in the PMSM drive. At high speeds, these ripples would be filtered out by the rotor inertia, but at low speeds, they can affect the performance of the drive severely. In particular, the accuracy and repeatability of position servo performance would deteriorate. It should be noted that in addition to this, the current oscillates around the reference value at high frequency, depending on the size of the hysteresis bands in a hysteresis current controller or the switching frequency of the ramp comparison controller. The net effect of this high frequency current oscillation is the production of high frequency oscillation in the torque, the magnitude of which would be lower than that produced by the commutation of the current. This high frequency torque oscillation is also present in the PMSM since a hysteresis or ramp comparison current controller is also needed here to maintain the current flowing into the motor as close to sinusoidal as possible. In practice, these torque oscillations are small and of sufficiently high frequency that they are easily damped out by the rotor inertia.

Figs. shows the starting torque of the PMSM and BDCM respectively. Both are subject to the high frequency torque pulsations due to the hysteresis or ramp comparison current controllers. These can be reduced by using smaller hysteresis windows or a higher PWM switching frequency. However, the torque pulsations in fig.. Due to the commutation of the phase current are clearly evident and are much larger than that produced as a result of the current controller action. This phenomenon has been observed by another. It is therefore preferable to use the BDCM for lower performance speed servos and position servos of low resolution, whereas the PMSM should be used for high performance speed and position servo applications like robotics. This is a significant advantage of the PMSM over the BDCM.

8) PERAMETER SENSITIVITY

Parameter changes in all electrical machines occur due to changes in temperature, current level, and operating frequency. In permanent magnet machines, an increases in temperature results in a partial loss of flux density of the parameter magnets and an increase in stator resistance. If the permanent magnet machines are rated at the maximum operating temperature, then at ambient temperature, higher than rated output would be obtainable due to the increase in flux density relative to the rated conditions. Conversely, if the machine is rated at ambient temperature, the output at elevated temperatures would be reduced. Higher than rated current values saturate the machine inductances. The saturation of the leakage inductances would cause a reduction in their value, thus allowing a greater potential difference between the dc bus and the back emf and, hence, providing greater current control.

Changes in machine parameters (notably stator resistance) due to increase in frequency is a secondary effect and can be taken into account at the system design stage proper performance. The majority of Permanent magnet machine are surface mounted. Hence, the reluctance torque term in is essentially zero, and the motor torque is produced by the interaction of the magnet flux and stator current vector. During current source operation, i_s is controlled, but the magnet flux can change due to the changes in temperature. This is true of both the PMSM and the BDCM and hence, each machine is equally sensitive to parameter changes in the magnet flux due to the temperature changes. Depending on the type of magnet, a 100^0 increase in the temperature can produce a 2 to 20% loss in magnet flux for samarium cobalt and ferrite magnets, respectively. Since the PMSM is capable of a higher speed range than the BDCM, it tends to be used for high speed applications. It may then become desirable to use a buried magnet configuration to make the machine more mechanically robust. In this case, the reluctances can affect the total output torque. The degree of parameter sensitivity that can be experienced in a buried PMSM is studied next.

Parameter sensitivity effects in a servo drive can be studied with the speed loop open (torque servo) or with the speed loop closed (speed servo). By expressing the actual machine variable with parameter change over the original unchanged variable, normalized curves are generated that give an indication of how other machines of different power ratings would behave. The ambient or unsaturated value of a variable is superscripted with a “*” this is referred to as a reference value.Saturation on the q axis of the machine is represented by defining the variable β, where β is the ratio of the saturated q axis inductance to the unsaturated value. Similarly, the reduction of magnet flux linkage as temperature increases is represented by defining the variable to be the ratio of the magnet flux at elevated temperature to the value at ambient. Can range from 0.7 to 1.0, indication as much as a 30% reduction in the q axis reactance, particularly for machines with a cage rotor, whereas for low performance magnets like ferrite, can be low as 0.75. Indicating a 25% loss in magnet flux. Hence, the range of chosen is 0.6 and 1.0 that of is 0.7 to 1.0. This study in parameter sensitivity is carried out at the maximum torque/unit current point, which can be calculated from (10).Fig. 1.11 shows the ratio of the actual torque to the reference value as a function of α, with β varying between 0.6 and 1. For a given value of α, a larger β results in a larger value of the ratio between the actual and reference torques. In fact, a change in β of 0.2 produces approximately a 1p.u. change in Tt / Tt * for a given a. This is because an increase in the saturation (lower β) results in a lower reluctance torque component. The stator current magnitude is held at 1 p.u. in this study.

Fig.1.12 shows the same results as fig 1.11 but with the x axis as β and with α varying between 0.7 and 1. This is done so that the application engineer need not have to back calculate these values from Fig. 1.11. Fig.1.13 shows the effects of different stator current magnitudes on Tt / Tt* . At higher currents, the reduction in Tt / Tt * is lower for a given α. This is because the reluctance torque increases as a square of the current, whereas the electric torque increases only linearly. Reluctance torque contribution to the total motor torque is reduced as β reduces. Similarly, the electric torque is reduced as α reduces, again demanding a larger reference torque for a given load torque.

III.APPLICATIONS

The typical applications are as follows.

1) Fiber spinning mills
2) Rolling mills
3) Cement mills
4) Ship propulsion
5) Electric vehicles
6) Servo & robotic drives
7) MAGLEV – linear synchronous motor propulsion.
8)

IV.CONCLUSIONS

This paper gives idea about the Application characteristics of permanent magnet synchronous motor. Hence Due to good Application characteristics it is used in automotive application.

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