

An approach to increase the efficiency of Permanent magnet synchronous motor

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ABSTRACT: Conventional permanent magnet synchronous motors are popularly used in electric vehicle application. This study addresses the theoretical design of a conventional permanent magnet synchronous motor (PMSM) for electric vehicles. The study applies to both surface mounted and inset magnet rotor configurations. Various losses estimations are embedded into the design procedures to ensure that the desired overall drive performance is achieved. Influences of parameters such as air gap size and magnet material on the performances are studied. Application of neodymium-iron-boron (Nd₂Fe₁₄B) and samarium cobalt (Sm₂Co₁₇) rare earth magnets results in high torque and power density, efficiency, and controllability, reliability, and ruggedness. Design of 47 kW PMSM with various magnets for electric car is presented.

Keywords: Electric car, Design theory, Nd₂Fe₁₄B, PMSM, Surface PM rotor.

I. INTRODUCTION

An electric car is an alternative-design automobile that uses an electric motor to power the car, with the electricity being provided by a battery. In an electric vehicle the traditional gasoline or diesel engine and fuel tank is replaced with an electric motor, a battery pack and controller. The vehicle also has a controller that powers the electric motor uses rechargeable batteries as its energy source. The motor itself can be either AC or DC. The main advantage to electric vehicles is that the motor and battery configuration allows the vehicle to run more fuel-efficiently [1]. The permanent magnet synchronous motor (PMSM) is considered to be a better fit for electric cars because the PMSM offers some advantages as low rotor inertia, high efficiency, efficient heat dissipation structure, and reduced motor size. The elimination of brushes reduces noise and suppresses the need for brush maintenance is another big advantage.

II. PRINCIPLE OF ELECTRIC CARS

Electric vehicles can be divided into three main types: hybrid electric vehicles (HEVs), plugable hybrid electric vehicles (PHEVs) and

full electric vehicles (FEVs/BEVs/EVs). Hybrid electric vehicles retain the internal combustion engine and drive, while also incorporating a small battery and electric drive motor. While the higher efficiency of the electric drive and the capacity for regenerative braking results in decreased fuel consumption, the vehicle cannot be powered by electricity alone and still relies on petrol or diesel. Full EVs are generally mechanically less complex than both internal combustion and hybrid vehicles, as shown in Fig.1. Consequently, the vehicle can be driven over short ranges where it only consumes electricity from the battery. However, beyond a defined level of battery consumption the vehicle reverts back to using the internal combustion engine alongside the electric motor like a standard hybrid. Table I shows the description of components in Fig 1. By replacing the fuel tank with a high energy density battery and the internal combustion engine with an efficient electric motor, EVs are capable of achieving significant efficiency improvements and emission reductions. Their range, efficiency, cost and torque-speed characteristics are predominantly determined by their battery pack and electric motor(s).

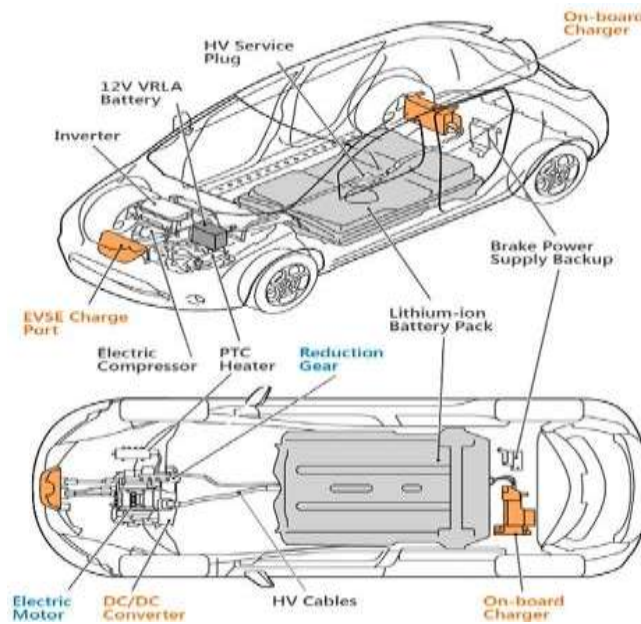


Fig 1.Key Functional Components Typical to an EV [1].

TABLE I: Description of Components in Figure-1

Components	Description
Electric Motor	Permanent magnet synchronous motor powered by three-phase AC from the inverter that supplies
Li-ion Battery	High specific energy electrochemical supply for powering the vehicle during operation
Reduction Gear Inverter	Steps down motor speed and increase torque
HV Junction Box	Converts DC power from Li-ion battery to three-phase AC power for controlling the motor
Electric Compressor	Interfaces the Li-ion battery with high-voltage systems
PTC Heater	Compressor for cabin air conditioning
Charge Ports	Positive temperature coefficient heat source for the interior cabin
Charge port	Standard connection ports for interfacing with EVSE to recharge the battery
On-board Charger	Converts AC power supplied to the standard charge port into DC power for recharging the battery
DC/DC Converter	Steps down the HV Li-ion supply to recharge 12V VRLA battery
VRLA Battery	12V valve-regulated lead-acid battery that powers the low voltage systems; headlights, audio, display
HV Cables	High rated conductors for carrying DC current between battery and HV systems
Service Plug	Allows the HV systems to be manually disconnected from the battery
Power Supply Backup	Capacitor-based power system that supplies power to the brakes and emergency system if 12V battery fails

III. PERMANENT MAGNET SYNCHRONOUS MOTOR

The PM Synchronous motor is a rotating electric machine where the stator is a classic three phase stator like that of an induction motor and the rotor has surface-mounted permanent magnets. In this respect, the PMSM is equivalent to an induction motor where the air gap magnetic field is produced by a permanent magnet. The use of a permanent magnet to generate a substantial air gap magnetic flux makes it possible to design highly efficient PM motors. A PMSM is driven by sine wave voltage coupled with the given rotor position. The generated stator flux together with the rotor flux, which is generated by a rotor magnet, defines



Fig.2. Stator Case with Winding.

B. Stator Coil Arrangement

The windings are connected in wye. The two windings in each phase are wound in the same direction. At any instant in time, the magnetic field generated by one particular phase will depend on the current through that phase. Since the currents in the three windings are 120° out of phase, the magnetic fields produced will also be 120° out of phase. The three magnetic fields will combine to produce one field, which will act upon the rotor. In an AC induction motor, a magnetic field is induced in the rotor opposite in polarity of the magnetic field in the stator. Therefore, as the magnetic field rotates in the stator, the rotor also rotates to maintain its alignment with the stator's magnetic field. This motor used six winding for electrical configuration of stator winding, two for each of the three phases. The coils are wound around the soft iron core material of the stator. When current applied each winding become electromagnet with one winding is a north pole and the other is south pole, the polarities of the winding also reverse.

C. Winding Insulation

Insulation of the winding is one of the

the torque, and thus speeds, of the motor.

A. Stator Construction

The stator is the stationary part of the motor. The core of the stator is made up of several hundred thin laminations. Stator laminations are stacked together forming a hollow cylinder and coils of insulated wire are inserted into slot of the stator core. The basic concept of the motor operation is electromagnetism which is, each group of coils together with the steel it surrounds form an electromagnets. The stator winding are connected directly to the power circuit. Fig 2 below shows the stator case with the winding insulator.

most critical parts in this design. When the insulation breaks down, the machine shorts out. The cost of repair machine with shorted insulation is expensive and sometimes impossible. The temperature of the winding should be limited to prevent the insulation from breaking down because of the overheating. This can be prevented by providing circulation of cool air over the windings. The continuous power supplied to the machine usually limited by the maximum temperature of winding. The increased in temperature usually degrades the insulation. Life of the machine is halved for a temperature rise of 10 percent above the rate temperature winding. In this motor prefer used type F insulation class. This type of insulator is the most commonly used for motor. The allowable temperature 105°C rise from ambient temperature 40°C .

D. Rotor Construction

The type of rotor used is permanent magnet type. With a permanent magnet mounted on a shaft can be substituted for brush-type shaft with slip ring of rotor. When stator winding are energized, a rotating magnet is established. The

magnet has its own magnetic field that interacts with rotating magnetic field of the stator. The north pole of the rotating field attracts the south pole of the magnet, and the south pole of rotating magnetic field attracts the north pole of the magnet. As the magnetic field rotates, it pulls the magnet along. NdFeb rare earth magnet is the type of permanent magnet suitable used to produce strong magnetic field. Fig 3 shows the mounted magnet on the rotor shaft.

DESIGN THEORY OF PMSM Synchronous machines are designed to achieve the following information regarding its various partssupply.

- Main dimensions of statorframe,
- Complete details of the statorwinding,
- Details Design of the PM rotorand

- Performance of the designed parts, in order to justify the design of the aboveparts.

Design of electrical machines mainly consists of obtaining the dimensions of the various parts of the machine to suit given specifications, using available material economically and then to furnish these data to the manufacture of the machine.

A. Main Dimensions of Stator Frame

Internal diameter and gross length of the stator frame are its main dimensions. It is essential to develop an equation connecting the output of synchronous motor with its main dimensions in order to estimate the latter.

For the synchronous motor,

$2L$

Fig.3. Mounted magnet on the rotor shaft.



$$D_{in} i$$

$$\square \frac{P_{out}}{p n_s} \square \varepsilon$$

(1)

E. Rotor Configuration

Where,

$$\square \square 0.5 \pi k$$

$$A_m B_{mg}$$

$$\eta \cos \phi$$

p ωl

Permanent magnet synchronous motors are usually built with one of the following rotor configurations.

- Classical (Merrill's rotor), with salient poles, laminated pole shoes and a cage winding,
- Interior-magnet rotor,
- Surface-magnet rotor,
- Inset-magnet rotor and,
- Rotor with buried magnets symmetrically distributed.

F. Surface PM Rotor

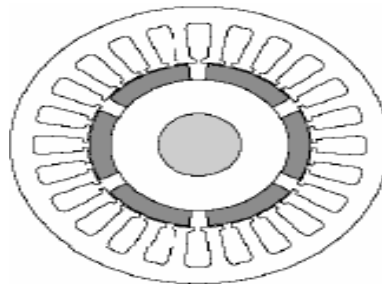


Fig.4. Surface-magnet rotor.

The surface magnet motor can have magnets magnetized radially or sometimes circumferentially. An external high conductivity non-ferromagnetic cylinder is sometimes used. It protects the PMs against the demagnetizing action of armature reaction and centrifugal forces, provides an asynchronous starting torque, and acts as a damper as shown in Fig.4. If rare-earth PMs are used, the synchronous reactances in the d- and q-axis are practically the same.

- D_{in} — Internal diameter of stator, (cm)
- L_i — Gross length of stator, (cm)
- P_{out} — Designing power, (W)
- \square_p — Output coefficient
- ϵ — Relative eccentricity
- N_s — Synchronous speed, (rev/s)
- $k \square_1$ — Winding coefficient
- A_m — Specific electric loading, (A/m)
- B_{mg} — Air-gap magnetic flux density, (T)
- η — Efficiency
- $\cos \phi$ — power factor

The size and cost of synchronous machine is decreased by choosing comparatively a higher value of air gap flux density. However, operating flux density in stator teeth and core increases, which results into higher iron losses. Thus reducing the efficiency and raising the temperature rise of the machine. With improvement in magnetic materials, it is possible to choose comparatively higher value of flux density in modern synchronous machines. Output equation clearly indicates that the size of the machine for the same output can be reduced by choosing higher value of specific electric loading, which amounts to decreased cost of the machine. Moreover, the leakage reactance and the armature reactance of synchronous machine are higher with large value of specific electric loading.

Internal diameter and gross length of the Slot pitch, which depends upon the number of slots, should have approximately the following values for different cases. For low voltages

stator can be calculated from the product $D2L$. And a suitable relation is assumed between D and L . For round pole- The ratio of pole arc to pole pitch may be assumed from 0.6 to 0.7 and pole arc may be taken equal to the axial length of the stator core. The length of air gap in synchronous machines is an important design parameter because its value greatly influences the performance of the machine. However, longer length of air gap will require increased values of field mmf making the machine costly.

B. Stator Winding

$$D_{out} = D_{in} + 2h_s + 2d_c$$

Mean length of stator turn,

$$l_{1e} \square 2.5 \square_p$$

$$l_{mt} \square (2L \square 2.5 \square_p \square 0.05kV \square 0.15)$$

Resistance of stator winding,

$$\square \frac{l_{mt} N^2}{s} \quad R = \quad a$$

(9)

(10)

(11)

(12)

machine: Less than or equal to 3.5 cm. Normally, the number of poles is quite large in non-salient pole synchronous machine and the number of slots

per pole per phase may be assumed from 1 to 3. Number of turns per phase can be calculated, using the emf equation of synchronous machines.

Total number of stator slots, $S = mpq$
 Where, m = number of stator slots per pole per phase
 Conductors per slot,
 Where, ρ — resistivity
 a_s — sectional area of stator conductor, [mm²]

C. Rotor Magnet Dimension

$N_{cs} \propto \frac{N_1}{\rho}$
 no : of conductor/ phase

(2)
 Turns per phase,
 $N \propto \frac{A_m p \tau_p}{\rho}$

Where,

The pole pitch,
 $l = \frac{3\sqrt{I_a}}{2p}$

$\tau_p \propto \frac{\pi D l_{in}}{2p}$
 Where, τ_p — pole pitch, m; y — number of slots per pole
 Air gap flux per pole,
 $\phi_f \propto \frac{2 \tau_p L_i B_m g l}{\pi}$

Stator winding factor
 $k_w \propto 1$
 may be assumed as per the winding details. For full pitch coils with infinitely distributed winding, stator winding factor, is $k_w \propto 1$
 number of turns should be an integer. Sectional area of the conductor for the stator winding can be calculated, based on the stator current per phase and operating current density for the stator winding.

Sectional area of conductor,
 $a_s \propto \frac{I_a}{J_s}$

(6)
 Current density, J_s should be assumed as per the cooling system used. Usual values for the current density in the stator winding can be assumed varying from 3 to 5 A per mm².
 Width of the teeth,
 b_t

The volume of all PMs used in a motor $V_M \propto 2p h_M w_M l_M$ depends on the quality of PM material (maximum energy). In above equation $2p$ is the number of poles, and $h_M, w_M,$ and l_M are the height, width and length of the PM, respectively. The output power of a PM synchronous motor is proportional to V_M . The maximum electromagnetic power developed by PM synchronous motor can be

expressed as follows:

$$P_{max} \propto \frac{\pi^2 \xi f B_r H_c V_M}{f}$$

$$P_{max} \propto \frac{2k_f k_{ad} (1 - \xi)}{f}$$

(3)
 (4)
 k_f — form factor of the rotor
 k_{ad} — d-axis armature reaction factor
 ξ — coefficient of utilization of the PM
 f — input frequency
 B_r — remanent magnetic flux density

(5)
 H_c — coercive force

D. Efficiency of PMSM

Copper Losses of Stator Winding,

$$P_{cu} = 3 I_a^2 R_s$$

Eddy current losses in the stator conductors,
 (13)

Average loss factor,

$$\text{equal to } 0.955. \text{ The } K_{dsv} = 1 + (\alpha h_c)^4 \frac{m^2}{9}$$

Eddy current Loss,

$$P_{eddy} = (K_{dsv} - 1) P_{cu}$$

Efficiency of the motor,
 (14)

$$(15) \quad \eta = \frac{P_{out}}{P_{out} + \text{Total Losses}} \times 100\%$$

(16)

IV. DESIGN CALCULATION OF 47 KW PMSM

In this paper, 47kW three-phase surface mounted PMSM is designed for EV. At the speed of PMSM

range from 0 to

$$b_t \frac{L_i}{N_t} B$$

Where, N_t — the number of teeth per pole arc
 Flux core section,
 in EV is calculated as follow,

$$\frac{1}{2} \frac{1}{c} \frac{1}{f}$$

(8)
 pole
 n_s
 $\frac{1}{2}$
 3000

(17)

The outer diameter of the stator is calculated from:
 The input line to neutral voltage;

$$V_{ph} \frac{380}{\sqrt{3}}$$

The armature rated current;
 I_a
 $\frac{1}{219.39V}$

Table II shows the detail designed data sheet for

(7)
 2000 rpm, the maximum torque is 180 Nm, but the
 EV PMSM is controlled by the number of poles of
 PMSM used

$$120 \frac{1}{f}$$

$$120 \frac{1}{50}$$

P_{out}

(18)

The Fig.5 shows the efficiency of the permanent
 magnet synchronous motor. The different type of
 permanent magnet materials such as Sm_2Co_3 ,
 Sm_2Co_{17} and NdFeB are mounted on the rotor of
 PM. By changing the magnets, the efficiency of the
 PMSM is also changed.

$$(19) \quad \frac{3V_l \eta \cos \phi}{3 \times 219.39 \times 0.94 \times 0.8} = \frac{47000}{94.959A}$$

V. CONCLUSIONS

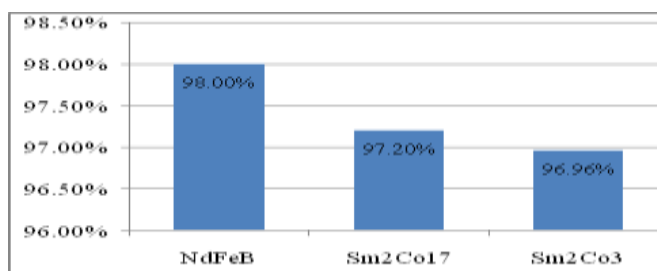
The design considered in this paper is 47 kW, 3000
 rpm surface mounted magnet PMSM. By changing the
 magnet

47kW surface mounted magnet PMSM.

TABLE II: Detail Designed Data Sheet for PMSM with Magnet NDFEB

Specification	Symbol	Unit	Value
Full Load Output	P_L	kW	47
Line voltage	V	Volts	380
Phase	-	-	3
Frequency	f	Hz	50
Speed	n	r.p.m	3000
Internal diameter of stator	D_{int}	mm	140
Gross Length of stator	L_g	mm	210
Peripheral Speed	V	m/s	219.91
Flux per phase	Φ_m	Wb	32×10^{-3}
Turns per phase	N_t	-	24
Number of slots	N_s	-	12
Conductor per slot	N_{cs}	-	12
Conductor area	a_c	mm ²	27.3
Width of slot	b_{cs}	mm	18
Depth of slot	h_s	mm	68
Resistance of winding	R_s	Ω	0.031
Leakage reactance	X_s	Ω	0.124
Outer diameter of the stator	D_{ext}	mm	414
Length of PM	l_m	mm	210
Height of PM	h_m	mm	15
Width of PM	w_m	mm	$4 \times 3 = 12$
Copper losses in stator winding	P_{cu}	W	838.62
Eddy current losses in conductors	P_{edc}	W	126.538
Stray load losses	P_s	W	144.774
Total losses	P_t	W	1109
Rotor losses	-	-	-
Efficiency	η	%	98

Fig.5. Efficiency of designed PMSM for Various Magnet.



material, not only the internal diameter of
 the stator and gross length of the stator but also the

efficiency of the motor is also changed. As the
 magnetic flux density of the different magnet

materials are not the same, the output coefficient is changed and other parameters concerned with the output coefficient are also changed. In this design, the NdFeB is chosen magnet to mount on the surface of the rotor because it has high efficiency compared with other magnet. The efficiency of the PMSM used NdFeB magnet is 98 per cent. The design of PMSM is suitable for EV. PMSM offers some advantages as low rotor inertia, high efficiency, efficient heat dissipation structure, and reduced motorsize.

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