A review: high power density motors for electric vehicles

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Abstract: The review of High Power Density Motor (HPDM) is presented, the high power density refers to ratio of output power to volume of the motor. As a result even a small envelope motor can have high power output. HPDM are also known as low speed high torque motors. The HPDM are compact, lightweight, has high torque and less cogging torque, finding application in automotive field, especially in electric and hybrid electric vehicles. This paper analyses the design, performance and efficiency of various HPDM. Comparative analysis of thirteen different HPDM are reviewed and tabulated for power density, speed, weight, rating and its applications.

1. INTRODUCTION

Power generated per volume in HPDM’s are high. The structure of the HPDM’s are very simple, embedded with compact windings in all coils. HPDM’s have less weight and high weight to power ratio. A constant air gap length are provided at all the design parameters of HPDM to obtain high power density. HPDM’s majorly adapts high electromagnetic load and lightweight structure motor design to improve the power density of the motor. This structural design of HPDM reduces the mass of the motor, without disturbing the flux density distribution through periodic duty cycle. High power density of motors are achieved by proper arrangements of rotor permanent/ electromagnet, stator slots and windings. By employing multiple magnetic circuits and one coil span motor power density, efficiency is increased and cogging torque is reduced [3]. To enhance the output power density of the motor, no load back EMF and phase current has been improved without changing the size of the motor [4]. The power density of motors depends on airgap flux density, ampere turns density and cooling conditions of the motor. For a given power and efficiency requirements the weight of the motor decreased with high power density [6]. Equation (1) describes the relationship between output power \( P_{out} \), efficiency \( \eta \), stator inner diameter \( D_s \) and stack length \( L \) [6]. Equation (1), it is concluded that, the main dimensions of the motor and efficiency are inversely proportional. The output power is directly proportional to the main dimensions. So high power density concept is helpful in reducing the dimensions of the motor.

\[
D_s^2 L = \frac{P_{out}}{\eta} \tag{1}
\]

Figure 1. Dimensions of electric rotating machine [6]
The main dimensions of rotating machine as shown in Figure 1. D is the stator diameter and L is the core length. The high power density motors find applications in following areas: electric vehicle, solar unmanned aerial vehicle, solar powered aircraft etc., which need to enhance output power. The aerospace motors recommend High Power Density (HPD) and high reliability due to highly risky operating environment and restricted space. Considering all these points in view, it is concluded that the HPDM will give high torque and speed with better power, lightweight structure, sinusoidal back EMF, reduced cogging torque, reduced losses, high efficiency, high mechanical strength [1-9]. Due to these advantages HPDM have become more attractive compared to conventional motor. There are many high power density motors and are discussed in next section.

2. HIGH POWER DENSITY SYNCHRONOUS MOTORS

There are various research has been done on synchronous motors to achieve high power. The synchronous motor’s design is modified and high power, high torque is achieved. The various modified synchronous motors and its working is discussed in this section.

2.1. Design 1 (High Power Density Permanent Magnet Variable Speed Motor, HPDPMVSM)

The conventional fabrication technique of rotor is introduced in the paper [7]. A 5kW, 1500rpm poly-phase multiple square wave permanent magnet motor in comparison with SRM and Induction Motor IM. Power per unit volume is limited in the present motor due to its commutating ability. The weight of the motor is reduced by reducing the circuit arrangement of magnetic path, reducing volume of yoke. A five phase, Twenty-two pole motor is shown in Figure 2, the motor has twenty slots, ten coils. Two sides of the first coil phase1 are located in two adjacent slots. The rotor of the motor consists of twenty-two permanent magnet poles. One pole pair is two adjacent poles (total 11 pole pairs). When currents in slots of S poles flows outward and currents in slots of N poles flows inward, then the torque direction in the rotor is either anti-clockwise or clockwise. The operation between stator slots and rotor poles has four phase windings conducting and one phase winding in non-conducting mode. In Figure 2 one phase non-conducting mode and when the rotor turn 18° electrical angle, the next phase will be in non-conducting mode. Phase difference between adjacent phases is 36°. The motor designed with conventional inner rotor for general purposes and outer rotor for wheel motor. This unique arrangement results in increased torque and power output [7].

2.2. Design 2 (High Power Density Wound Field Flux Switching Motor, HPDWFFSM)

HPDWFFSM is non-permanent magnet machine. A 12slot, 10 pole HDPWFFSM is designed for sport vehicle. Figure 3 illustrate sectional view of HDPWFFSM. The best technologically advanced electric motor for HEV is Interior PMSM [8]. This motor consists of hughedimensions of rare earth
permanent magnet in its rotor. This increases cost and transportation of rare earth magnet. As a result, research on non-permanent magnet HPDWFFSM machine is performed. Pros of this motor is that weight of the motor is reduce. In Figure 3, stator slots are embedded with three phase armature windings and field excitation coils. The rotor is of salient pole construction with 10 poles and coils wound on it, so it’s suitable for applications with high speed. The core of stator and rotor is made up of 35H210 electromagnetic steel. When field excitation coils are energized by DC current, the field flux is generated in the coils at different rotor positions. The flux in the field coils will be changing with rotor positions. The position between stator and rotor teeth are un-aligned resulting in field flux yields positive flux linkage. At unaligned position between stator and rotor teeth the field flux yields negative flux linkage. The voltage induces in armature coil due to the continuous alternating flux linkage to armature coil with respect to rotor. The torque is produced by controlling current with phase angle for the induced voltage. The current vector control is performed for testing HPDWFFSM. As a result, the very high power density is achieved. The high magnetic saturation quality of the motor make is highly unreliable.

2.3. Design 3 (High power density in-wheel motor, HPDIWM)

The weight reduction technique is employed in In-wheel type motor for HPD [9]. Weight of the rotor core is reduced by reduction of gear ratio. Reduced weight of the motor is achieved by changing the ratio of stator diameter to stack length. From equation (2), the maximum torque is directly proportional to rotor volume. TRV is Total Rotor Volume, T is torque, D is dia of rotor, Lstk is rotor length of stack. It is clear that, if gear ratio is increased, the rotor volume is reduced, that is reduction in motor weight.

\[
TRV = \frac{T}{4D^2L_{stk}} [kNm/m^2]
\]

(2)

The stack length, volume of rotor and stator is considerably reduced in In-wheel type motor. The optimal design of the motor is obtained. Figure 4 gives region of optimization in rotor part. The power density of the motor is improved to 57% for the rotors optimal design technique. The stack length, volume of rotor and stator is considerably reduced in In-wheel type motor. The areas which don’t come under rotor magnetic paths are cut using optimal design technique. The power density of the motor is improved to 57% for the rotors optimal design technique.

![Figure 4. Region of optimization in rotor](image)

![Figure 5. 2D view of 14-pole/15-slot motor](image)

2.4. Design 4 (High Power Density Outer Rotor PMSM)

The high efficiency of PMSM is gains more attention in electric vehicles and solar unmanned aerial vehicles applications. The electromagnetic parameters have been analyzed on efficiency and power density. Research on Hallbach array is performed to get maximum output torque and minimum core loss [10]. The PMSM motor is consists of inner stator and outer rotor. The power density of the motor is increases as phase current and airgap flux density is increased. But the copper loss and core loss is also increases. Efficiency and power density of the motor have mutual effect. The stator armature windings are in inner part of motor due to the structural characteristics of outer rotor. Greater the PM
higher the flux per pole and the magnetic torque. The outer rotor has larger PM compared to inner rotor, so flux density in outer rotor is greater than inner rotor. Figure 5 shows 14-pole/15-slot motor design, here L is axial length, D1 is the diameter (outer)of the rotor, D2 diameter (inner)of rotor, D1 is the outer diameter of stator, and D2 is the inner diameter of the stator, h is the thickness of magnet. The optimizing Halbach array rotor, the stator tooth width and magnet depth has got optimal structure of the outer rotor. This improves the efficiency of the motor with HPD.

2.5. **Design 5 (High Power Density PMSM, HPDPMSM)**

A high power density PMSM is developed for formula one race-car in this paper [11]. The frequent acceleration and deceleration of the race-car needs high dynamic performance of motor, low inertia materials. Figure 6 shows spoke-type rotor structure design. Resulting in concentrated of flux and HPD. Two layer Fractional Slot non-overlapping Concentrated Windings (FSCW) gives high fill factor resulting in high efficiency and power density. The power density of the race car motor is increased by reducing leakage flux and by increasing magnetic and electric loading. Low density materials are used in construction of motor to achieve high power density.

![2D view of HPDPMSM](image1)

![2D view of SMHPDPMSM](image2)

2.6. **Design 6 (Surface Mounted High Power Density PMSM, SMHPDPMSM)**

A surface mounted magnet PMSM is designed, used for propulsion motor of a passenger ferry [12]. A multiphase and HSPMSM can reach power density between range 6 to 12 kW/kg. Conventional PMSM with less poles can achieve power density of 0.3 to 0.5 kW/kg, whereas PMSM with large number of poles can achieve 1.5 kW/kg. Low speed pod propulsion system demands PMSM with inner rotor, surface mounted PM and concentrated winding. High quality silicon steel is selected for both stators and rotor core [12]. Round copper wires are implanted in slot of width bso. Figure 7 gives the 2D view of the whole PMSM motor. Where Ds is stator inner diameter, Dr is rotor diameter, δ is airgap length, Im is magnet thickness, Do is stator outer diameter. The optimization method adopted in design of PMSM is used in pod propulsion systems.

2.7. **Design 7 (High Power Density Wound Field Synchronous Motor, HPDWFSM)**

The design method is to enhance power density and efficiency of WFSM is discussed in [13]. Achieved by hairpin rectangular winding for EV’s. The hairpin type rectangular windings are used to reduce the copper loss and volume of the motor. Considerably the power density and efficiency is also increases. The WFSM design has high fill factor in stator core, resulting in high winding resistance and copper loss. The rotor core has high magnetic flux density so results in high iron losses. In order to overcome these problem, hairpin type rectangular winding is applied and width of yoke and tooth is reduced. The advantage of hairpin winding is gap between tooth and coil is reduced and current density is also reduced. So greater number of wires in same amount of space as shown in Figure 8b. The efficiency is increased as iron loss and flux density is reduced. Figure 8a shows the structure for hairpin winding. The volume of the motor is reduced for designed windings and power density is also improved to 8.5%.
3. HIGH POWER DENSITY HYBRID EXCITATION MOTOR

3.1. High Power Density Hybrid Excitation Flux Switching Machine (HPDHEFSM)
HEFSM is the modified design of IPMSM. By altering the design torque, power density and mechanical strength of the machine is increased. The proposed designed motor in the paper [14] has 6 slots, 8 pole with rare earth permanent magnet is embedded in the stator along with stator windings. Figure 9a shows sectional view of designed 6S, 8P HPDHEFSM and Figure 9b shows flux distribution by PM and FECs for given current density in it. Here the stator part of motor includes PM and Field Excitation Coils (FEC). On the PM the FEC in wound to reduce torque pulsation. Magnets are mechanically 1200 apart from each other, creating a hybrid stator winding. The working principle of HEFSM is similar to IPMSM. The armature coil alternately linked such that PMs and MMF of FEC are switched by rotor rotation and flux flow generation. The, the flux linkage of one periodic cycle in the armature coil results in 1/8 of a revolution of rotor. Thus frequency of back emf induced is 1/8th the mechanical frequency. This machine finds wide application in automotive industries.

3.2. Rare Earth Magnet High Power Density Hybrid Excitation Motor (REMHPDHEM)
The hybrid excitation motor is investigated as less PM and high power density motor for traction drive vehicle applications. As investigation result the motor makes possible to reduce the volume of PM by making power density constant [15]. Figure 10 shows general view of the REMHPDHEM machine. The major differences between REMHPDHEM machine and conventional PM machine is PM rotor is sandwiched by N and S pole of rotor core and magnetized in axial directions and Soft Magnetic Composites (SMC) with field coil is joined at each end of the machine in axial direction. In Figure 10 the black arrows are PM flux passing through radial airgap. This flux will link with armature winding and it will help in torque production. In the figure, green arrows are flux generated by DC excitation of field and helpful in field strengthening. Here both black and green arrows will link the armature windings it leads to higher torque production. In Figure 10, pink arrows are main flux paths and the flux linking with armature winding is zero. It results to field weakening and also
reduces induced back EMF of armature winding. In order to reduce the volume of PM motor, the rotor construction is made similar to that of hybrid stepper machine. From the equation (3), it is clear that PM weight is directly proportional to square of outer diameter. So by reducing the volume of PM the size of the machine will reduce.

\[
W_m = C_m \times t_m \times \frac{\pi (D_{no}^2 - D_{shaft}^2)}{4}
\]

(3)

Where, \(W_m\) is PM weight, \(D_{no}\) is Outer diameter, \(t_m\) is Thickness, \(D_{shaft}\) is shaft diameter, \(C_m\) is Specific gravity of rare earth magnet.

**4. HIGH POWER DENSITY BRUSHLESS DCMOTOR**

4.1. High Power Density Brushless Permanent Magnet DC Motor (HPDBPMDCM)

A 5 phase, 22pole, exterior rotor brushless DC motor is modified for multiple magnetic circuit and one slot coil span design. The permanent magnet synchronous motor is compared with proposed motor [16-17]. The cup type rotor made of soft iron with NdFeB ring magnet fixed inside the cup and is designed for 20 slots and10 coils. So the proposed design requires single die-cast zinc bearing support rather than two bearings. Multipole magnetic circuit design allows reduction of volume and weight. Figure 11 shows the 2D view of the HPDBPMDCM. The modified design is able to achieve high power density, high efficiency and small cogging torque [16]. In the new arrangement each phase conducts at 144° and it will conduct at 36° at both positive and negative cycles. This motor finds application in automotive industry.

**4.2. High Power Density Flux Switching Motor (HPDFSM)**

Electronically commutated brushless flux switching motor compared with switched reluctance motor and DC motor. Figure 12 shows HPDFSM with double salient structure like switched reluctance motor. Figure 12 shows the HPDFSM motor design. The designed prototype helps in achieving high output power and high efficiency. The HPDFSM operates with interaction of both AC- DC magnetic
fields are produced by armature (A) and field (F). The subsequent flux vector directed along stator poles axis \( \theta_1 \) [18-19]. This results in rotor and stator pole alignment. When magnetic circuit is excited, the torque produced by the alignment action is at position of minimum reluctance. This motor finds the application in domestic appliances.

5. COMPARISON OF DIFFERENT HIGH POWER DENSITY MOTORS

The review of different HPD motors is performed in the paper. These motors are composed of different characteristics, speed, power, weight. The different parameters of these motors are tabulated in Table 1.

| Si. No. | Types of motors                      | Power Density (kW/kg) | Speed (rpm) | Weight (kg) | Rating (kW) | Applications             |
|--------|-------------------------------------|-----------------------|-------------|-------------|-------------|--------------------------|
| 1      | HPDPMVSM(Design1)                   | 2                     | 1500        | 8.05        | 5           | Electric drives/          |
| 2      | HPDHEFSM(Design2)                   | 3.5                   | 16000       | 1.1         | 124         | HEV                      |
| 3      | HPD PMSMIWM (Design3)               | 1.2                   | 8000        | 13          | 25          | Industries               |
| 4      | HPDPMISM(Design 5)                  | 6                     | 9000        | 1.67        | 10.02       | Aero-spaces              |
| 5      | HPDWFSM (Design 7)                  | 4.2                   | 6000        | 43.2        | 123         | HEV                      |
| 6      | HPDHEFSSM(Design 1, Hybrid excitation)| 3.2                  | 12400       | 1.1         | 123         | HEV                      |
| 7      | HPDHEM (Design 2, Hybrid excitation) | 3.5                   | 20000       | 550         | 123         | HEV                      |
| 8      | HPDSCM (Design 1,BLDC)              | 2.68                  | 2700        | 28          | 164         | Aircraft                 |
| 9      | HPDWFSM (Design 2,BLDC)             | 2.32                  | 10000       | 500         | 120         | EV traction              |

6. CONCLUSION

Review on various high power density motors has been carried out, it is concluded that power density of the motor is the important parameter for the application in traction, electrical vehicles and aircraft vehicles. The paper discusses the different designs of improving power density in various motors. It is observed that, the power density of the motors has improved around 0.5kW/kg to 2kW/kg for hybrid electric vehicle applications.

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