Axial Flux Permanent Magnet brushless machine, a new topology of electrical machines and brief about it

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Abstract— From the beginning of invention the electric machine, it has been developed to many shapes many times. After development for traditional machines, new requirements have been appeared. The humanity has made many modifications to achieve majority of its needs. Because of that special machine has appeared. The objective of this paper is to provide a brief about Axial flux permanent magnet (AFPM) and comparative summary which made by many published works.

Index Terms— Axial flux permanent magnet (AFPM), diameter ratio k_d, sizing equation, quantities of the comparison (QOC).

◆

1. INTRODUCTION:-

Nowadays, all organizations and institutions direct to the product which has less cost and high both of efficiency and productivity. There are many selections but not all selections achieve all purposes. AFPM is one of these choices.The reduction of rare-earth PM prices' and the development in power electronics technology have played important part in fabrication and manufacturing process of all PM brushless machines during the last forty years ago. These machines have become very useful and deserve many of attentions.

2. NOMENCLATURE

$A(r)$	the linear current density
B_{max}	The maximum value of permanent magnet's flux density.
r_{in}	The inner radius of the stator.
r_{out}	The inner radius of the stator.
m	The number of phases.
N_{ph}	The number of coil turns in series per stator phase winding.
I	The RMS of winding conductors current
A_{in}	The linear current density on the inner radius
k_d	The diameter ratio.
T_{em}	Electromagnetic torque.
N_1	The number of turns per phase per one stator.
I_a	The phase armature current in stator winding.
E_f	The back EMF per phase per stator winding.
p	Number of pole pair.
τ	Pole bitch.
S_{elm}	The apparent electromagnetic power.
ϵ	EMF to phase voltage ratio.

3. LIMITS OF CONVENTIONAL MACHINES:-

Today many fields require more of things like high power density, low weight, low material, low cost, good cooling and ventilation … etc.There are many limits to achieve all requirements in conventional radial flux (RF) machines. There are some reasons to prevent achieving all requirements in the design. The most important reasons are [5, 9, 6, 7, 11,3]:

1- The bottle-neck feature for the flux path at the root of the rotor tooth in the state of induction and D.C commutator machines or brushless machines with external rotors (Fig. 1).
2- Much of the rotor core around the shaft (rotor yoke) is hardly utilized as a magnetic circuit.
3- Dissipated Heat from the stator winding is transferred to the core of stator and then to the frame — there is poor heat removal through the stator air gap, rotor and shaft without forced cooling arrangements.

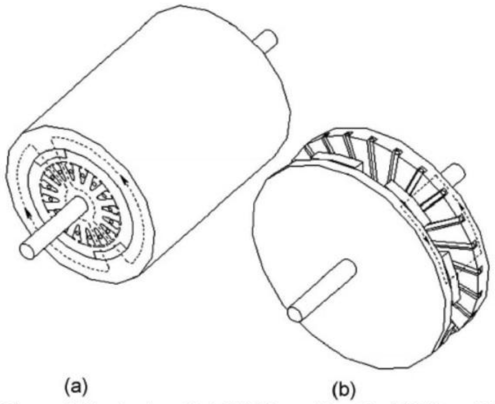

Figure 1. Topologies of (a) RFPM machine (b) AFPM machine.

Because of previous limitations which are inherently bound with radial flux constructions, it is needed a new topology or new technology in metallurgy of materials. After that, we can avoid these problems and achieve what are adopted [14, 9, 6, 7].

4. AXIAL FLUX PM MACHINES:-

The reduction of rare-earth PM prices' and the development in power electronics technology have played important part in fabrication and manufacturing process of all PM brushless machines during the last forty years ago. These machines have become very useful and deserve many of attentions. This has been happened because it's high power density and efficiency. All of that led to use these machine instead of traditional DC commutator and Induction machines in many fields. It's also called disc type machine. Cylindrical (RF) machine can be replaced by the equivalent Disc type because of its pancake shape, compact construction and high torque density. It is mainly suitable for electrical vehicles, pumps, fans, valve control, centrifuges, machine tools, robots and many of industrial equipment. The large diameter rotor with its high moment of inertia can be utilized as a flywheel. It can also operate as small to medium power generators.

5. FEATURES AND ADVANTAGES OF AFPM:-

Despite of AFPM machines is more compact that its RF counterpart, It is recognized that it has the capability to get more power density than the RF machines. After that, it can be summarized (general special proprieties of AFPM, which make it better than RF counterpart machines in certain applications) as follows [12, 6,3]:-

1- AFPM machine has much larger diameter to length ratio than RF machine.
2- AFPM machine has a planar and somewhat adjustable air gap.
3- Capability of being designed to possess a higher power density with some saving in core material.
4- The larger the outer diameter of the core, the higher the number of poles that can be accommodated, making the AFPM machines a suitable choice for high frequency or low speed operations.
5- The topology of an AFPM machine is ideal to design a modular machine in which the number of the same modules is adjusted to power or torque requirements.

So, disk type machine is particularly suitable for traction, servo, distributed generation and special-purpose applications because its properties offer featured advantages over their conventional RF counterparts.

6. TORQUE PRODUCTION AND DIAMETER (OR RADIUS) RATIO EFFECT:-

The torque production of a machine is very important element. It can detect if this machine is suitable or not. To get the electromagnetic torque expression of the AFPM machine, we consider and assumed that [2,3]:-

- An idealized axial-flux machine structure with double air-gaps.
- The permanent magnets produce a square wave flux density distribution into the air-gap with maximum value B_{max}.
- All the winding conductors carry constant current with RMS value I.
- The current is appropriately timed and perpendicularly oriented with the flux density distribution in the air-gaps.
- The conductors are located as closely together as possible on the inner radius of the stator core r_{in}.

From what have been mentioned above, the line current density and the machine torque can be gotten. The line current density A on radius r can be written as:-

$$A(r) = \frac{A_{in} r_{in}}{r}$$

$$A_{in} = \frac{m N_{ph} I}{\pi r_{in}}$$

The machine torque can be calculated from the elementary forces dF acting quadrature on the surface of the stator core. The elementary torque component dT_{em} on radius r takes the form

$$dT_{em} = 2\pi r_{in} A_{in} B_{max} r dr$$

Integrating the previous equation over the machine radius the electromagnetic torque for the ideal double-sided axial-flux machine

$$T_{em} = \int_{r_{in}}^{r_{out}} dT_{em} = 2\pi A_{in} B_{max} r_{in} \int_{r_{in}}^{r_{out}} r dr$$

$$T_{em} = 2\pi A_{in} B_{max} r_{out}^{3} k_d (1 - k_d^{2})$$

$$k_d = \frac{r_{in}}{r_{out}} = \frac{D_{in}}{D_{out}}$$

The electromagnetic torque produced by a real machine is somewhat reduced due to the actual distribution of the flux density in the air-gaps and in the current waveform and the other losses in the machine (electrical and mechanical losses). Then, it is possible to drive the optimal diameter ratio for the idealized axial-flux machine by taking the first derivative of the electromagnetic torque T_d with respect to K_d and equating it to zero,

$$T_{em} = 2\pi A_{in} B_{max} r_{out}^3 (k_d - k_d^3)$$

$$\frac{dT_{em}}{dk_d} = 2\pi A_{in} B_{max} r_{out}^3 (1 - 3k_d^2)$$

$$\therefore 1 - 3k_d^2 = 0 \, , k_d = \frac{1}{\sqrt{3}} \cong 0.58$$

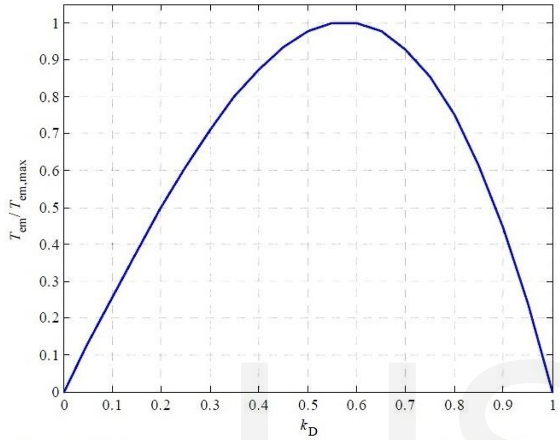

Fig. 2 Electromagnetic torque of an ideal axial flux machine as a function of the machine diameter ratio

Note that, the diameter ratio is an important design parameter (as axial-flux machines are concerned). The torque production capability of the machine, as a function of k_d, is described in Fig. 1.2 The curve is scaled for the maximum torque to be equal to value 1.

Finally, it has been shown that the machine torque density reaches its maximum value when the diameter ratio is between 0.6 and 0.65. Considering the previously discussed mechanical considerations in relation with the torque density characteristic of the axial-flux machine, it is correct to conclude that the practical optimum for the diameter ratio lies between 0.6 and 0.7.

In the same side, In 1994 F. Caricchi et al.it has been mentioned that the optimized value of the ratio $k_d = 0.63$ for AFPM machine, to achieve a high value of both the torque and torque-to-weight ratio [13].

In practice, the optimal value of k_d is different depending upon the optimization goal. Moreover, for given electrical loading and flux densities, even when the optimization criterion is the same the optimal value of k_d also differs for different rated power, pole pairs, converter frequency etc. Further, if different materials or different structures are involved, the optimal k_d will have a significantly different value.

In 1974 P. Campbell derived an optimized value of $k_d = 1/\sqrt{3}$ for the maximum armature power in a permanent magnet axial field DC machine [14]. In 1994 F. Caricchi et al. presented an optimized value of the ratio $k_d = 0.63$ for AFPM machine, to achieve a high value of both the torque and torque-to-weight ratio [13]. In practice, the optimal value of k_d is different depending upon the optimization goal. Moreover, for given electrical loading and flux densities, even when the optimization criterion is the same the optimal value of k_d also differs for different rated power, pole pairs, converter frequency etc. Further, if different materials or different structures are involved, the optimal k_d will have a significantly different value.

Referring to [1], the only independent term is k_d while the other terms either depend on k_d or have certain physical limitations. The relationships between power density and efficiency of the AFTPM machine vs. ratio k_d are shown on both Fig. 3 and 4. Respectively, it is very clear that the ratio k_d has a more significant effect on power density than on efficiency. It should be noted that, because of the curve of efficiency vs. k_d has a flat shape, from the design point of view it is advantageous to choose an optimal value of h to achieve the maximum power density.

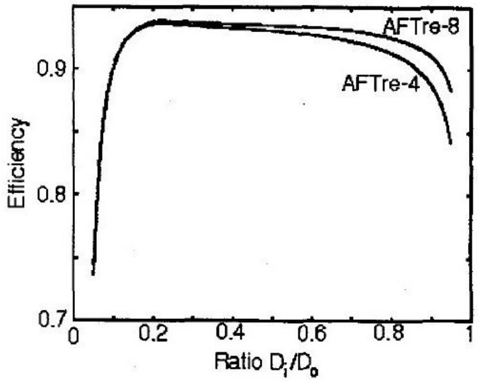

Fig. 3 efficiency of the AFPM machines vs. ratio k_d

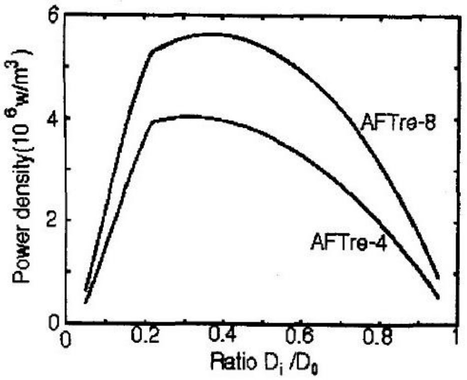

Fig. 4 power density of the AFPM machines vs. ratio k_d

7. SOME MADE COMPARISONS:-

Many published works have been made to compare between AF and traditional counterpart RF machines. To compare power production of axial flux machines with traditional counterpart topologies, different waveforms of back emf and current, general purpose sizing and power density equations for such machines are needed. In this paper, it will show two kinds of comparisons, theoretical method and practical method.

7.1. SIZING EQUATION AF VS RF:-

Dimension is one of the most important characters for any machine. By depending on machines dimensions, it can be replaced by another more suitable one. As we said before, AFPM machines have a benefit. The main dimensionsof an AFPM brushless machine can be determined by using many assumptions. As an example, for single-sided PM brushless machine with internal disc rotor, we can use the following assumption:-

a) The outer diameter of PM is equal to the outer diameter of the stator core D_{out}.
b) The electric and magnetic loadings are known.

The peak line current density at the average radius is expressed as the following:-

$$A_m(r) = \frac{m_1\sqrt{2}N_1 I_a}{p\tau(r)} = \frac{m_1\sqrt{2}N_1 I_a}{\pi\, r_{avg}}$$

Replacing the radius by an average diameter:-

$$r_{avg} = \frac{D_{avg}}{2} = 0.5(D_{out} + D_{in})/2 = D_{out}\,(1 + k_d)/4$$

Then

$$A_m = \frac{4 \cdot m_1\sqrt{2}N_1 I_a}{\pi D_{out}(1 + k_d)}\ , \therefore I_a = \frac{\pi D_{out}\,(1 + k_d)}{4\sqrt{2}m_1 N_1} \cdot A_m$$

The induced emf in the stator winding by the rotor excitation system is as the following:-

$$E_f = \pi\sqrt{2}n_s p N_1 K_{w1}\Phi_f$$

$$E_f = \frac{\pi}{4}\sqrt{2}n_s N_1 K_{w1} B_{mg} D_{out}^2 (1 - K_d^2)$$

The apparent electromagnetic power is:-

$$S_{elm} = m_1 E_f I_a$$

$$= \frac{\pi^2}{16} K_{w1} n_s B_{mg} A_m D_{out}^3 (1 + K_d)(1 - K_d^2)$$

$$S_{elm} = \pi^2 k_D K_{w1} n_s B_{mg} A_m D_{out}^3$$

Where

$$k_D = \frac{(1 + K_d)(1 - K_d^2)}{16} = \frac{(1 + K_d)^2(1 - K_d)}{16}$$

- *In case of multi-disc machine (double sided or more) and the connection of them are series or parallel, number of the stators must be multiplied in the previous equation.*

$$S_{elm} = \epsilon P_{out}/\cos\varphi\ , \epsilon = \frac{E_f}{V_1}$$

- ϵ *is used here to show the value of decreasing where* S_{elm} *is calculated from* EMF *and we need to know the output power* P_{out} *not internal power.*
- $\epsilon < 1$*for motors and* $\epsilon > 1$ *for generator.*

By combining the last two equations for S_{elm}, the outer diameter of the stator is as follow:-

$$D_{out} = \sqrt[3]{\frac{\epsilon P_{out}}{\pi^2 k_D K_{w1} n_s B_{mg} A_m \eta \cos\varphi}}$$

And by substituting Electromagnetic torque instead of Power, $T_d = \frac{P_{out}}{2\pi n_s}$, we get the following:-

$$D_{out} = \sqrt[3]{\frac{2\epsilon T_d}{\pi k_D K_{w1} B_{mg} A_m \eta \cos\varphi}}$$

It’s noted that outer diameter D_{out} is proportional to the cube root both of power and torque. $D_{out} \propto \sqrt[3]{P_{out}}$,$D_{out} \propto \sqrt[3]{T_d}$. This is one of many reasons which make the disc-type construction preferred for large and medium power machines and not preferred in small scale power.

And what is worth to mention

$$T_d = \frac{P_{elm}}{2\pi n_s} = \frac{S_{elm}\cos\psi}{2\pi n_s} = \frac{\pi}{2} k_D K_{w1} D_{out}^3 B_{mg} A_m \cos\psi$$

Because of what has mentioned before, the small power AFPM machines have relatively large diameter. However, the outer diameter is also one of the most important elements for designing of the AFPM machines.

- *As the output power of the AFPM machine increases, the contact surface between the rotor and shaft becomes smaller in comparison with the rated power. It will be mentioned that the length of machine is constant and power is proportional to cube of diameter leads to problem in manufacture.*

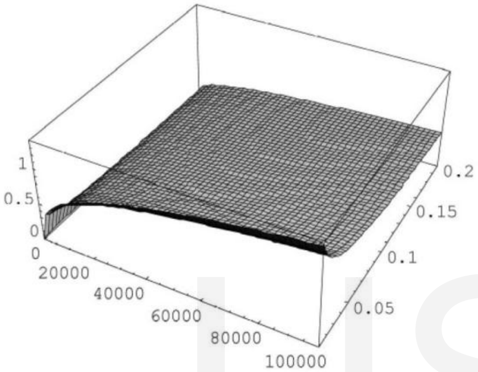

Figure 5. outer diameter D_{out} as a function of the output power P_{out} and parameter k_d for $\epsilon = 0.9$, $K_{w1}\eta\cos\varphi = 0.84$, $n_s = 1000\ rpm = 16.67\ rps$,

7.2. PRACTICAL COMPARISON AF VS RF:-

On the same side, some of published works have made comparisons in a Practical way. To make equitable comparison, there are many parameters must be equivalent between compared machines. One of these researches has been made between a conventional RFPM machine and four topologies of AFPM machines of different configurations at five power levels ranging from 0.25 to 10 kW.The comparison has been based on the following:-

-The comparison is done at five power levels ranging from 0.25 to 10 kW.

-Several parameters are held constant or very near to each other to make the comparison.

-A rated speed of 2000 rpm is chosen for the 0.25 kW designs while 1000 rpm is chosen for therest of the designs to be the rated speed with a non-load maximum speed of 2000 rpm for all the machines except 0.25 kW machines.

-2000 rpm was the rated speed for these machines, with a 3000 rpm no-load speed at 375 V DC.

-All the machines are designed using 375 V DC as the rated supply voltage.

-The winding currents are assumed to be limited at rated speed.

-All the performance calculations are made using a three-phase six-step drive and the back-EMFs of all the machines are assumed to be trapezoidal.

-The 0.25 kW machines used a 12-slot eight-pole combination while all the other slotted designs used a 24-slot eight-pole design.

<u>The quantities of the comparison (QOC) as the following:-</u>

A. Volume
B. Moment of Inertia
C. Steel Weight
D. Copper
E. Magnet Weight
F. Copper
G. Iron Losses
H. Total Losses
I. Torque per Unit Moment of
J. Power per Unit Active
K. Power per Unit
L. Active

<u>The result diagrams of the comparisons as the following:-</u>

A. <u>Volume:-</u>

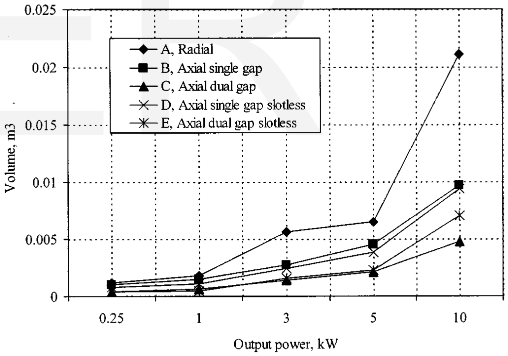

Fig. 6.Active volume versus output power.

B. <u>Moment of Inertia:-</u>

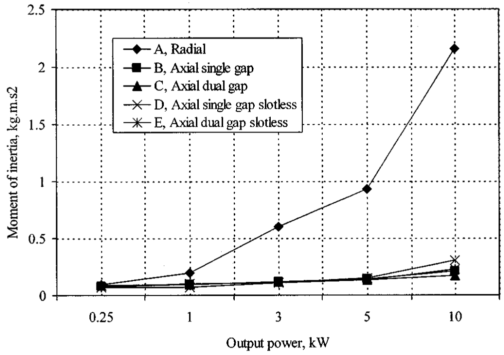

Fig. 7.Moment of inertia versus output power.

C. *Steel Weight:-*

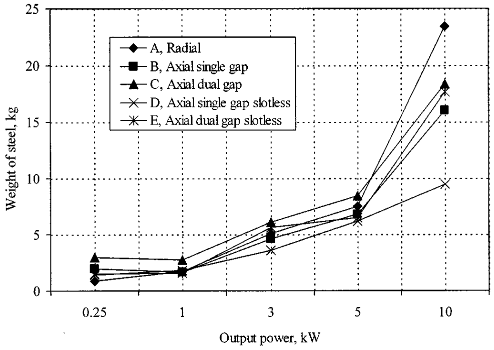

Fig. 8.Steel weight versus output power.

D. *Copper Weight:-*

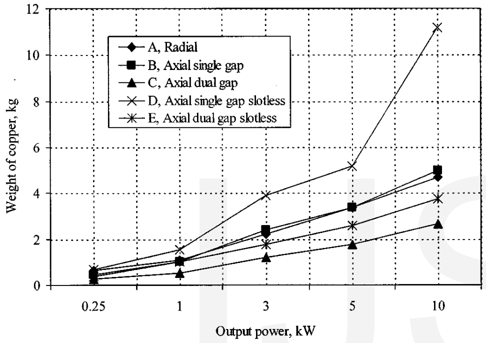

Fig. 9.Copper weight versus output power.

E. *Magnet Weight:-*

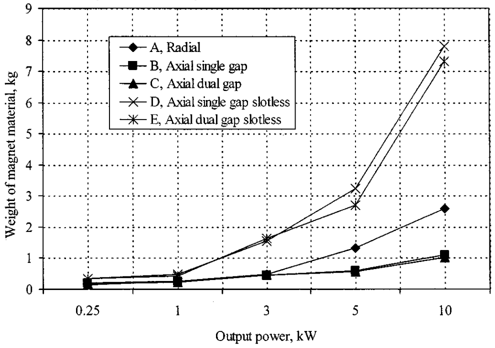

Fig. 10.Magnet weight versus output power.

F. *Copper Losses:-*

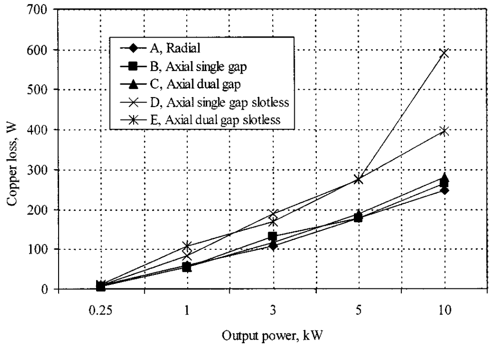

Fig. 11.Copper loss versus output power.

G. *Iron Losses:-*

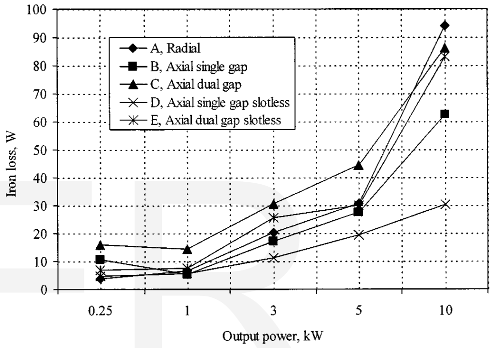

Fig. 12. Iron loss versus output power.

H. *Total Losses:-*

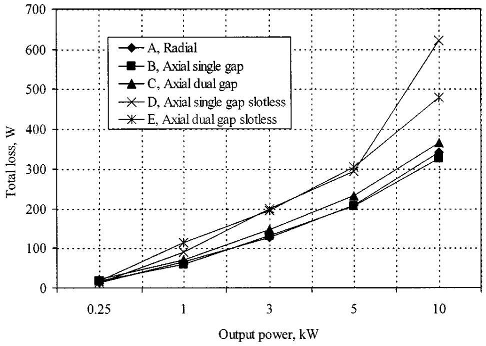

Fig. 13.Total loss versus output power.

I. Torque per Unit Moment of Inertia:-

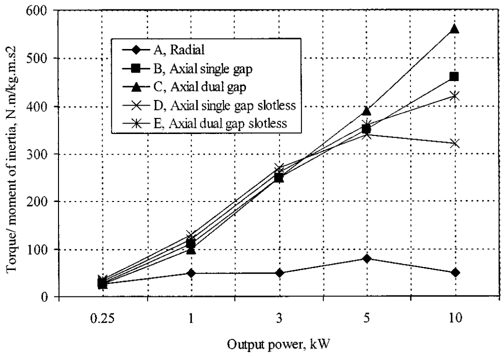

Fig. 14.Torque/moment of inertia versus output power.

J. Power per Unit Active Weight:-

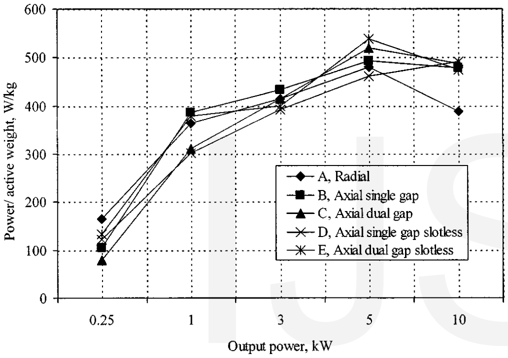

Fig. 15.Power/active weight versus output power.

K. Power per Unit Active Volume:-

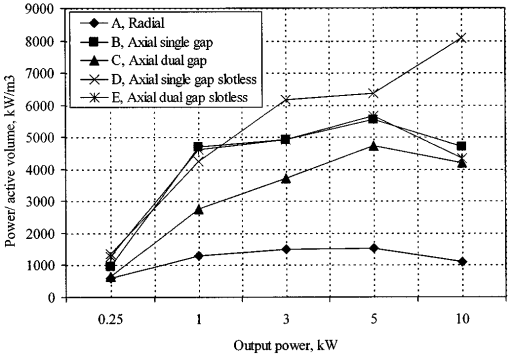

Fig. 16.Power/active volume versus output power.

We can summarize the results in the following table:-

(QOC)	AF	RF	Notes
A. Volume	*smaller*	*Bigger*	---
B. Moment of	*less*	*more*	---
C. Steel Weight	*less*	*More after 10 kW*	---
D. Copper Weight	*Slotless slightly more*	----	*Nearly Equal*
E. Magnet Weight	*Slotless slightly more*	----	*Nearly Equal*
F. Copper Losses	*Slotless slightly more*	----	*Nearly Equal*
G. Iron Losses	*Slotless slightly less*	----	*Nearly Equal*
H. Total Losses	----	----	*Nearly Equal*
I. Torque per Unit Moment of Inertia	*more*	*less*	*Indication of the acceleration & mechanical response of the rotor*
*J. Power per Unit Active Weight**	----	----	*Nearly Equal*
*K. Power per Unit Active Volume***	*more*	*less*	---

8. POWER LIMITATION OF AFPM MACHINES:-

To be honest and fair in this paper, it should be mentioned the disadvantages of AF machines its advantages are mentioned. The AF machines have some of limitations and disadvantages which make it can't be used for some fields. The following terms are some of famous limitations and problems of these machines [3] and may be summarized as follows:

1- Strong axial (normal) magnetic attraction force between the stator and rotor.
2- Fabrication difficulties, such as cutting slots in laminated cores and other methods of making slotted stator cores.
3- High costs involved in manufacturing the laminated stator cores.
4- Difficulties in assembling the machine and keeping the uniform air gap.
5- It is more difficult to design a high mechanical integrity for rotor-shaft mechanical joint in the higher range of the output power.

These previous reasons were the main purpose of shelving for the AF machine. This may be a cause of limiting design consideration for the high power rating of a single-stage disc machine as the power level can always be increased by simply stacking of disc machines on the same shaft and in the same enclosure.

9. USAGES OF AXIAL FLUX MACHINES:-

Brushless PM electrical machines are the primary generators for distributed generation systems. They are compact, high efficient and reliable self-excited generators. The distributed generation is any electric power production technology that is integrated within a distribution system. Distributed generation technologies are categorized as renewable and nonrenewable. Renewable technologies include solar, photovoltaic, thermal, wind, geothermal and ocean as sources of energy. Nonrenewable technologies include internal combustion engines, combined cycles, combustion turbines, micro-turbines and fuel cells.

AFPM brushless generators can be used both as high speed and low speed generators. Their advantages are high power density, modular construction, high efficiency and easy integration with other mechanical components like turbine rotors or flywheels. The output power is usually rectified and then inverted to match the utility grid frequency or only rectified.

Disc-type rotors can be embedded in power-transmission components or flywheels to optimize the volume, mass, number of parts, power transfer and assembly time. For electric vehicles (whether Hybrid electric and Battery electric vehicles) with built-in wheel motors the payoff is a simpler power train, higher efficiency and lower cost. Dual-function rotors may also appear in pumps, Mobile drill rigs, Vibration motors, Computer hard disc drives, Electromagnetic aircraft launch system, elevators, energy storages and other machinery, bringing added values and new levels of performance to these products.

10. CONCLUSION:-

1- It is noted that the axial machines have higher power density than the traditional induction machine particularly when a rare earth magnet is applied and the degree of improvement could reach a factor of three. If cost is a dominating factor, the power density still increases by a factor of two with a ferrite magnet [1].
2- It is shown that the ratio $k_d = D_{in}/D_{out}$ has a strong effect on the power density and has relatively less effect on machine efficiency. Optimization of k_d will achieve a maximum power density as well as nearly the highest efficiency [1].
3- It is argued that the optimal value of k_d depends upon electrical loading, flux density, frequency, materials, and machine topology etc. and cannot be reduced to a simple numeric value as previously reported. However it is highly dependent on the machine topology and remains in a relatively narrow band [1].
4- From the data presented in the previous sections, it is inferred that axial field machines have a smaller volume for a given power rating, making the power density very high [4].
5- For a given magnet material and air-gap flux density, the rotor moment of inertia of the radial field motor tends to be larger than all of the axial field machines in this comparison [4].
6- The weight of iron required in the axial field designs is lower than that required in the radial field motor, making the active weight of axial field machines smaller [4].
7- The slotless axial field machines require more magnet material than the radial field machine.
8- However, the slotted axial field machines require less material than the radial field machine.
9- The copper loss in the slotless dual-gap machines is higher than that of the slotted radial field machine.

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