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Air Gap Effect on the AFPM Generator (Inner Rotor) Performance

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Abstract:- The axial flux permanent generator double stator- single rotor ((inner rotor) is presented in this paper. The aim study is find the relation between air gap size and output performance of the generator. By changing, the air gap size and observe the output generator are discussed. Torque types of the coreless AFPM generator (initial torque and electromagnetic torque) are calculated. The stators (S_1 &S_2) can be connected either in parallel to get more voltage or in series to get more current. Finite Element Analysis (FEA) is used to calculate flux density of the permanent magnet at deferent air gap size by using (ANSOFT Maxwell) software. Also the output voltage sine wave of the generator and the phase angle between each pairs of the phases are verified. Moreover the output voltage can be controlled by control in air gap size, when the shaft speed was fixed is discussed.
Keywords: - AFPM generators, air gap, torque, finite-element analysis, magnetic field measurement, attractive force.

I. INTRODUCTION

Recently, axial flux permanent magnet (PM) generators are used increasingly in ample applications with high efficiency, weight, small size, and reliability. The main parts in axial flux permanent magnet generator are rotor and stator. A rotor has permanent magnets for produce an axial flux density. A stator disc contains phase windings. By combining or arranging the stators and rotors and their numbers, many variations of AFPM generators can be developed. The simple design is a single stator - single rotor .also there are many forms available such as double-stator-single rotor, double rotor-single stator, and multi stator-multi rotor designs [1,2]-[13]-[20]. In single stator single rotor (iron) of AFPM, the axial force between it is very high therefore, it required more complex bearing arrangement and more thick rotor back-iron [3]. To calculate the behaviour of the magnetic flux and verify the accuracy of the analytical result, the (Ansoft maxwel) Software can be used. In AFPM coreless machine, the attractive force between the stator and rotor does not exist, at no load [4, 5] AFPMG single rotor – double stator (SR-DS), has two stators and one PM rotor disc. The disc with PMs rotates between two stators. The advantage of this structure has two-stage output voltage, short axial length and more output power. Also disadvantages that it needs more coils. In this research, this type will be study. The Double sided Stator and Single Rotor (DS-SR), it consist of back to back rotor place in between the stator, therefore the weight of rotor is less as compared to double sided rotor . Starting torque of this generator is low, therefore it give an output instantly. The double-sided rotor simply called twin rotor with PMs is located at two sides of the stator, also called a double-sided generator with internal stator. The AFPMG with stator between rotors with S-N and N-S arrangement, iron losses are absent and only copper losses exists [6].

It has the greatest torque production capability due to the increased volume of PM material used [7, 8]-[13]. As the magnetic losses in rotor PMs and disks are very small, thus can be neglected, as there is no change in the flux direction in the rotor back iron, the disadvantage of the double-rotor AFPM topology is the strong magnetic attractive force between the two opposing PM-rotor disks[9]-[18]. As the magnetic losses in rotor PMs and disks are very small, and can be neglected, as there is no change in the flux direction in the rotor [10]. Multiple stage axial flux generator is the one with iron and ironless stator. This type of generator can be built multiple rotors and armature windings. In general, the multi stages generator structure has N stator and N±1 or N/2 rotor discs where N is the number of the stators, the rotors share the same mechanical shaft [11]-[19]. The stator windings of the N stator can be connected either in parallel or series .In a multi-stage AFPG the flux driven by magnets passes axially from a north- pole on one rotor to a facing south -pole on the other. Therefore, only the external rotor discs must be made of material with good magnetic properties (typically mild steel), since they are used to provide a path for flux, [12,13]-[15]. Our study will focus on the double stator-single rotor generator as shown in Fig.1.Neodymium-iron-boron (**NdFeB**) magnetic material was used for the permanent magnets in the rotor. The rotor construction can be made from light materials such as Plexiglas, epoxy, aluminium, etc., and they use magnets, the shape magnet also may trapezoidal, rectangular, or circular. The stators can be made from Non-magnetization as the rotor. The shape of the coil should be like magnetic shape. The shapes, weights, and size of AFPM generators are reasonably small when compared to conventional generators. The relation between the number of coils and the number of magnets. If the ratio is an integer, then the rotor has zero-torque positions. In order to avoid a zero-torque position, a non-integer ratio is required. For true alternating three-phase emf waveform with 120°, 1.33 magnets per coil is needed[14, 15] .Our system is a three-phase pr/ps =9/12 generator. ps is the number of poles of the stator, and pr is the number of poles of the rotor. Armature windings are stator coils. However, the rotor has permanent magnets for poles rather than some excitation windings.

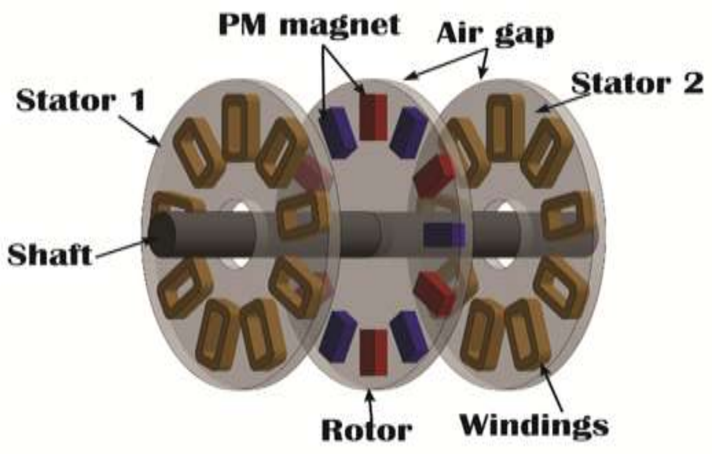

Fig.1: Construction of AFPM Generator (double stator – single rotor)

II. AXIAL FLUX PERMANENT MAGNET GENERATOR (DOUBLE- STATOR AND ONE-ROTOR)DESIGN

The prototype core less generator used in this study had a double- stator and one- rotor configuration with 9 poles. The stators was manufactured by using a non-ferromagnetic material called Plexiglas in which the stator coils were embedded. They are arranged in a 3-phase configuration as shown in Fig.2.

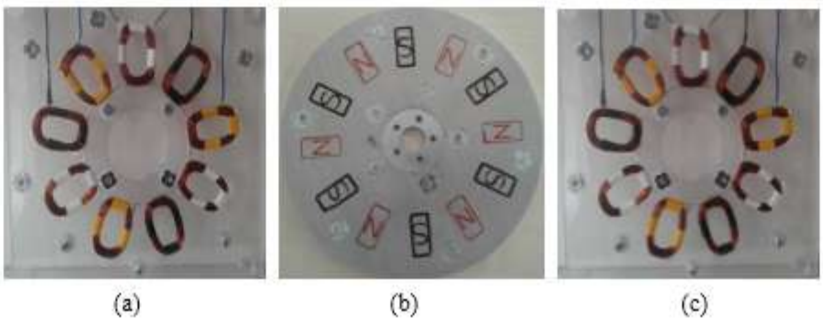

Fig.2: (a) The stator (I), (b) The stator (II) is manufactured by using a non-ferromagnetic material with the coils (Plexiglas), and (c) The rotor is a circular non ferromagneticmaterial(aluminium) with permanent magnets

The stators are manufactured by using a non-ferromagnetic material (Plexiglas) to carry the coils, which arranged in a 3-phase configuration) as illustrated in Fig.2 (a,c). The rotor is a circular- based (aluminium) disc supporting neodymium permanent magnets (sintered NdFeB with 0% Co-having magnetic strength of 42 MGOe) as shown in Fig.2(b). The sizing equation to calculate diameter of the generator by using Eq.1 and Eq.2,[16]-[18].

$$\mathrm{D_o} = \left(\frac{1.205 \times \mathrm{P_s}}{\omega_{\mathrm{r.p.m}} \times \mathrm{B_{peak}}}\right)^{\frac{1}{3}} \quad (1)$$

$$\mathrm{D_i} = \mathrm{D_o} \times 0.576 \quad (2)$$

Where D_o is the outer diameter, D_i is inner diameter of the generator, Ps is the output power of one stator, $\omega_{r.p.m}$ is the speed of the shaft and the B_{peak} The peak value flux density of magnetic flux generated by the permanent magnet and which affecting on windings stator. The peak value of flux density B_{peak} in the air-gap can be calculated by Eq (3):-

$$B_{p.v} = 0.91 \times B_r \times (1 - e^{-62.822 * h_m}) \quad (3)$$

In Eq.3, h_m is axial height of the magnets and B_r is the remanent magnetic flux density. By using finite Element Method magnetic (Ansoft Maxwell) software the peak value of the air gap flux density is determined $B_{p.v}$=(0.350 , 0.250 , .200) Tesla, at air gap (2 , 4 ,6) mm , respectively , as illustrated in Fig.3.

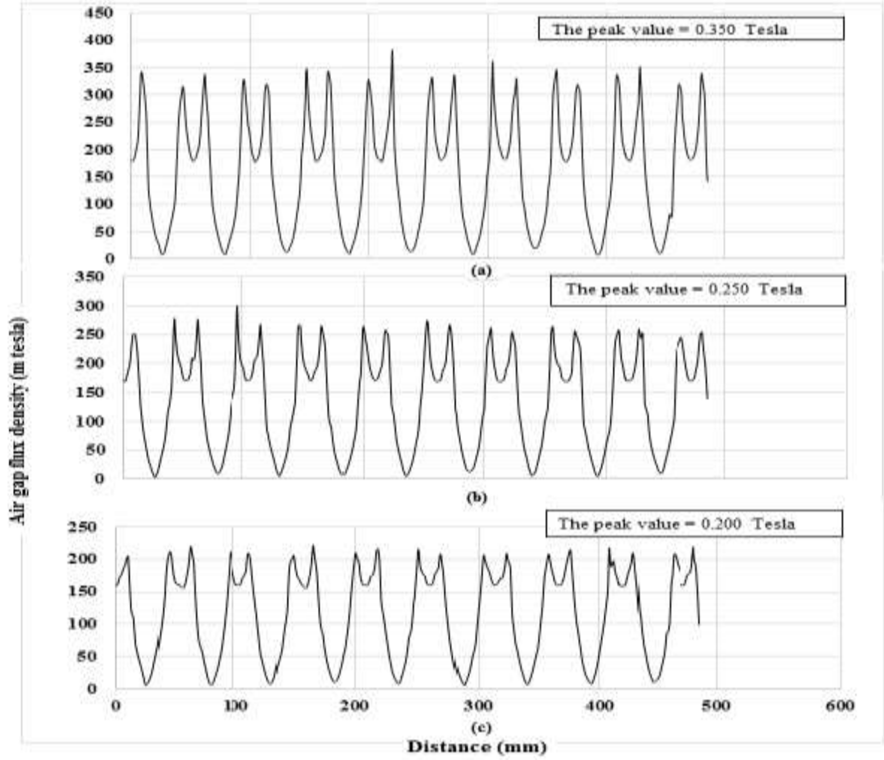

Fig.3: The peak value of flux density in the air gap with deferent sizes :,(a) Air gap (2 mm), (b) Air gap (4 mm), (c) Air gap (6 mm),

The system design parameters are given in Table I. The system requirements are 3-phase, 200W power, 120 rpm,. The parameters such as coil resistances, inductances, and the physical dimensions are listed in the table.

Table I: Design parameter of the generator for a power of 200 watts

Parameter	Value	Unit
power output	200	W
Average mechanical speed of rotor	120	R.P.M
Y-Connection		V
Number of Phases	3	-
Resistance of stator coil	1.5	Ω
Inductance of stator coil	1.2	mH
Number of Rotor Poles	12	-
Number of Stator Poles	9	-
Dimensions of permanent magnets		
Axial height	0.01	m
Axial width	0.02	m
Axial length	0.04	m
Peak flux density in air gap (calculated from ASOFT Maxwell)	0.350	T
Dimensions of Generator		
Outer diameter	0.1790	m
Inner diameter	0.1390	m
Electromotive force (EMF) constant	0.302	V.sec

III. INITIAL TORQUE AND ELECTROMAGNETIC TORQUE

In general, torque (N.m) is defined as a force around a given point, applied at a radius from that point. Therefore, a net torque will cause the machine to rotate with an angular acceleration. The initial torque to move or rotate the rotor can be determined by measuring the weight required to start to rotate the rotor, and the weight should be at 90 degrees with the radius then calculate by Eq. 4.

$$T_{initial} = F_{rotate} \,.\, r.\sin(\theta) \quad (4)$$

Where $F_{rotate} = M.a$ is force given by Newton's low. The equivalent of the total torque in machine is given by Eq.5, if we assume a friction torque (bearing friction) is very small, and can be neglected [3]-[17,18].

$$\sum T = J\frac{d\omega}{dt} = T_m - T_e \quad (5)$$

Where ω is angular speed, T_m is a mechanical torque. A mechanical torque applied to turn magnetic field through a conductor and generate electric current and T_e is electromagnet torque. If the machine is rotating at constant speed $T_m = T_e$, the sum of torque will be zero that means $\sum T = J\frac{d\omega}{dt} = 0$, and if $T_m > T_e$ the rotation shaft will accelerate (torque increase). Also if $T_m < T_e$ the rotation shaft will deceleration (torque decrease). In our case a coreless AFPM machines does not produce any normal attractive force between the stator and rotor at no-load. Also, no produce cogging torque,

The magnetic motive force (m.m.f) of the stator and the rotor are existed only when the generator is loaded, thus the electromagnetic torque (T_e) can be given by Eq.6, [2]-[19]-[20].

$$T_e = \frac{1}{\omega_m}\left[v_{a(t)}.i_{a(t)} + v_{b(t)}.i_{b(t)} + v_{c(t)}.i_{c(t)}\right] \quad (6)$$

Or

$$T_e = \frac{1}{\omega_m}\left[V_a.I_a + V_b.I_b + V_c.I_c\right] \quad (7)$$

Where $v_{a(t)}$, $v_{b(t)}$ & $v_{c(t)}$ are instantaneous voltages of three phases, $i_{a(t)}$,$i_{b(t)}$ & $i_{c(t)}$ are load currents of three phases of AFPM generator and ωm is the mechanical shaft speed of AFPM generator in rad/sec. When the load is balanced, the electromagnetic torque equation can be written as

$$T_e = \frac{1}{\omega_m} 3.(V.I) \quad (8)$$

IV. EXPERIMENTS RESULTS

A. The phase angle

The 3-phase generator that which designed and manufactured is driven by a dc motor with a speed controller to simulate the wind during the experiments. The output voltage waveforms of the generator are shown in Fig.4. As seen, a phase angle 120 degrees is available between each pairs of the phases.

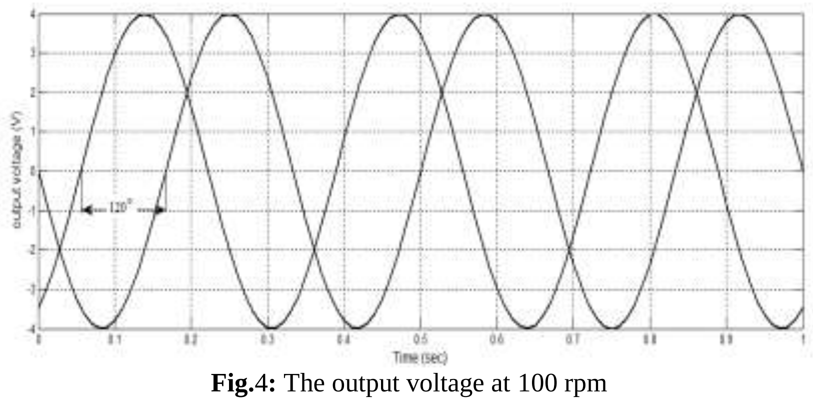

Fig.4: The output voltage at 100 rpm

B. Out voltage at no load

The output of the two stators (S_1&S_2) can be connected either in parallel or in series, at low speed S_1 & S_2 can be connecting in series to get more voltage, and can be connecting in parallel at high speed to get more current as shown in Fig.5.

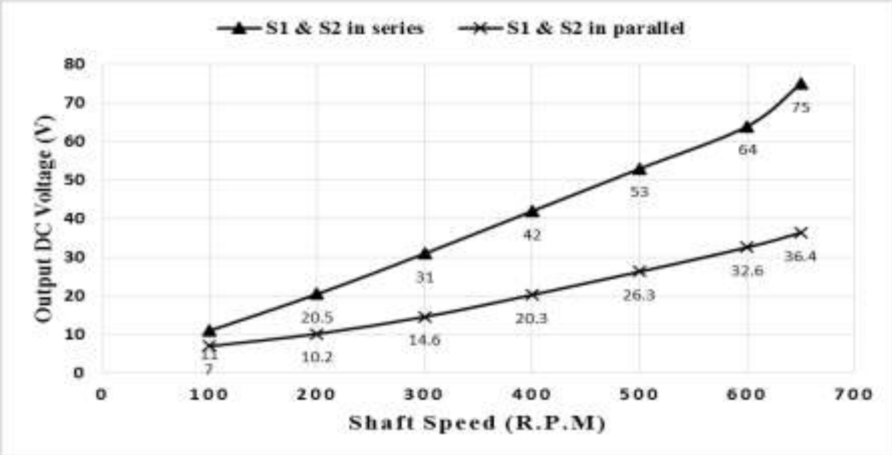

Fig.5: The output voltage of two stators (S_1&S_2) at no load connected in parallel and in series

C. Air gap effect

The impact of air gap size on the output voltage was noted. When the air gap increases, the magnetic flux density decreases, and therefore, the output voltage is decrease and vice versa, as shown in Fig.6, Fig.7. In Fig.8 when the air gap size is changed the output voltage is changed also, thus may can control of the output by control in air gap size.

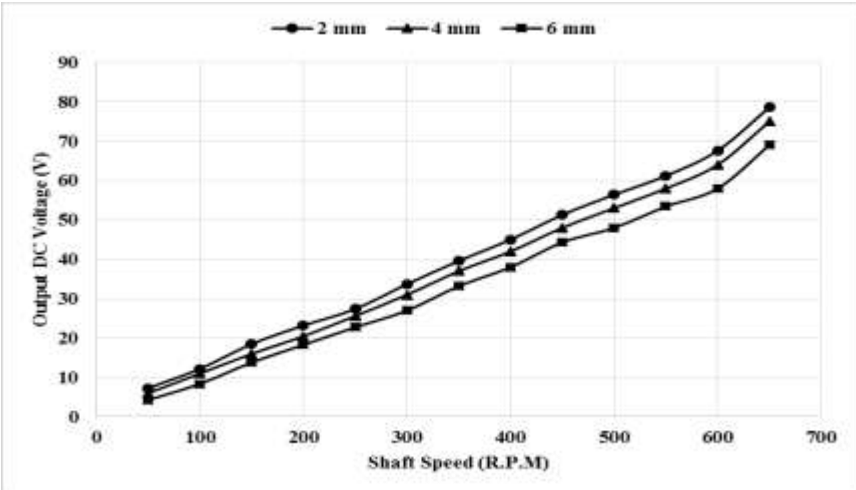

Fig.6: The air gap effect on the output voltage of the generator when (S_1 & S_2 in series)

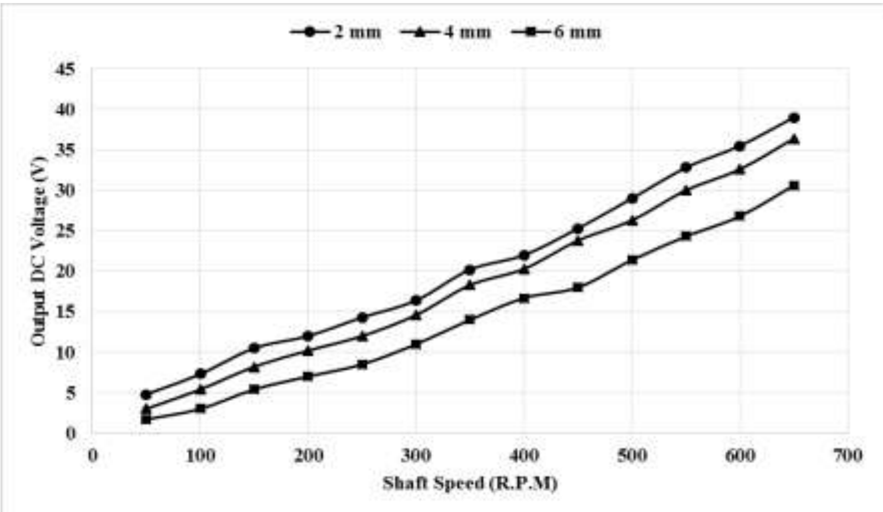

Fig.7: The air gap effect on the output voltage of the generator when (S_1 & S_2 in parallel)

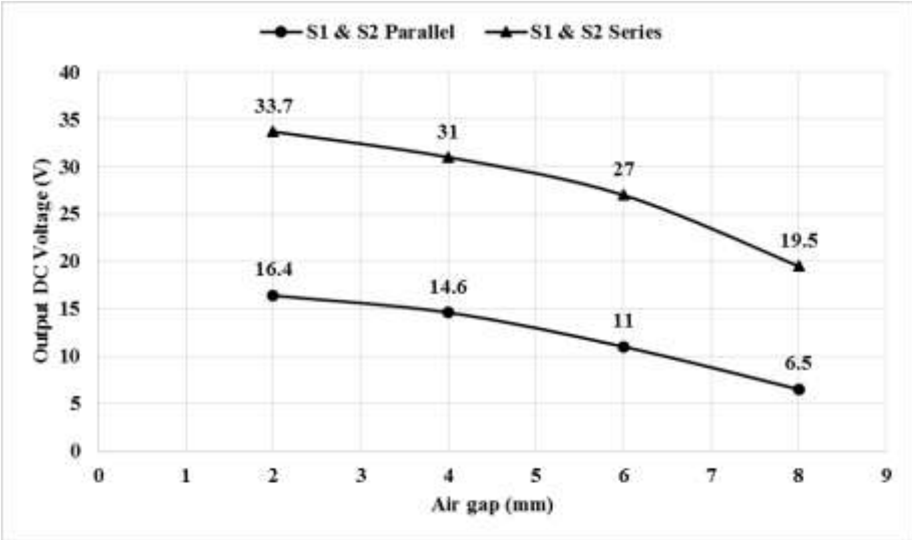

Fig.8: The air gap effect on the output voltage of the generator at fixed speed (300 r.p.m)

D. Types of torque in coreless MS-AFPM

There are two types of torque in coreless AFPM generator, the initial torque at the beginning and the electromagnetic torque when the load exist

1. The initial torque

The initial torque $T_{intial} = 0.250$ N.m , is calculated using Eq.4.

2. Electromagnetic torque:-

The electromagnetic torque has been calculated by using Eq.8 at load resistor 50 Ω. When the air gap size as small as possible the air gap flux density will increase which in turn improves the electromagnetic torque, as illustrated in Fig.9.

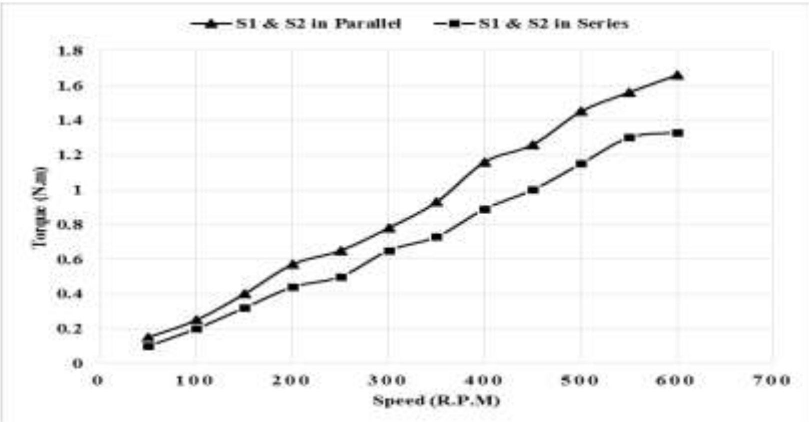

Fig.9: The electromagnetic torque at load 50Ω

VII. CONCLUSIONS

In this paper, coreless AFPMS generator double stator - single rotor designed and tested. The relation between number of coils and the number of poles are chosen to ensure a three-phase output of the generator. The coils was Arranged to get a phase angle 120 degree between each two phases is verified. In this type of generator, the two stator should be working in the same time, also the air gap stator (S_1) /rotor and stator (S_2)/rotor should be the same size to keep balanced rotor forces. The peak value of flux density in the air gap was calculated by using software (Ansoft Maxwell) with different sizes in the air gap. The influence of the air gap size on output the generator was found, it is clear that when the air gap size increasing the output voltage or power would decrease. Thus, lowest value of the air gap is recommended. The output voltage can be controlled by control in air gap size, when the shaft speed fixed. There is no attractive force between the stators and the rotor at no-load and the initial torque is very small if compared as normal, thus this generator can be used in low speed (wind turbine) direct-coupled without gearbox.

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