Design and Modeling of an Axial Flux Permanent Magnet Consequent Pole Machine

Abstract

The use of consequent pole structure has been common in radial flux machines before, and no axial flux machine with consequent pole structure has been produced so far. In this article, a sample of consequent pole axial flux generator example is introduced. The proposed generator has double-sided structure with a sector coil and poles, where N identical poles (with only N sequence and iron poles between them) are installed on the rotor and the stator is placed between the rotors. The stator consists of coils that are wrapped concentrically around the teeth. In this new structure, despite the significant reduction of the magnet used, followed by the reduction of production costs, the voltage induced in the coils has not changed compared to the sector axial flux generator, which has all its poles made of magnets. Also, the cogging torque is reduced. In order to evaluate the characteristics of the proposed generator, finite element analysis method has been used.

Keywords: An Axial Flux Machine, Permanent Magnet, Consequent pole, Iron, Generator

1-Introduction

Due to the reduction of fossil fuel resources, the trend towards new energies to reduce greenhouse gases, the advancement of battery technology and the management of the power grid, there has been a fundamental change in the production of electric vehicles. It is expected that the number of customers for these cars will increase rapidly in future. One of the most important parts of electric cars is the part which produces electric energy to be used in different parts of the car. In modern cars, the amount of electrical energy consumption has increased significantly compared to conventional and old cars, this increase is to provide more comfort, well-being and security for passengers [1].

With the increase in energy consumption, solutions should also be provided to raise the production of electrical energy in these cars. Due to the dimensional limitations of the car engine cabin, the use of generators with high power, high efficiency, small dimensions and light weight along with reasonable price (compared to old generators) is one of the important challenges of designers. Meanwhile, axial flux permanent magnet machines are a suitable option for this purpose due to their characteristics such as compact structure, light weight, high torque, low losses, the ability to integrate quickly and easily with other mechanical equipment and the possibility of increasing

the number of poles [2]. The appearance of rare-earth permanent magnets such as Nd-Fe-B has created a revolution in the design and construction of axial flux permanent magnet machines in a way that has made it possible to build machines with a large air gap. This development makes it possible for axial flux machines to return to the field of competition [3]. This type of magnet (permanent rare-earth magnets) has a favorable property in terms of magnetic residuum density (Br) [4].
For example, the American company “Arnold Magnetic Technologies”, produces a wide range of permanent magnets with a residual flux density (Br) in the range of 1.10-1.49 (T) and the ability to work at a maximum temperature of 220-80 (C°). Depending on the type of placement of PM in the machine, there are different structures such as poles mounted on the surface or SPM, consequent poles, internal poles and poles buried in the rotor. In addition, in other types of PM machines such as flux-switching and flux reverse, the PMs are placed in the stationary part of the machine. Due to the simple structure of SPM and CPPM machines, their use is more common than other types of PM machines [5]. The use of these magnets makes it possible to achieve high power density in a small volume, and also helps designers to produce machines with high efficiency and low losses with less material consumption [5] [6]. The shortage crisis of rare-earth permanent magnets and their environmental consequences have directly affected the permanent magnet machine industry, and it seems that the high price and continuous supply of permanent magnets are the biggest threats to this industry. To tackle these problems, reference [7] suggests the use of consequent pole structures for PM machines, which will reduce the consumption of magnets. If the N poles are kept in a machine and ferromagnetic materials such as iron are used instead of the S poles, it leads to a type of consequent pole machine. In this machine, by reducing the number of magnetic poles and replacing them with iron, the magnetic flux will pass through the iron. This feature has some advantages such as reducing construction and maintenance costs, reducing leakage flux, increasing linkage flux and reducing eddy current losses in PMs (due to the flux passing through the iron poles) [8].
Axial flux permanent magnet machines have different types of structures based on the placement of magnets, slots, cores, coils, and multi-stage. In general, these machines can be classified into three categories: single-side, double-side and multi-stage [9].

Single-side machines consist of one rotor and one stator, the force of attraction between the rotor and the stator in these machines causes unbalance. Multi-stage machines consist of several rotors and stators that are placed in a row, which increases the axial length of the machine. Changing the number of rotors and stators makes it possible to change the size of the torque based on the axial length. Double-side machines are divided into two categories: AFIR[1] internal rotor and AFIS[2] internal stator. Both categories are superior in terms of production to single-sided and multi-stage machines. Because on the one hand almost no axial magnetic attraction occurs and on the other hand, they have a simpler structure than multi-stage machines [10], [11] and [12]. The double rotor structure will be a solution to overcome the axial magnetic attraction force because the net axial force to the rotor is about zero. In addition, it leads to achieving higher power density [13]. In the AFIS structure, the stator is placed in the center and the permanent magnet rotors on its sides, which results in fewer end windings in the stator. This reduction significantly improves the machine's efficiency [14]. Another name used for machines with internal stator and external rotor combination is TORUS structure. Usually, TORUS machines are offered in two types, NN and NS, the main difference of which is the arrangement and sequence of polarity in the poles, the type of winding and the thickness of the stator yoke [15]. Another way to enhance efficiency is to design a suitable winding for the machine. Using concentrated and non-overlapping coils, in addition to reducing the amount of copper used in the coil head, decreases losses and the overall dimensions of the machine. Moreover, it simplifies the construction of the machine, which subsequently leads to the reduction in production costs [16].

The purpose of this article is to introduce and analyze a sample of a three-phase axial flux permanent magnet generator with consequent pole structure (CP-PM). The selection of the type of machine is based on several key advantages, including high power density and low construction cost compared to conventional axial flux generators. The analysis and evaluation of machine performance has been done by 3D finite element analysis in ANSYS Electronic Desktop software. It can be seen that the simple structure, high efficiency, reduced consumption of raw materials, and low manufacturing costs have made the proposed generator an economic model that can be a suitable choice for cars and a suitable replacement for old AFPM generators.

1 - Axial Flux machines with Internal Rotor
2 - Axial Flux machines with Internal Stator

2-Introducing new structure and modeling

According to the studies, it is clear that the consequent pole structures are common in radial flux machines and have not been investigated and used in axial flux machines. Therefore, we decided to present a new structure in which we tried to implement the structure of consequent pole machines (which has been discussed and investigated in radial flux machines so far) in axial flux machines, and from the combination of these two machines, we will present an optimal and economical model. This model, not only reduces the consumption of magnets, but also results in the reduction of production costs. Figure 1 shows the structure of the permanent axial flux magnet generator with consequent pole, which consists of a double side structure with two rotors and one stator. A concentric copper sector winding is wrapped around the iron teeth of the stator and is placed between the two rotors with an air gap of 1 mm. Sector-shaped magnetic poles made of Nd-Fe-B magnet are placed on the disc-shaped rotor and instead of using magnetic S poles, iron poles (the same type of rotor) are used. (The dimensions of N and S poles are equal). Figure 2 shows the arrangement of machine components from the side view. In this machine, the rotors are movable and the stator is stationary. Figure 3 shows the arrangement of machine poles and flux paths in the proposed generator.

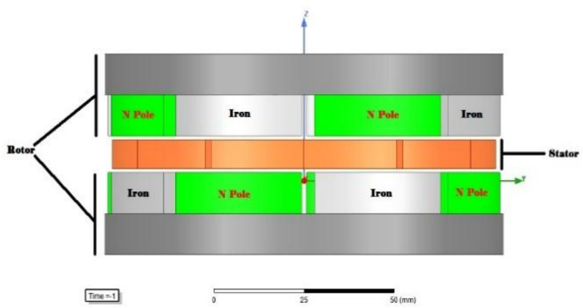

Fig 1. Structure of the proposed model

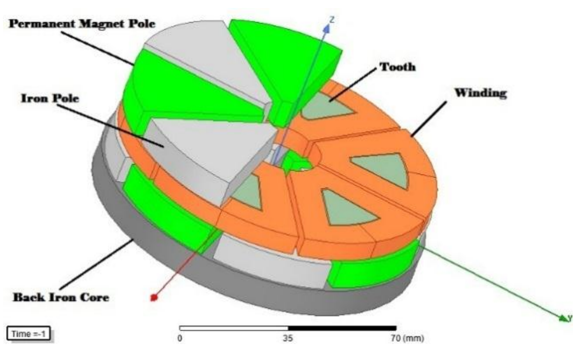

Fig 2. Side view of the proposed model

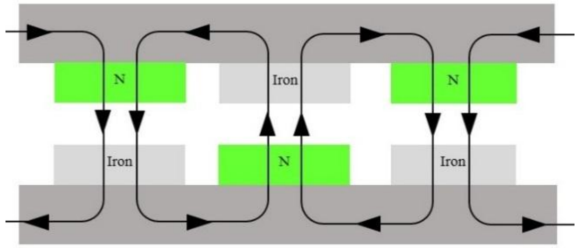

Fig 3. Magnetic flux path

The voltage of each phase of the generator is obtained from the sum of the voltage of two coils that are connected in series, which can be calculated from equation 1 [1]:

$$V_{phase} = 4.44 * f * N_{phase} * \emptyset_{pole} \quad (1)$$

In this equation, f is the output frequency of the generator, N_{phase} is the total number of turns of the series coils of each phase, and $\emptyset_{pole}$ is the magnetic flux of each pole. In this order the volt-ampere value of the machine is obtained through equation 2.

$$VA = C_0 * D^2 * L * n_s \quad (2)$$

$$\mathrm{n_s} = \frac{60*\mathrm{f}}{\mathrm{p}}$$

In this equation, C_0 is the output power coefficient, D is the diameter of the stator, L is the axial length of the machine andn_s is the synchronous speed of the machine. The output power factor depends on the electric and magnetic load of the machine. The total number of coils depends on the number of poles, which is used to calculate from equation 3.

$$\mathrm{n}_{coil} = \frac{3}{4} 2p \quad (3)$$

In references [1] [2] and [6], due to space limitations, designers have considered eight poles and six concentrated coils for the generator. Figure number 4 is the schematic of the analytical model with a linear structure, in which the sector poles are shown as rectangles. Figure 5 shows the placement of sector poles in a geometric quadrant of the machine, which is made of N-Iron compound. The radius of pole and iron is equal to 43 degrees and the distance between them is 2 degrees. The analytical formula of the normal component of the magnetic flux density in the middle of the air gap is as described in equation 4 [6].

$$\hat{B} = \frac{4}{\tau_p(r)} \frac{B_{rem}}{u(r)\mu_r} \sin(0.5u(r)d_m) \frac{\sinh(u(r)t_m)}{\sinh\left(u(r)\frac{g}{2}\right)} \qquad (4)$$

$$B_y(x, r) = \hat{B}\cos(p\theta)$$

$$\tau_p(r) = \frac{\pi r}{p} \quad , \quad u(r) = \frac{\pi}{\tau_p(r)}$$

where $\tau_p(r)$, d_m, t_m, B_{rem} , and μ_r are the pole pitch in different radii, PM width in circumferential direction, PM thickness, residual flux density, and PM relative permeability, respectively.

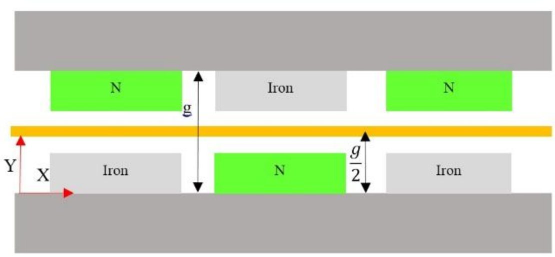

Fig 4. Schematic of analytical model with linear structure

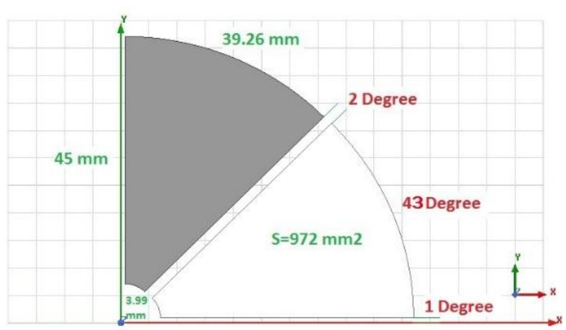

Fig 5. The dimensions of the sector poles

Figures 6 and 7 show the coil and teeth of the generator, respectively. The coils are similar to the poles in the form of a sector that is wrapped concentrically around the teeth. In order to calculate the induced flux and voltage, we use equation 5:

$$V_{coil} = \frac{d\lambda}{dt} \quad (5)$$

$$\lambda = \lambda_{max}\, cos(\omega t)$$

$$\lambda_{max} = N \iint B_y(r,\theta) r dr d\theta$$

$$0 \le r \ \le 0.5(r_o + r_i) \ \ , \ \ 0 \le \Theta \le 2\pi$$

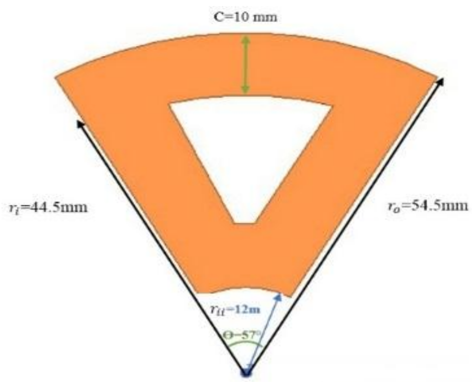

Fig 6. Stator coil

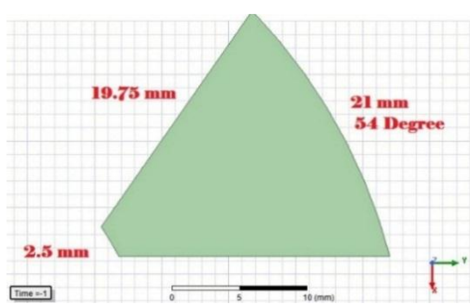

Fig 7. Stator tooth

3-simulation

Since one of the goals of the CP-PM permanent magnet generator is to provide an economical and cost-effective model with similar dimensions, but a higher capacity than the previously built generators, in the modeling process, the dimensions of the generators made in references [1] and [6] were considered, and the CP-PM generator with the same dimensions was designed. Each phase of the generator has two sets of concentrated coils that are connected in series and the total voltage of the two coils forms the output voltage of each phase of the generator. The general specifications of the CP-PM generator are listed in Table No. 1.

Table 1. Characteristics of consequent pole permanent magnet generator

Parameter	Values
Number of Phases	**3**
Number of Coils	**6**
N_{Coil}	**60**
$N_{S\,phase}$	**120**
Wire Diameter	**0.75 (mm)**
Number of Poles (NdFe35)	**8**
B_{rem}, Residual Flux Density Of PM	**1.2 (T)**
Radial Outer Length Of PM	**45 (mm)**
Radial Inner Length Of PM	**4 (mm)**
Permanent Magnet Angel	**43°**
Thickness Of Back Iron	**10 (mm)**
Outer Radius Of Back Iron Disc	**55 (mm)**
Axial Length Of Generator	**52 (mm)**
Outer Radius Of Back Iron Disc	**55 (mm)**

Figure 8 shows the structure of the machine with circular poles and coils. In the first step, we simulated the generator by changing the shape of the poles and coils from a circle to a sector in the ANSYS Electronic Desktop software using finite element analysis. Assuming the stator to be stationary, the poles mounted on the rotor were rotated at a speed of 1000 rpm by 90 mechanical degrees in transient mode for 15 milliseconds with time steps of 0.0001 seconds. We put the voltage and cogging torque variables as a reference for comparison with the proposed machine.

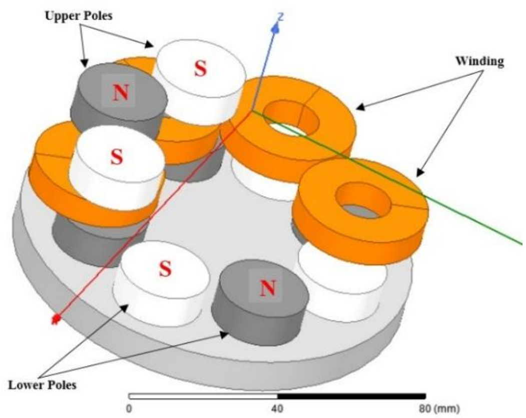

Fig 8. Machine structure with circular poles and windings

In the second step, by removing the S poles and implementing the consequent pole structure machines, the generator was simulated again with the same conditions as the first step. The results of the variables of voltage, linkage flux, magnet and iron consumption are given in table number 2. Comparing the results of sector permanent magnet generator and consequent pole permanent magnet generator, we can see that with a 50% decrease in the magnet in the CP-PM generator, the link flux decreases by only 29.1% and then the maximum voltage decreases by 28%. It is due to the removal of S poles which is not unlikely. Also, by reducing the magnet and replacing iron instead of S poles, the amount of iron consumption increased by 39.5%. Figure 9 shows the induction voltage diagram of the sector generator and the sector consequent pole.

Table 2. The results of the analysis of the sector generator and consequent pole generator

Machine Type	Sector PM Machine	Sector CP-PM Machine
Induced Voltage (V)	**17.5**	**12.6**
Linkage Flux (Wb)	**0.0466**	**0.033**
Magnet Used (mm3)	**155488**	**77744**
Iron Used (mm3)	**197040**	**274784**

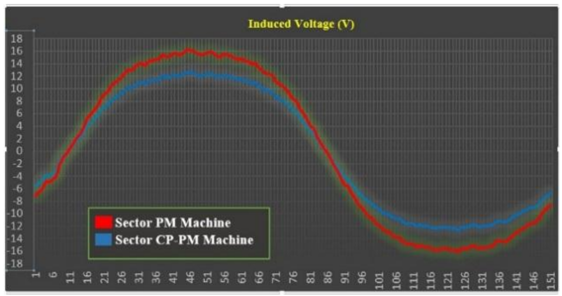

Fig 9. Induced voltage of sector generator and the sector consequent pole

By studying and examining the magnet in different states, we found that although the magnet plays the main role in permanent magnet machines, we are faced with limitations such as height, width and the phenomenon of magnetic saturation. As we have seen, in the consequent pole machine, the induction voltage is reduced by removing the S poles, in order to increase the induction voltage, we use teeth for the coils. The presence of the teeth increases the linkage flux, concentrates and passes the flux through the coil, and also reduces the leakage flux. Figure 10 shows the movement and concentration of the flux towards the teeth. Thus, by adding a tooth to the CP-PM generator, we repeat the simulation and examine the results.

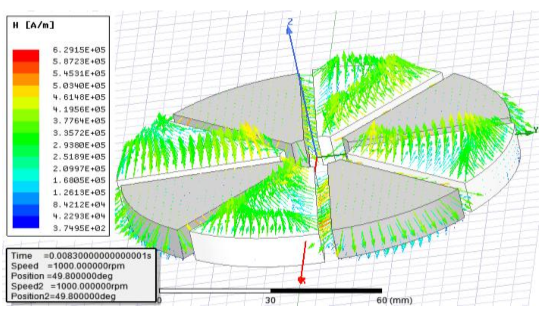

Fig 10. Flux movement towards the teeth

Figures 11 and 12 show the magnetic flux density in the poles and the back plate of the CP-PM machine, respectively.

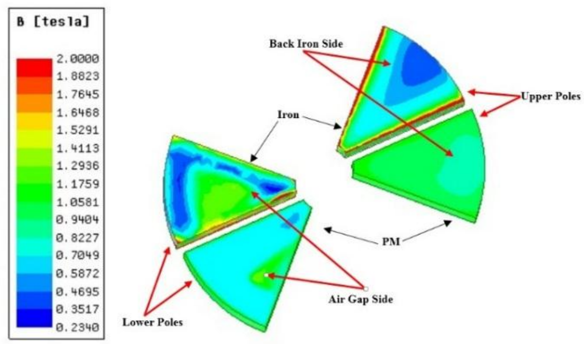

Fig 11. Magnetic flux density in CP-PM generator poles

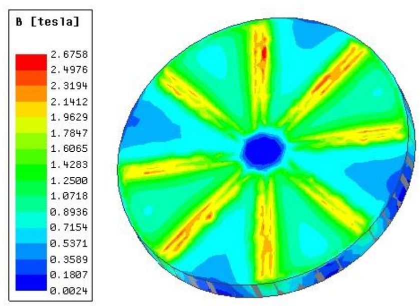

Fig 12. Flux density in the back plate the CP-PM generator poles

Figures No. 13 and 14 show the induced voltage in the windings of the toothed sector generator and the toothed consequent pole sector. As can be seen in Figure 15, the toothed consequent pole sector produces the same voltage as the toothed sector pole generator in which magnets are used in all poles.

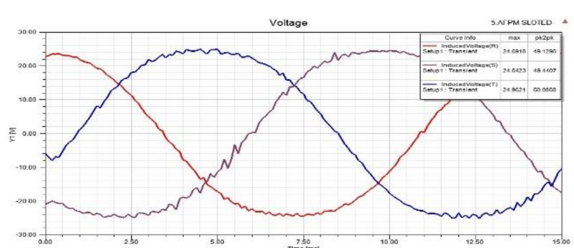

Fig 13. Induced voltage of toothed sector generator

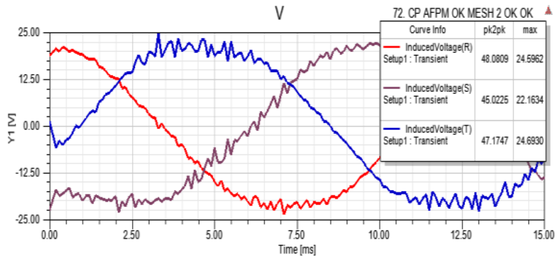

Fig 14. Induced voltage of a toothed consequent pole sector generator

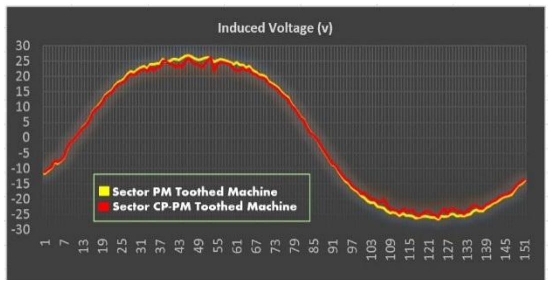

Fig 15. Induced voltage of toothed sector generator and toothed consequent pole sector generator

By examining the linkage flux diagram of the toothed sector generator and the toothed consequent pole sector, it can be seen that with a 50% decrease in the magnet, the linkage flux is reduced by only 17%, but the presence of the tooth prevents the leakage flux and the concentration of the flux in the machine. It also induces better voltage. Figure 16 shows the link flux diagram of the proposed machine.

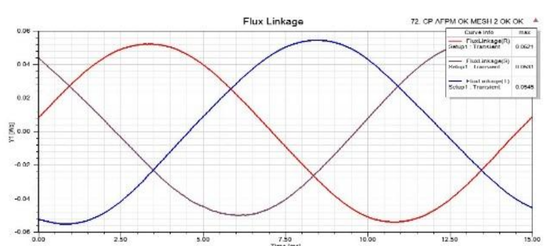

Fig 16. Linkage flux of CP-PM generator

Figures 17 and 18 respectively show the cogging torque of the toothed sector generator and the toothed consequent pole sector. By examining the cogging torque diagrams, we can see that the sector generator has a higher cogging torque than the consequent pole sector generator. The average cogging torque in the sector generator is equal to 127 mNm and in the consequent pole sector generator is equal to 67 mNm. We can see that the proposed structure improves the amount of cogging ripple and average torque.

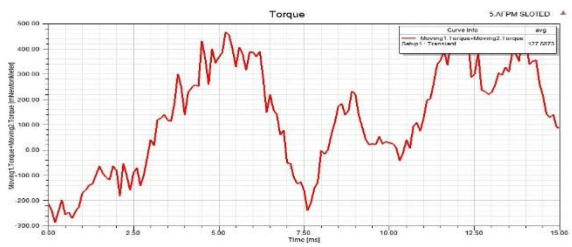

Fig 17. Cogging torque in toothed sector generator

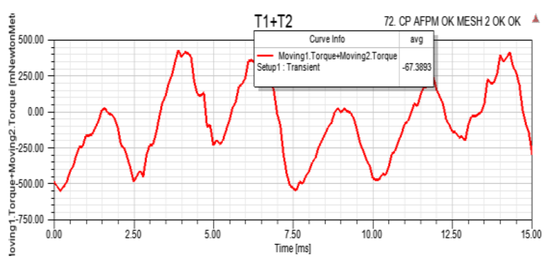

Fig 18. Cogging torque in toothed consequent pole sector generator

Now, in order to observe magnetic parameters such as flux density in the air gap, we use magneto static analysis. Figure 19 shows the flux density in the air gap. As we can see, the maximum flux density is equal to 615 mT.

Fig 18. Flux density in the air gap of the in toothed consequent pole sector generator

Table No. 3 shows the results of the variables of voltage, linkage flux, magnet and iron consumption in the toothed sector generator and the toothed consequent pole sector generator. The conditions of both machines are the same and the only change has been made in the arrangement of the poles of the machine. We can see that by reducing the magnet by 50% and increasing the iron by 37.5% in the consequent pole machine, the voltage is maintained in the desired range and in addition, the cogging torque is optimized.

Table 2. Generator analysis results of the toothed sector generator and toothed consequent pole sector generator

Machine Type	PM Generator	CP-PM Generator
Induced Voltage (V)	**24.5**	**24.5**
Linkage Flux (Wb)	**0.0615**	**0.051**
Magnet Used (mm3)	**155488**	**77752**
Iron Used (mm3)	**206640**	**284392**

4-Conclusion

Previously, using the structure of consequent pole has been common in radial flux machines and has not been used in axial flux machines. Therefore, according to the advantages of consequent pole machines, in this article, we presented a model of an axial flux generator with consequent poles. In permanent magnet machines, the magnet plays an essential role, since the cost of producing this type of magnet is very high compared to iron, by presenting this new structure, while significantly reducing the consumption of magnets, and then reducing production costs, the variable induced voltage in the coils is preserved compared to the permanent magnet sector generator, which has all its poles made of magnets. Also, the effect of the structure of consequent poles in reducing the torque is evident, so that the cogging torque ripple of the consequent pole generator is much less than that of the sector generator. Additionally, the average torque in this machine is 89.3% less than that of the sector machine and is equal to 67 mNm, this value is close to zero and can be ignored. In this generator, the amount of magnet consumption decreased by 50% and iron consumption increased by 37.5%. Considering the higher price of permanent magnet (about 10 times) compared to the price of iron, using this design significantly saves production costs. According to the investigations, we conclude that the optimal structure is the simultaneous use of consequent poles and a toothed stator. In this case, increasing the voltage along with reducing the magnet consumption is justified and turns the car into an economical machine.

5-Reference

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