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A Review of Torque Ripple on Permanent Magnet Generator for Wind Turbine Applications

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Abstract. Permanent magnet generators have been gaining importance for wind turbine applications because they have the advantage of higher power density and/or torque density than machines with electromagnetic excitation. Torque pulsations such as torque ripple produce magnetic vibration and noise in permanent magnet machines. Thus, it is important to minimizing the torque ripple in permanent magnet generator design. To reducing the torque ripple, there are several ways to do, e.g. skewing of the stator and/or rotor, choosing the right combination of pole and slot numbers and adjusting some design parameters such as the permanent magnet pole arc width and/or the slot opening width.

Introduction

The use of environment friendly renewable energy sources are getting rapidly higher, due to the reasons like energy needs, pollution and green house gasses. Providing reliable access electricity to all and reducing environmental impacts has been recognized as the key challenge of the global electricity sector. For reducing the environmental impacts, renewable energy sources such as wind energy can be an alternative to generate electricity. To convert wind power into electricity, wind turbines have an electric machine called a generator as a major component.

Permanent Magnet Generator

Electrical machines have a huge influence on the reduction of energy consumption. The consumption of electrical energy can be saved by designing the construction of electrical machines with better efficiency. The use of PMs in construction of electrical machines can improve the efficiency and reliability of the machines by eliminating the excitation losses [1, 2]. By eliminating gearbox, direct drive PM machines have many advantages such as higher reliability and efficiency, reduced maintenance, noise and weight [3].

PM machines have been widely used, such as electric and hybrid electric vehicles, pumps, and wind generators. That's because they have the advantage of higher power density and/or torque density than machines with electromagnetic excitation [1, 4].

There are various types of machine topology for the application of PM generator to the wind power generation systems has been developed to maximize the electrical energy, improve power quality and minimize costs. According to the flux direction in the air gap, PM machines can be divided into radial-flux permanent magnet (RFPM) machine, axial-flux permanent magnet (AFPM) machine and transverse-flux permanent magnet (TFPM) machine [2,3]. The flux of RFPM machine flows radially through the air-gap while the current circulates in the axial direction (Fig. 1). In AFPM machine (Fig. 2), the flux flows axially through the air-gap while the current flows in the radial direction. Fig. 3 shows the basic topology of TFPM machine [3]. TFPM machine does not seem very common yet in wind power generation [2].

In [2], the authors provided a comparison among seven configurations consisting both radial flux machines and axial flux machines.

Conventional PM machines are generally of the radial-flux type. The rotor configuration may be classical configuration (Fig. 4a), interior magnet type (Fig. 4b), surface magnet type (Fig. 4c),

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inset magnet type (Fig. 4d), rotor with buried magnets symmetrically distributed (Fig. 4e) and rotor with buried magnets asymmetrically distributed (Fig. 4f) [1].

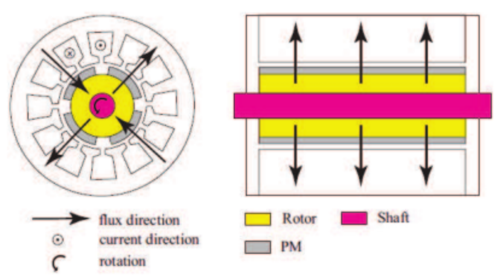

Fig. 1. Flux and current directions of RFPM machine

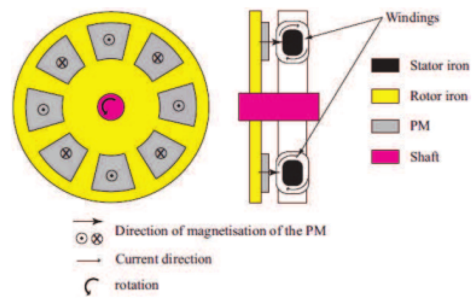

Fig. 2. Flux and current directions of AFPM machine

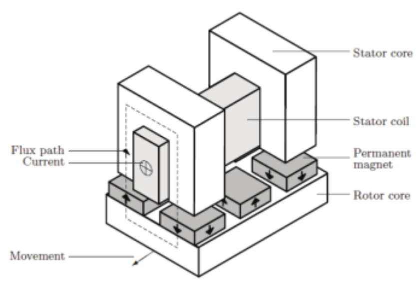

Fig. 3. Basic single-phase transverse flux topology

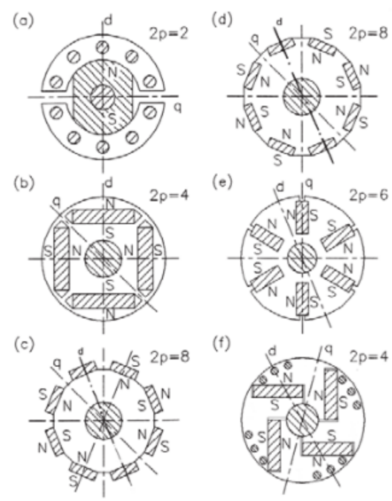

Fig. 4. Rotor configurations for PM machines: (a) classical configuration; (b) interior-magnet rotor; (c) surface-magnet rotor; (d) inset-magnet rotor; (e) rotor with buried (spoke) magnets symmetrically distributed; (f) rotor with buried magnets asymmetrically distributed

The design and analysis of a dual-rotor radial flux permanent-magnet (DRRFPM) generator is presented in [9-11]. The purpose of the optimal design is to maximize the output voltage [11] and to reduce cogging torque [10, 11]. The design was calculated by finite element analysis (FEA).

Comparison between air-cored and iron-cored non overlap winding radial flux PM direct drive wind generators are investigated in [12]. Generators with air-cored windings have zero cogging torque. In [13], the authors presented the electromagnetic and mechanical design of the double rotor radial flux permanent magnet generator with non overlap air-cored (ironless) stator windings for direct drive wind generator applications. The purpose of the optimal design is to minimize the mass of active material of generator.

In [14], the authors proposed the methodology for the design, analysis, and optimization of coreless brushless permanent magnet machines especially for generator applications. The performance features and parameter of various ironless machine technologies are presented in this paper.

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In [4-8], the authors proposed the optimal design of dual stator radial flux permanent magnet (RFPM) generator for reducing cogging torque. Fig. 5 shows the structure of RFPM generator. An inner-rotor type RFPM generator has a rotor located inside of the stator (Fig. 5a) and the outer-rotor type RFPM generator has a rotor positioned externally (Fig. 5b). The shape of proposed design of dual stator radial flux permanent magnet (DS-RFPM) generator, which is a combination of the inner and outer-rotor types, is shown in Fig. 5c.

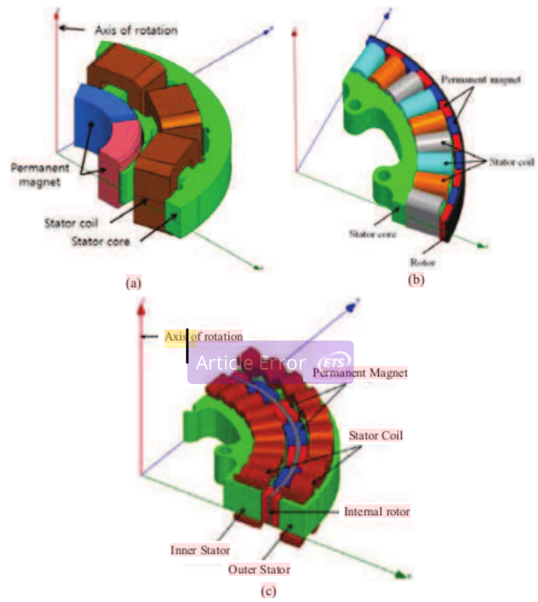

Fig. 5. The structure of RFPM generator: (a) inner-rotor type; (b) outer rotor type; and (c) the shape of proposed DS-RFPM

The AFPM machines are formed by pancake shape rotor and stator [1, 15]. From this basic shape, many various researches are possible including double side external slotted cores stator and inner rotor (double slotted cores stator with internal rotor) [15, 16], double side inner coreless stator (double rotor with coreless internal stator) [17-19], double side external rotor and a slotted stator [20-22] and single sided slotless/coreless stator [23, 24].

Torque Ripple

For designing a low speed direct drive generator, torque quality is one of the challenges. Torque distortions such as cogging torque and torque ripple produce magnetic vibration and noise. In direct drive applications they are transmitted directly to the load and drive shaft, which in return, affect the lifetime of the drive train. That's why in designing PM generators, it is important to minimizing the torque ripple. Cogging torque is given by the interaction between the rotor magnetic flux by PMs and reluctance variations due to the slotting of the stator (cogging torque also called "no current torque"). Torque ripple is caused by the non ideal distribution of flux density in the air-gap. It is generated by the interaction of the current fundamental harmonic and the EMF harmonics [25]. The torque ripple can be calculated from the harmonics in the back-EMF if the machine is supplied with a sinusoidal current [3]. Fig. 6 shows how cogging torque and torque ripple are calculated.

Basically, there are two approaches for reducing the torque ripple [26, 27]. One is to improve the magnetic design of the machines by changing the stator and rotor pole structures. The other one is to use the electronic control technique which is based on optimizing the control parameters such as supply voltage, turn-on and turn-off angles, and current level.

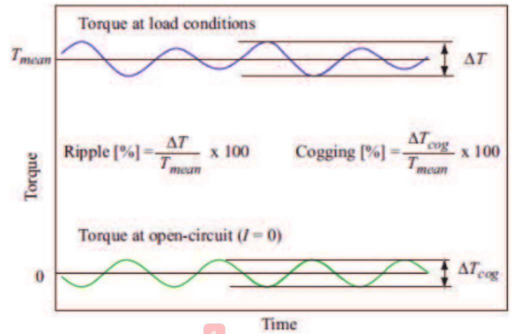

Fig. 6. Definition of cogging torque and torque ripple

But minimizing the torque ripple by electronic control techniques may caused the average torque reduced. The electronic control techniques are used in [25-29] to reducing the torque ripple. Improve the magnetic design of the machines are more effective on reducing torque ripple than the electronic control [30]. It is because the first method can also reduce cogging torque and optimize back EMF, whereas the electronic control techniques need precise real time excitation current profiles, depend on the reliability and accuracy of the sensors.

Design optimization for low torque ripple and cogging torque by changing the magnet arc and choosing an optimum flux barrier shape for interior PM machine using 2D FEA are presented in [31]. Table 1. presents the cogging torque value with different magnet arc length. It was found that minimum cogging torque produces when the magnet arc length is 40.84 mm. To investigate the torque ripple in the machine, the authors proposed three different flux barrier designs as shown in Fig. 7.

Table 1. Cogging torque value with magnet arc variations

Magnet arc length (mm)	Cogging torque (Nm)
38.92	10.46
39.00	11.10
40.84	2.00
42.20	5.83

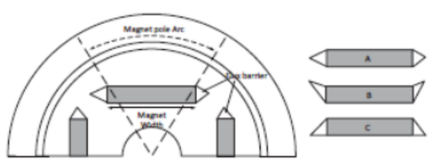

Fig. 7. Flat shape interior PM machine with variations of flux barrier shape

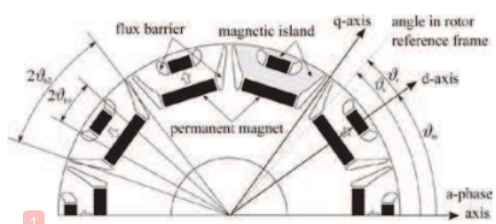

Fig. 8. Reference frame and rotor structure for interior PM analytical model

Optimizing flux barrier angles also used in [32] besides adopting a multilayer structure for stator windings to reduce the torque ripple in interior PM motor fractional-slot non-overlapping windings (also known as concentrated windings). Fig. 7 shows the rotor geometry structure with two flux barrier per pole. Analytical model results for 12 slot 10 pole machine shows that the torque ripple achieved lower than 1.5% at full load.

In [33], the authors using magnet pole shaping technique for torque ripple reduction on an 18 slot and 12 pole surface mounted PM Brushless DC (PM BLDC) motor. The performance parameters were computed and analysis by 2D FEA.

In [34], the authors investigated the effectiveness of skewing rotor method with/without magnet shaping on the torque ripple for surface mounted PM machine. Although the cogging torque can be fully eliminated, it was proven that skewing not fully eliminated the torque ripple, because in this case the skewing angle should be 360° electrical, which is made the average torque will also be zero.

Skewing rotor also used in [35] for torque ripple and cogging torque reduction on surface mounted PM synchronous motor. However, the results show that skewing may cause the torque ripple increase if the magnet shape is not designed carefully. The authors used surface mounted PM synchronous motor with 9-slot/6-pole non-skewed and skewed for the test. Tests were also conducted on a 12-slot/10-pole non-skewed surface mounted PM synchronous motor.

The reduction of the torque ripple harmonics with the lowest orders (6th and 12th) for PM synchronous machines with fractional-slot non-overlapping windings by teeth widths adjustment is presented in [36]. The authors investigated the phenomenon of torque ripple in two type machine, outer rotor surface mounted PM synchronous machines and inner rotor interior PM synchronous machine. The optimization technique was carried out by FEA. Influence of the permanent magnet skewing on the torque ripple reduction and cogging torque elimination was also investigated.

Shaping the stator teeth for reducing the torque ripple also use in [37]. The authors compared three models of surface mounted PM motor with different stator teeth shape. Fig. 9 shows the three models of surface mounted PM motor with different stator teeth shape. The initial model is shown in Fig. 9a, in the second model (Fig. 9b), the top of the stator teeth is flat, and the third model (Fig. 9c) shows the air-gap becomes large toward the stator teeth tip. The analysis results show that the minimum value of cogging torque and torque ripple is not at the same point of design. Therefore, the design parameter should be chosen carefully.

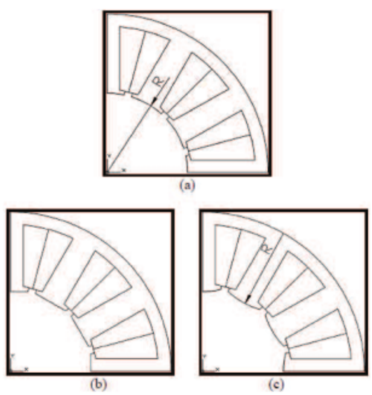

Fig. 9. Cross section shapes of: (a) Model 1; (b) Model 2; (c) Model 3

In [38], the authors investigated cogging torque minimization and torque ripple reduction in surface mounted PM synchronous machine using different magnet widths. Fig. 10 shows the different between normally magnet widths and the method that the authors proposed. It shown that normally the dimension of magnet and interval spaces between them are the same (Fig. 10a). Fig. 10b shows one magnet has different width from the other.

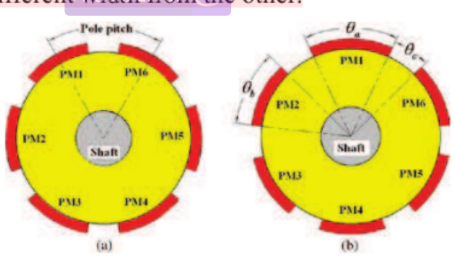

Fig. 10. Cross section of rotor (a) uniform magnet widths; (b) different magnet widths method

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An analytical approach for optimizing inner rotor surface mounted PM synchronous generator with concentrated windings design for wind power applications is presented in [39]. The authors using both the PM shape design and skewing stator to reducing the torque ripple and cogging. Fig. 11a shows the analytical model of skewing stator of PM synchronous generator to reducing the cogging torque. Fig. 11b shows analysis model for deriving the PMs magnetic field, where α, β, γ and γ are the radian of each region. The performance of PM synchronous generator is experimentally verified under AC and DC load conditions.

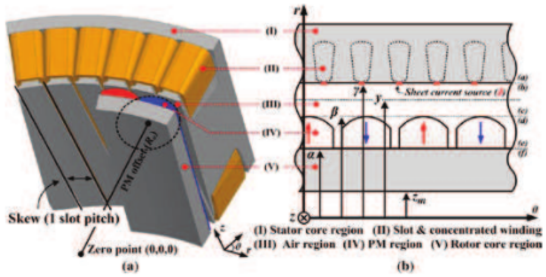

Fig. 11. (a) 3-D FE analysis model based on skewing; (b) analytical model based on PM shape

Conclusion

This paper provides a literature review on reducing the torque ripple in permanent magnet generator. There are several ways to minimize the torque ripple, e.g. skewing of the stator and/or rotor, choosing the right combination of pole and slot numbers and adjusting some design parameters such as the PM pole arc width and/or the slot opening width. It was found that torque ripple could not be always reduced by skewing, and a low cogging torque does not always guarantee a low torque ripple. Therefore, to reducing the torque ripple we should find the optimal design of permanent magnet generator by choosing the right combination of pole and slot numbers and also shaping the rotor magnet and stator teeth.

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Sentence Cap. Remember to capitalize the first word of each sentence.

Article Error You may need to use an article before this word.

Missing "," You may need to place a comma after this word.

Proper Noun If this word is a proper noun, you need to capitalize it.

Article Error You may need to use an article before this word.

Article Error You may need to use an article before this word.

Wrong Article You may have used the wrong article or pronoun. Proofread the sentence to make sure that the article or pronoun agrees with the word it describes.

Article Error You may need to use an article before this word.

Article Error You may need to use an article before this word.

Article Error You may need to use an article before this word.

P/V You have used the passive voice in this sentence. Depending upon what you wish to emphasize in the sentence, you may want to revise it using the active voice.

Article Error You may need to use an article before this word.

Sp. This word is misspelled. Use a dictionary or spellchecker when you proofread your work.

Sp. This word is misspelled. Use a dictionary or spellchecker when you proofread your work.

Article Error You may need to use an article before this word.

Article Error You may need to use an article before this word. Consider using the article **the**.

Garbled Grammatical or spelling errors make the meaning of this sentence unclear. Proofread the sentence to correct the mistakes.

Sentence Cap. Remember to capitalize the first word of each sentence.

Article Error You may need to use an article before this word.

Article Error You may need to use an article before this word. Consider using the article **the**.

Article Error You may need to use an article before this word.

Garbled Grammatical or spelling errors make the meaning of this sentence unclear. Proofread the sentence to correct the mistakes.

Article Error You may need to use an article before this word. Consider using the article **the**.

Article Error You may need to use an article before this word.

Article Error You may need to remove this article.

Proofread This part of the sentence contains a grammatical error or misspelled word that makes your meaning unclear.

Wrong Article You may have used the wrong article or pronoun. Proofread the sentence to make sure that the article or pronoun agrees with the word it describes.

Article Error You may need to use an article before this word.

P/V You have used the passive voice in this sentence. Depending upon what you wish to emphasize in the sentence, you may want to revise it using the active voice.

Article Error You may need to use an article before this word. Consider using the article **the**.

Article Error You may need to use an article before this word. Consider using the article **the**.

Article Error You may need to use an article before this word. Consider using the article **the**.

Proofread This part of the sentence contains a grammatical error or misspelled word that makes your meaning unclear.

Frag. This sentence may be a fragment or may have incorrect punctuation. Proofread the sentence to be sure that it has correct punctuation and that it has an independent clause with a complete subject and predicate.

Article Error You may need to use an article before this word. Consider using the article **the**.

Article Error You may need to use an article before this word.

S/V This subject and verb may not agree. Proofread the sentence to make sure the subject agrees with the verb.

Article Error You may need to use an article before this word.

Article Error You may need to use an article before this word.

Article Error You may need to use an article before this word.

Proofread This part of the sentence contains a grammatical error or misspelled word that makes your meaning unclear.

Sp. This word is misspelled. Use a dictionary or spellchecker when you proofread your work.

Sp. This word is misspelled. Use a dictionary or spellchecker when you proofread your work.

Article Error You may need to use an article before this word.

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Garbled Grammatical or spelling errors make the meaning of this sentence unclear. Proofread the sentence to correct the mistakes.

S/V This subject and verb may not agree. Proofread the sentence to make sure the subject agrees with the verb.

Sentence Cap. Remember to capitalize the first word of each sentence.

Article Error You may need to use an article before this word.

P/V You have used the passive voice in this sentence. Depending upon what you wish to emphasize in the sentence, you may want to revise it using the active voice.

Article Error You may need to use an article before this word.

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