Torque Ripple Reduction Design Methods

Subjects: Engineering, Electrical & Electronic

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There are some phenomena that affect electric vehicle performance. One of those phenomena is the torque ripple of electric motors, which interferes with traction and the suspension system (causing vibration that stresses this system), and it can also introduce electric current harmonics into the battery, reducing its life, since torque ripple is partly a consequence of non-sinusoidal back EMF. For those reasons this is a topic worth investigating. The torque ripple of permanent magnets (PM) motors can be reduced in design or through control.

torque ripple cogging torque air-gap flux density back EMF

1. Introduction

Torque ripple is one of the undesired, but inherent, properties in motors with permanent magnets. The main causes of torque ripple are non-ideal back EMF waveforms, saturation of the machine's magnetic circuit, and cogging torque [1]. Cogging torque appears because of the attraction between rotor's permanent magnets and stator teeth, since they are made with ferromagnetic materials. When the magnet aligns with the maximum amount of stator teeth, the reluctance seen by the magnet flux is minimized, but increases as the rotor turns and the magnets move [2]. The increase of reluctance produces a force that tries to return the magnet back to alignment, and as a result, the instantaneous torque varies periodically in time [2]. This effect is especially important at low speed; at higher speed, inertia helps to minimize the drawbacks of cogging torque because the tendency of the rotor to move becomes considerably stronger than the attraction between the magnets and stator teeth, so that the effects of cogging torque in the motor's performance are decreased, although the cogging is still present.

The saturation of machine's magnetic circuit is a less common source of torque ripple, since it is almost always avoided in designs because of the additional problems that it brings. Saturation may increase torque fluctuations because not all the magnetic flux can pass through the path it should, so it has to move further in the airgap to find a way back to the magnet. In that process, the airgap flux density distribution is affected, and since airgap flux density is directly related to torque, higher fluctuations appear. In the literature revision, only one of the reviewed articles (the first cited one) mentions the saturation of machine's magnetic circuit, and its solution is briefly explained. However, it is important to take account of every possible cause of torque ripple to design better solutions.

In contrast, non-ideal back EMF waveforms are an important cause of torque ripple. Due to the magnet flux crossing the air gap, a voltage is induced in stator coils, and because of the rotor and stator geometric variables, the waveform of the induced voltage is usually not sinusoidal. This means that the back EMF has harmonics that interfere with the torque production. For its nature, this source of torque ripple is very hard to eliminate without affecting the machine's performance, especially the output torque, but it can be decreased to acceptable levels while keeping the machine's design parameters near to ideal.

In recent research on the innovations and design methodologies of permanent magnets motors, it was found that cogging torque and torque ripple reduction are topics that have been frequently investigated. Papers such as [3][4] show the relevance of better motor designs and the advances in this field, respectively, while [5] considers the effect of torque ripple in the suspension system of electric vehicles and [6] considers the consequences of motor's non-sinusoidal back EMF on electric vehicle battery performance. However, control techniques for reducing torque ripple are more commonly reviewed and compared than design methods, although there are a wide range of innovations in this field.

Control methods are preferred when the machine is already designed and optimized, and trying to reduce torque ripple by modifying the geometry could affect the desired performance. Additionally, design methods may complicate the manufacturing process and, hence, increase costs. The operating principle in the control methods is commonly the injection of current harmonics on top of the operating currents. This can be made by current reference-based methods, parameter-based methods, and adaptive methods [7].

Nonetheless, reducing torque ripple through control requires extra circuitry, which leads to higher risk of failure and more need of maintenance, and it also requires specialized personnel. When designing a motor, the requirements of the application should be considered, so that the best torque ripple reduction method is used, be it through design or control.

2. Torque Ripple Reduction Design Methods

There are several options for reducing torque ripple, depending on the cause of it, such as geometry optimization, specific slot/pole combinations, or stator winding type. Once the source of ripple is found and understood, the optimal method or combination of methods to reduce it should be applied. **Table 1** summarizes some relevant information about various design methods to reduce the torque ripple of rotor PM machines, including a couple for stator PM machines.

Table 1. Relevant data of the revised torque ripple reduction design techniques.

Reference	Machine Topology	Design Technique	Torque Ripple Reduction Ratio (%)	Slot/Pole Number	Rated Power (W)	Average Torque (Nm)	Rated Speed (rpm)
High Torque Density and Low Torque Ripple-Shaped Magnet Machines Using Sinusoidal Plus Third Harmonic-Shaped Magnets [8]	Radial flux, surface permanent magnets	Magnets shaping	88.50	24/8	54	184	2800
A Dual Notched Design of Radial-Flux Permanent Magnet Motors with Low Cogging Torque and Rare Earth Material [9]	Radial flux, surface permanent magnets	Gear-shaping the surfaces of magnets and teeth	62.8	18/12	80	−	10,000
Torque Ripple Reduction of Saliency-Based Sensorless Drive Concentrated Winding IPMSM Using Novel Flux Barrier [10]	Saliency-based, interior permanent magnets	Flux barrier design	28	9/6	5500	45	1750
Reduction of Torque Ripple in Consequent Pole Permanent Magnet Machines Using Staggered Rotor [11]	Consequent-Pole permanent magnet motor	Staggered rotor design	60	9/6	−	2.13	1500

Reference	Machine Topology	Design Technique	Torque Ripple Reduction Ratio (%)	Slot/Pole Number	Rated Power (W)	Average Torque (Nm)	Rated Speed (rpm)
Optimal Design to Reduce Torque Ripple of IPM Motor with Radial-Based Function Meta-Model Considering Design Sensitivity Analysis [12]	Radial flux, interior permanent magnets	Slots, teeth, and magnet size optimization	58	48/8	50,000	400	1200
Permanent Magnet Motor Design for Satellite Attitude Control With High Torque Density and Low Torque Ripple [13]	Radial flux, dual rotor	Slotless windings and Halbach array magnets	67	9/8	11.5	32.15 m	6000
Optimization of Torque Ripples in an Interior Permanent Magnet Synchronous Motor Based on the Orthogonal Experimental Method and MIGA and RBF Neural Networks [14]	Radial flux, interior permanent magnets	Stator, rotor, and magnets sizes optimization	84	24/8	5010	4.2	−
Asymmetric Rotor Design of IPMSM for Vibration Reduction Under Certain Load Condition [15]	Radial flux, interior permanent magnets	Asymmetric rotor shape	33.10	12/8	5000	24	2000

Reference	Machine Topology	Design Technique	Torque Ripple Reduction Ratio (%)	Slot/Pole Number	Rated Power (W)	Average Torque (Nm)	Rated Speed (rpm)
Ferrite PM Optimization of SPM BLDC Motor for Oil-Pump Applications, According to Magnetization Direction [16]	Brushless DC	Parallel magnetization direction of permanent magnets	69.20	12/8	126	0.33	3200
Design and Analysis of Halbach Ironless Flywheel BLDC Motor/Generators [17]	Brushless DC, outer rotor	Halbach array magnets	20	6/8	–	800 m	40,000
Design Optimisation of an Outer Rotor Permanent Magnet Synchronous Hub Motor for a Low-Speed Campus Patrol EV [18]	Radial flux, outer rotor	Similar number of slots and poles	29	51/50	–	94.5	600
Effect Comparison of Zigzag Skew PM Pole and Straight Skew Slot for Vibration Mitigation of PM Brush DC Motors [19]	Brush DC	Zigzag skewed magnets	37.5	24/4	800	2.147	2700
Analytical Prediction and Optimization of Cogging Torque in Surface-Mounted	Radial flux, surface permanent magnets	Air-gap length and magnet thickness optimization,	92.48	12/8	–	–	–

Reference	Machine Topology	Design Technique	Torque Ripple Reduction Ratio (%)	Slot/Pole Number	Rated Power (W)	Average Torque (Nm)	Rated Speed (rpm)
Permanent Magnet Machines With Modified Particle Swarm Optimization [20]		fractional slot-pole number, and parallel magnetization of permanent magnets					
Material-Efficient Permanent Magnet Shape for Torque Pulsation Minimization in SPM Motors for Automotive Applications [21]	Radial flux, surface permanent magnets	Magnets shaping and skewing	86.1	6/4	264.4	0.5053	1000
Modeling of Novel Permanent Magnet Pole Shape SPM Motor for Reducing Torque Pulsation [22]	Radial flux, surface permanent magnets	Magnets shaping	72.08	6/4	340.48	0.6503	5000
Reduction of Torque Ripple Caused by Slot Harmonics in FSCW Spoke-Type FPM Motors by Assisted Poles [23]	Spoke-type	Fractional slot concentrated winding and assisted poles	40	12/10	−	6.5	1500
Torque Ripple Reduction in Five-Phase IPM Motors by	Radial flux, interior permanent magnets	Asymmetrical rotor poles shifting	−	40/8	−	10.45	1500

Reference	Machine Topology	Design Technique	Torque Ripple Reduction Ratio (%)	Slot/Pole Number	Rated Power (W)	Average Torque (Nm)	Rated Speed (rpm)
Lowering Interactional MMF [24]							
Torque Ripple Reduction of a Salient Pole Permanent Magnet Synchronous Machine, with an Advanced Step-Skewed Rotor Design [25]	Salient-pole, surface permanent magnets	Eccentric airgap, advanced step-skewed rotor, and pole shoes skewing	91	36/4	1500	10.52	1500
Efficient Utilization of Rare Earth Permanent-Magnet Materials and Torque Ripple Reduction in Interior Permanent-Magnet Machines [26]	Radial flux, interior permanent magnets	Rotor made by segments arranged in the axial direction, and pole shaping	50	48/8	68,000	210	3080
Investigation of Short Permanent Magnet and Stator Flux Bridge Effects on Cogging Torque Mitigation in FSPM Machines [27]	Flux-switching	Short magnet and stator flux bridge	32.70	12/10	500	3.05	1500
Reduction of Torque Ripple in Inset Permanent Magnet Synchronous Motor	Radial flux, interior permanent magnets	Magnets shifting	28	48/8	–	244	–

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Reference	Machine Topology	Design Technique	Torque Ripple Reduction Ratio (%)	Slot/Pole Number	Rated Power (W)	Average Torque (Nm)	Rated Speed (rpm)
by Magnets Shifting [28]							

− Not reported.

2.1. General Classification

Figure 1 shows the general torque ripple reduction approaches reviewed and the different design methods in each of them. It is visible that geometry optimization is the widest category, followed by stator winding type and slot/pole combinations.

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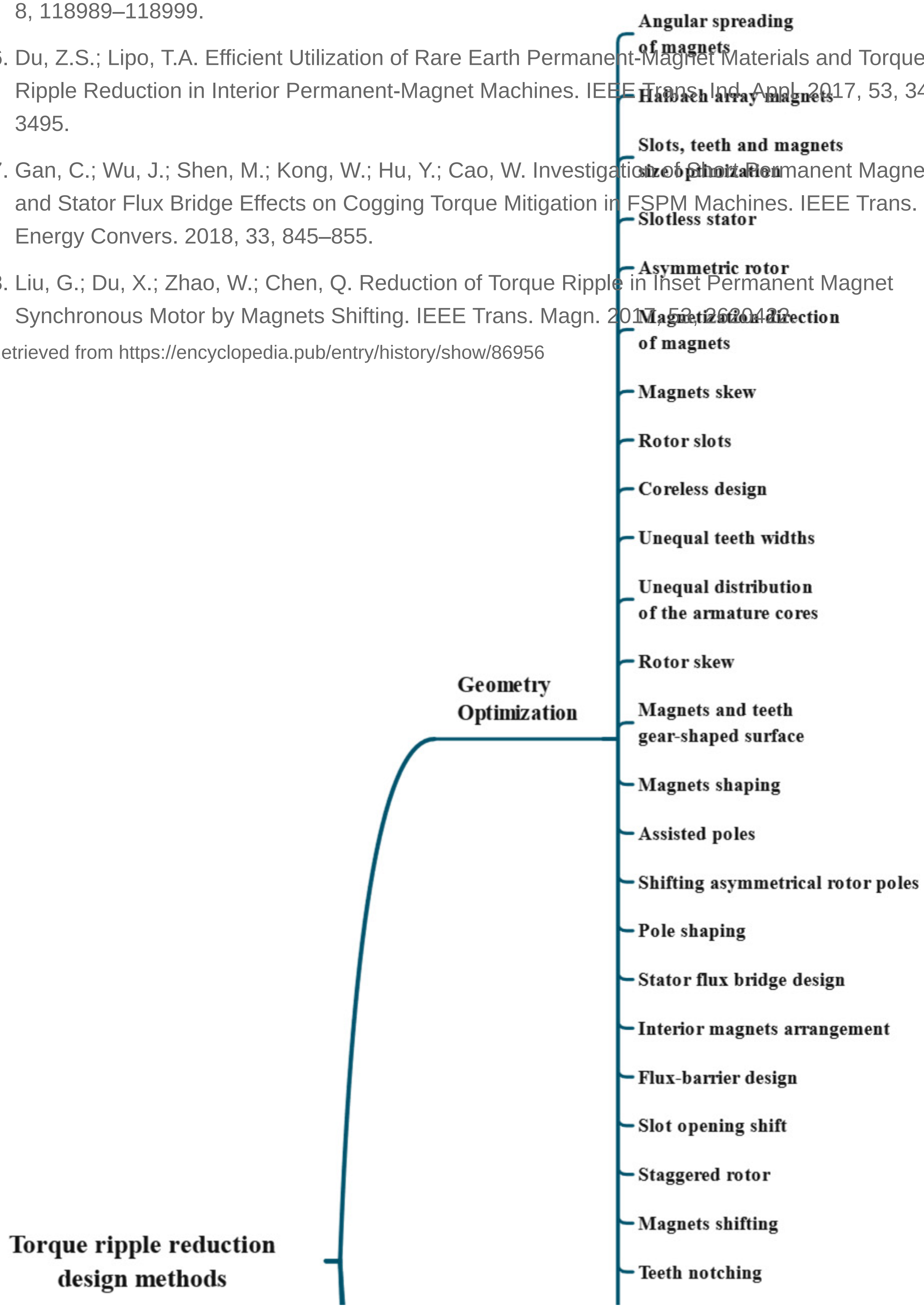

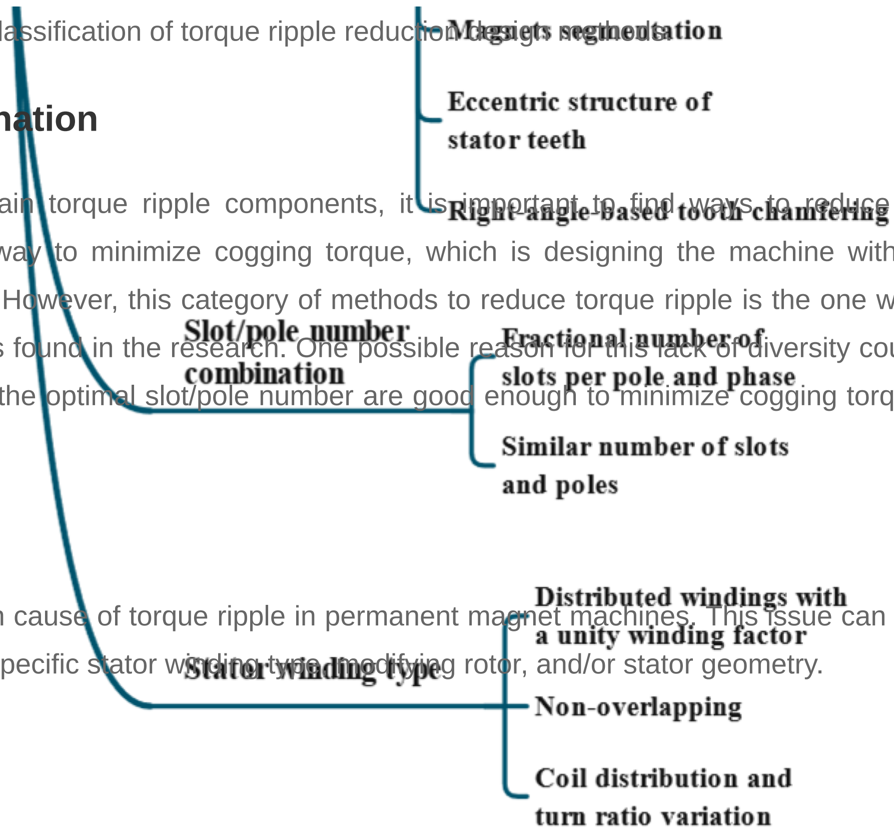

Figure 1. General classification of torque ripple reduction design methods.

2.2. Slot/Pole Number Combination

Since cogging torque is one of the main torque ripple components, it is important to find ways to reduce it. Fortunately, there is a relatively easy way to minimize cogging torque, which is designing the machine with a specific combination of slots and poles. However, this category of methods to reduce torque ripple is the one with the smallest number of design variations found in the research. One possible reason for this lack of diversity could be that the existing methods for finding the optimal slot/pole number are good enough to minimize cogging torque in most cases.

2.3. Stator Winding Type

Back EMF harmonics are the other main cause of torque ripple in permanent magnet machines. This issue can be addressed by two approaches: using a specific stator winding type, modifying rotor, and/or stator geometry.