

Performance Assessment of IPMSM Drives in Electric Vehicles Under Torque Ripple Conditions

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Abstract- This extensive research investigates the influence of torque ripples in Permanent Magnet Synchronous Motors (PMSMs) on the EVs by the performance measuring parameters of efficiency and driving range of electric vehicles (EVs). IPMSMs are frequently used in EVs due to their excellent performance and efficiency; nevertheless, torque ripple, which results from recurring variations in the torque output of the motor, can drastically lower motor efficiency and vehicle performance. An overview of IPMSMs in EVs, a definition of torque ripple, and an emphasis on its significance for optimising vehicle performance are all covered in the research review. The kinds and causes of torque ripple, including cogging torque, electromagnetic disturbances, and mechanical problems, are examined in detail. The study distinguishes between high-frequency torque ripple, which mainly results in energy efficiency losses, and low-frequency torque ripple, which influences vehicle vibration. The investigation also addresses torque ripple's detrimental effects on EV performance, emphasising how it shortens driving range and overall vehicle longevity by increasing energy consumption, speeding up battery deterioration, and decreasing regenerative braking efficiency. The findings of this study provide insights into improving IPMSM drive performance and enhancing the operational efficiency of electric vehicles.

Keywords: Model Predictive Control (MPC), Adaptive Direct Torque Control (DTC), and optimal inverter design, IPMSM, Convolutional Neural Network (CNN).

I. INTRODUCTION

The rapid growth of electric vehicles has intensified the demand for high-performance and energy-efficient motor drive systems. In recent years, Permanent Magnet Synchronous Motor has become more attractive because of the added advantage of high-power density, high efficiency, fast dynamic response, smaller in size, less weight, rugged in construction and easier to control compared to induction motors. Thus, it has been widely used in robot arm control and positioning devices and low-power applications.

In recent years, various solutions have been proposed for the estimation of rotor position and speed with a sensorless technique based on three categories. i.e.,

Model-based, Saliency-based, Artificial Intelligence-based methods [2]. The novel approach to the Sensor-less speed control of IPMSM was proposed in the literature [1-3]. It provides a solution for estimating the initial rotor position by applying two types of voltage pulses to the motor's stator windings. The current generated by the high-frequency voltage pulse applied to the motor produces low-amplitude torque. Several conventional sensorless control methods do not perform well at a wide range of speed operations and are very sensitive to changes in stator resistance during operation. To overcome this problem, sensorless control with the Extended Kalman Filter algorithm was proposed without knowing the information about the initial rotor position, mechanical parameters and also works well at medium and high-speed ranges [4-7]. The information about rotor position is mandatory for synchronization of the stator and rotor fields. Maintaining constant and perfect synchronization is challenging task in pmsm drives than in PM brushless DC motor[8-12]. Sensorless control of PMSM drive varies with the construction of rotor types. The signal injection method is suitable for low-speed operation of IPMSM Sensorless speed control drive because of its rotor saliency [13-17]. Yet, in this method, many filters are used for signal processing, which will produce unavoidable phase delay and reduced magnitude.

II. MATHEMATICAL MODEL OF IPMSM

Speed and Torque determination:

The mathematical model of IPMSM without damper winding has been developed in the rotor reference frame using the following assumptions [1];

- ❖ The conductivity of the permanent magnet material is assumed as zero;
- ❖ The core saturation and winding leakage inductance are ignored, and
- ❖ There are no damper windings on the rotor;
- ❖ Excluding the eddy current and hysteresis losses that the magnetic circuit is linear.
- ❖ The EMF wave of the stator winding is sinusoidal in phase, ignoring the higher harmonics of the magnetic field.

The voltage equations for IPMSM in the rotor reference frame can be expressed as follows:

$$V_d = R_s * I_d + L_d * \frac{dI_d}{dt} - \omega_e * L_q * I_q$$

$$V_q = R_s * I_q + L_q * \frac{dI_q}{dt} + \omega_e * L_d * I_d + \omega_e * \lambda_{fr}$$

The developed electromagnetic torque is expressed as,

$$T_e = 3 / 2 * N_p [(\lambda_{fr} * I_q) - (L_q - L_d)(I_d * I_q)]$$

The rotor mechanical equations are given by

$$T_e = J \frac{d\omega_{rm}}{dt} + B\omega_{rm} + T_L$$

And, $\theta_{rm} = \int \omega_{rm} dt$

$$\frac{d\omega_{rm}}{dt} = 1 / J [(T_e - T_L - B\omega_{rm})]$$

$$\omega_e = [P / 2] * \omega_{rm}$$

For IPMSM, L_d and L_q are not equal. Therefore, the equation can be rewritten as;

$$\frac{dI_d}{dt} = \frac{V_d}{L_d} - \frac{R_s * I_d}{L_d} + \left(\frac{\omega_e * L_q * I_q}{L_d} \right)$$

$$\frac{dI_q}{dt} = \frac{V_q}{L_q} - \frac{R_s * I_q}{L_q} - \left(\frac{\omega_e * L_d * I_d}{L_q} \right) - \frac{\omega_e * \lambda_{fr}}{L_q}$$

And $\lambda_d = L_d I_d + \lambda_{fr}$

$$\lambda_q = L_q I_q$$

Where, V_d, V_q denotes d and q axes of stator voltage, respectively

I_d, I_q are the d and q axes of stator currents

R_s is stator resistance,

L_d, L_q are d and q axes inductances

λ_{fr} is Rotor flux linkage (due to Permanent magnet flux)

λ_d, λ_q are the d and q axes of stator flux linkages

ω_e is the electrical angular speed

$\omega_r = \omega_{rm}$, is the mechanical angular speed in rad/Sec

B is the coefficient of Viscous Friction, J is the moment of Inertia.

I. FIELD ORIENTED CONTROL OF IPMSM

To achieve high dynamic performance and efficiency, the vector-based control strategy offers a superior solution compared to scalar control. Vector Control or Field Oriented Control architecture is implemented on a Permanent magnet Synchronous Motor drive system for smooth and efficient control of PMSM. The objective of FOC is to decouple the stator currents into equivalent flux and torque-producing current components for independent and accurate control of flux and torque, as shown in the phasor diagram of the fig.

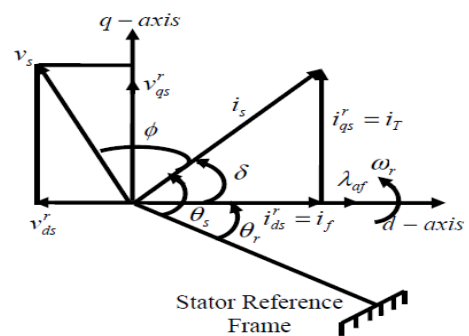


Fig. Phasor diagram of FOC of PMSM

From the fig., the rotor flux linkage revolves at rotor speed ω_{rm} and is located away from the stationary reference by the rotor angle θ_{rm} . Stator current is placed at an angle of δ from the rotor flux linkage phasor. The condition under which speed varies from zero to rated speed, the stator flux current component equals zero at an angle $\delta = 90$. $I_f = I_s \cos \delta = 0$

The fig.2, shows the schematic diagram of the Field-Oriented Control of the PMSM speed drive system. The main idea of field-oriented control (FOC) is to decouple the torque and flux generating components to control the torque variation demand, thereby achieving desired speed control. FOC strategy will apply to a PMSM in association with an SVPWM inverter to control the machine phase currents. The stator currents and rotor position angle are measured by using sensors. The machine phase currents are then converted into α and β axes currents by Clark's transformation, and then, $\alpha\beta$ axes currents are transformed into d and q axes currents by using Park's transformation. The transformation from three-phase current quantities into two-phase current quantities can be written in matrix form [Ravindra Kumar et al]:

SVPWM scheme is very tedious and requires a large number of mathematical calculations, depending on the number of levels in the inverter output.

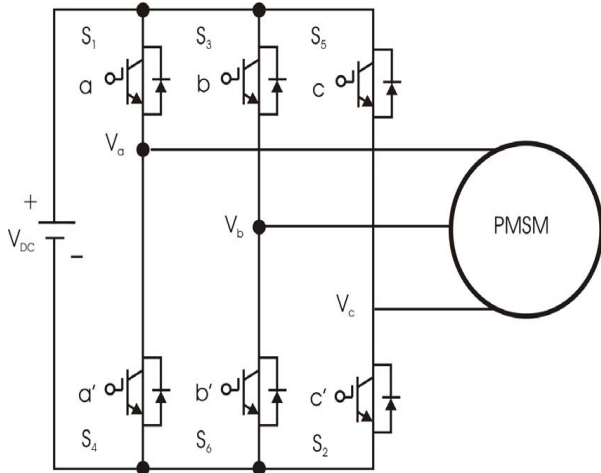


Fig.3 Two-level three-phase voltage source IGBT inverter

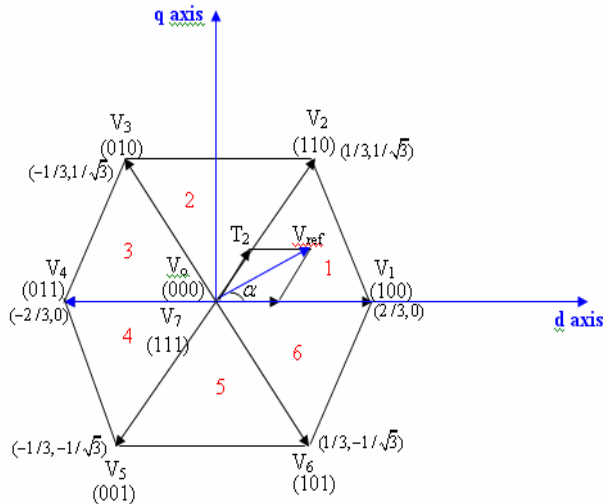


Fig.4, Six sector switching pattern/Vector diagram of SVPWM

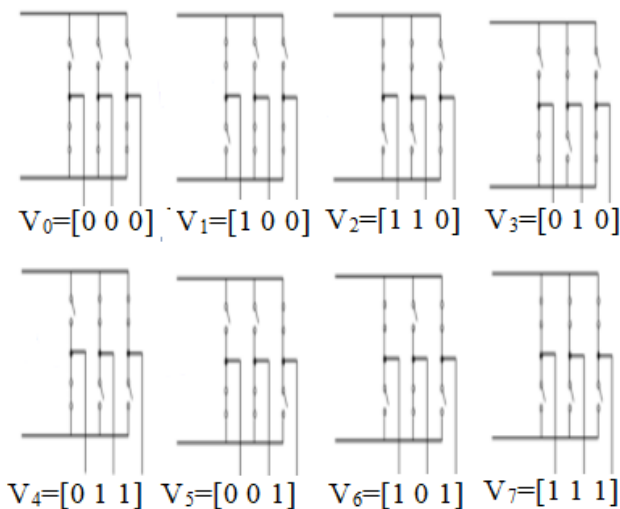


Fig.5, Eight inverter voltage vectors

Table 2 Switching voltage vectors and corresponding line-to-line voltages

Voltage Vectors	Switching Vectors			Phase voltage			Line-Line voltages		
	a	b	c	V _a	V _b	V _c	V _{ab}	V _{bc}	V _{ca}
V ₀	0	0	0	0	0	0	0	0	0
V ₁	1	0	0	2/3	1/3	1/3	1	0	-1
V ₂	1	1	0	1/3	1/3	2/3	0	1	-1
V ₃	0	1	0	1/3	2/3	1/3	-1	1	0
V ₄	0	1	1	2/3	1/3	1/3	-1	0	1
V ₅	0	0	1	1/3	1/3	2/3	0	-1	1
V ₆	1	0	1	1/3	2/3	1/3	1	-1	0
V ₇	1	1	1	0	0	0	0	0	0

The mathematical model of PMSM is fed through inverter output voltage which is controlled by SPWM technique used for pulse generation. The PMSM motor parameters are listed in table 1. The PMSM stator currents, actual speed and electromagnetic torque are being obtained to get the reference d and q axis currents which is further employed by park and Clarke transformation to get desired speed. The inverter output is controlled by pulse generation obtained from SVPWM technique. The new reference speed and torque signal is given to motor to enhance the PMSM motor drive performances using vector control approach.

Matlab-Simulink implementation of Vector control-based speed control of PMSM drive system using SVPWM technique

V. CONTROLLERS

A Sliding Mode Controller is a kind of nonlinear controller and is insensitive to parameter variations and outside disturbances, while its control is discontinuous. The aim of SMC-based vector control of PMSM is that the speed and torque can be controlled to attain desirable and satisfactory dynamic performance. Further, it also provides strong and

robustness to internal disturbances and external uncertainties.

SMC has an auto-adjust online controller structure that provides protruding features such as rapid response and robustness. The structure of the SMC. The sliding mode controller design comprises the selection of a sliding surface and a control law. Once the system state enters the sliding surface, the system's transient state is determined by the chosen sliding surface. To improve the dynamic performance of the PMSM control system when load torque and motor parameters change in conditions, a new novel control law of SMC is essential.

The Model Reference Adaptive Control (MRAC) technique is employed to improve the dynamic performance of the IPMSM drive by continuously adjusting the controller parameters based on the reference model. MRAC enhances system stability and tracking accuracy by adapting the control law in response to variations in system parameters and operating conditions.

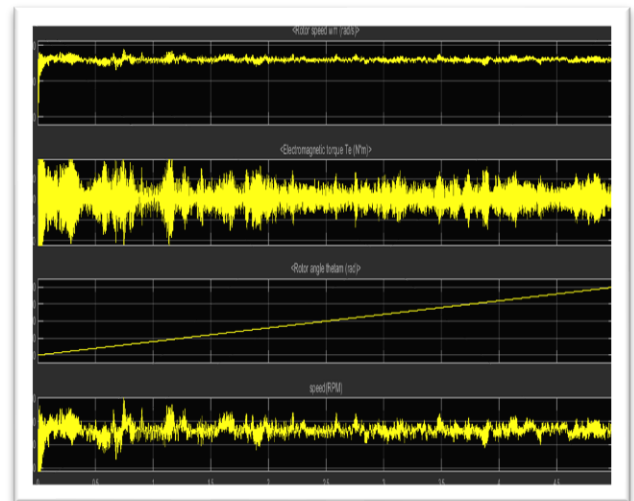


Fig. 7. Performance Characteristics of the IPMSM Drive Without Control.

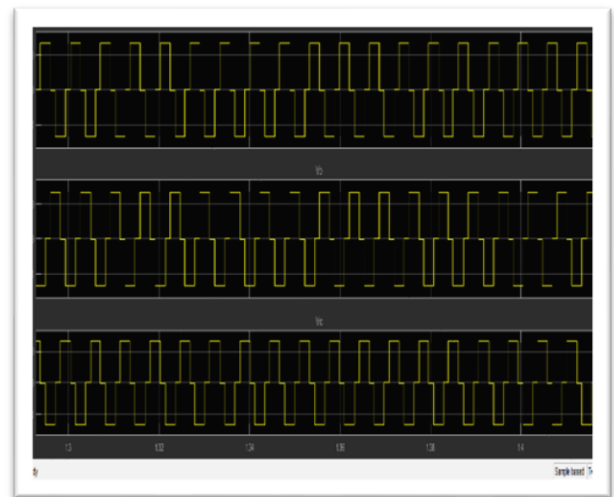


Fig. 8. Inverter Voltage for the IPMSM Drive Without Control.

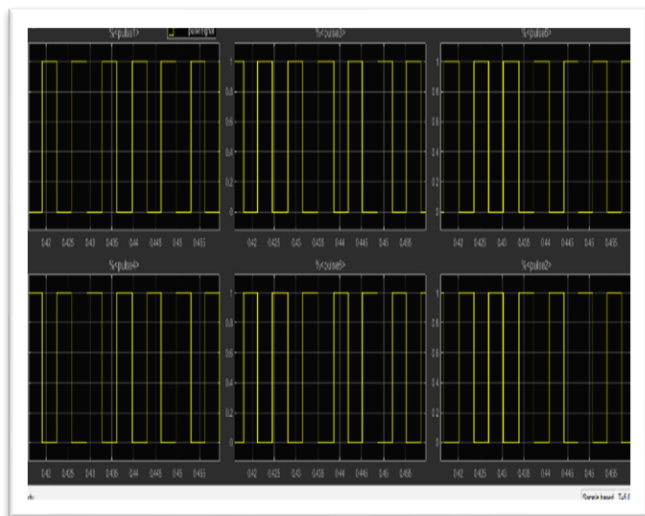


Fig. 6. SVPWM Gate Signals

VI. RESULTS AND DISCUSSION

To verify the feasibility of the proposed vector control-based speed control of the PMSM drive system simulation have been carried out using the MATLAB environment, and the model is simulated by some reference commands. The reference signal is compared with the actual speed. The simulation is carried out to obtain the desired speed and required torque to run the motor efficiently. Results attained from the simulation, we can conclude that the proposed PMSM drive system parameter reaches nearly close to the reference signal and can achieve various desired speeds according to the reference speed.

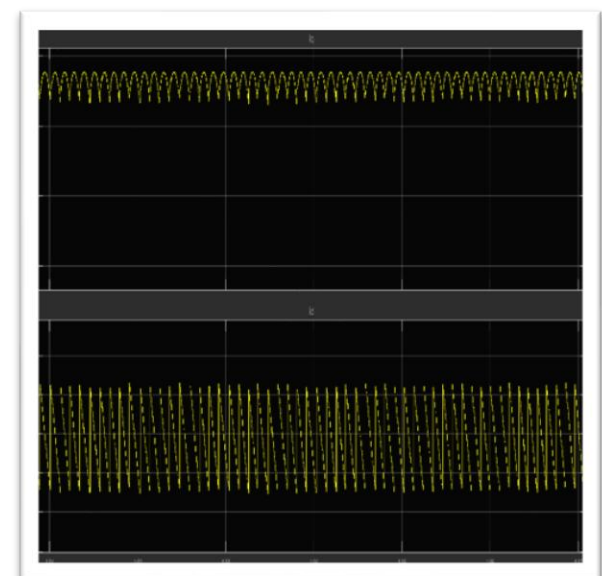


Fig. 9. dq-Axis Stator Voltage Components

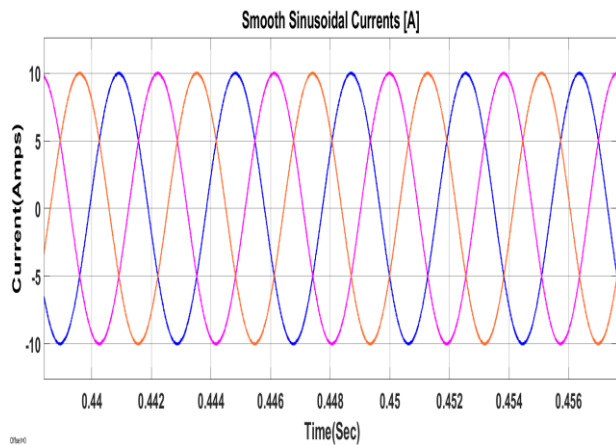


Fig.14. Three-Phase Stator Currents of the Motor with MRA Control.

Conclusion:

This study has systematically examined the impact of torque ripple in Interior Permanent Magnet Synchronous Motors (IPMSMs) on electric vehicle (EV) performance using key performance metrics such as efficiency, torque response, and speed regulation. Based on the mathematical modeling of the IPMSM in the rotor reference frame, vector control implementation using Field Oriented Control (FOC), and Space Vector Pulse Width Modulation (SVPWM) techniques, the dynamic behavior of the PMSM drive system was evaluated under varying operating conditions.

The analysis confirms that torque ripple, originating from electromagnetic interactions, inverter switching effects, and load disturbances, significantly influences motor smoothness, energy utilization, and overall drive quality. High-frequency torque ripple contributes to additional copper and core losses, thereby reducing system efficiency, while low-frequency torque ripple introduces speed oscillations and mechanical vibrations that can affect ride comfort and long-term drivetrain reliability in EV applications.

Simulation results demonstrate that the vector control-based speed control strategy effectively regulates torque and speed, enabling the actual motor parameters to closely track reference commands under both no-load and load conditions. The integration of the advanced control approach MRA controller further enhances robustness against parameter variations and external disturbances, thereby mitigating torque ripple effects and improving dynamic performance, compared with Sliding Mode Control.

From a system-level EV perspective, minimizing torque ripple is not only a motor control objective but also a critical factor in extending driving range, improving regenerative braking efficiency, and enhancing battery longevity. Therefore, optimized inverter design, accurate rotor position estimation, and advanced nonlinear control

strategies are essential to achieve high-performance, energy-efficient IPMSM-based EV drives.

In conclusion, the proposed vector control framework combined with robust control techniques provides a reliable and effective solution for torque ripple reduction in IPMSM-driven EV systems. Future work may focus on experimental validation, real-time hardware implementation, and the integration of intelligent algorithms such as machine learning-based ripple prediction models to further enhance performance under practical driving conditions.

REFERENCES:

- [1] Cao, Z., Mahmoudi, A., Kahourzade, S., & Soong, W. L. (2021, September). An overview of electric motors for electric vehicles. In 2021 31st Australasian Universities Power Engineering Conference (AUPEC) (pp. 1-6). IEEE
- [2] Hashemnia, N., & Asaei, B. (2008, September). Comparative study of using different electric motors in the electric vehicles. In 2008 18th International Conference on Electrical Machines (pp. 1-5). IEEE
- [3] Krings, A., & Monissen, C. (2020, August). Review and trends in electric traction motors for battery electric and hybrid vehicles. In 2020 International Conference on Electrical Machines (ICEM) (Vol. 1, pp. 1807-1813). IEEE.
- [4] Kim, K. C., Lee, J., Kim, H. J., & Koo, D. H. (2009). Multiobjective optimal design for an interior permanent magnet synchronous motor. IEEE
- [5] Transactions on Magnetics, 45(3), 1780-1783. [7] Rong, F., & Manfeng, D. (2012, October). Optimisation design and analysis of a 30kW interior permanent magnet synchronous motor used in electric vehicles. In 2012 15th International Conference on Electrical Machines and Systems (ICEMS) (pp. 1-5). IEEE.
- [6] Liu, X., Chen, H., Zhao, J., & Belahcen, A. (2016). Research on the performances and parameters of interior PMSM used for electric vehicles. IEEE
- [7] Transactions on Industrial Electronics, 63(6), 3533-3545. [9] Yan, J., Yang, K., Zhang, S., Feng, Y., Chen, Y., & Yang, H. (2017). Comparative investigation of inset-type and V-type IPMSM for light electric vehicle. International Journal of Applied Electromagnetics and Mechanics, 54(4), 515-524.
- [8] Zhou, C., Huang, X., Fang, Y., & Wu, L. (2018, September). Comparison of PMSMs with different rotor structures for EV application. In 2018, XIII International Conference on Electrical Machines (ICEM) (pp. 609-614). IEEE.
- [9] Murali, N., & Ushakumari, S. (2020, November). Performance comparison between different rotor configurations of PMSM for EV application. In 2020 IEEE REGION 10 CONFERENCE (TENCON) (pp. 1334-1339). IEEE
- [10] C. Mi, "Analytical design of permanent-magnet traction-drive motors," IEEE Trans. Magn., vol. 42, pp. 1861-1866, July, 2006.
- [11] Y. Fujishima, S. Vakao, M. Kondo, and N. Terauchi, "An optimal design of interior permanent magnet synchronous motor for the next generation commuter train," IEEE Trans. Applied Superconductivity, vol. 14, pp.1902-1905, June 2004.
- [12] F. Magnussen, P. Thelin, and C. Sadarangani, "Design of compact permanent magnet machines for a novel HEV propulsion system," in Proc. 20th Int. Electric Vehicle Symposium and Exposition, Long Beach, California, USA, 15-19 Nov., 2003, pp. 181-191.
- [13] S. Wu, L. Song, and S. Cui, "Study on improving the performance of permanent magnet wheel motor for the electric vehicle application," IEEE Trans. Magn., vol. 43, pp. 438-442, Jan 2007.
- [14] Chin Y-k, Soular J. Modelling of iron losses in permanent magnet synchronous motors with field-weakening capability for electric vehicles.

Int J Automot Tech- nol 2003;4(2):87–94.

- [15] Jahns TM, Han S-H, EL-Refaie AM , Baek J-H, Soong WL. Design and experimental verification of a 50kW interior permanent magnet synchronous machine. In: Industry applications conference; 2006. p. 1941–6 .
- [16] Stumberger B , Stumberger G , Jesenik M , Gorican V , Hamler A , Trlep M . Power capability and flux-weakening performance of interior permanent magnet syn- chronous motor with multiple flux barriers. In: 12th Biennial IEEE conference on electromagnetic field computation; 2006. p. 419.
- [17] Hwang, K.Y.; Jo, J.H.; Kwon, B.I. A Study on Optimal Pole Design of Spoke-Type IPMSM With Concentrated Winding for Reducing the Torque Ripple by Experiment Design Method. IEEE Trans. Magn. 2009, 45, 4712–4715. [CrossRef].6