*EVS28*
*KINTEX, Korea, May 3-6, 2015*

# Comparison of Hybrid-excitation Fault-tolerant In-wheel Motor Drives for Electric Vehicles

Fei Lin[1], K. T. Chau[1], Chunhua Liu[1], C. C. Chan[1], and T. W. Ching[2]
[1]*Fei Lin, The University of Hong Kong, Pokfulam Road, Hong Kong, China, linfei@eee.hku.hk*
[2]*T. W. Ching, University of Macau, Macau, China, twching@umac.com*

**Abstract**

Hybrid-excitation in-wheel motor drive receives the attractive merit for its fault-tolerant operation. This paper gives the performance comparison of three types of hybrid-excitation in-wheel motor drives in electric vehicles (EVs) for their fault-tolerant operations. By using finite-time element analysis, the torque output is utilized as the fault indicator to investigate the performances of each motor drive under normal, faulty, and remedial operations.

*Keywords: Fault-tolerant, electric vehicles (EVs), hybrid-excitation machine, in-wheel motor drive*

## 1 Introduction

In recent years, electric vehicles (EVs) have been paid great attention on their fault-tolerant operation [1]-[4]. A single failure of the core components in EVs could lead to unexpected shutdown. In the literatures, the faults of EVs can be divided into four main sections, namely, battery, electric motor, power electronics, and powertrain [5]-[10]. Among them, electric motor drives receives great attention for its fault-tolerant operation [3].

As the main motive power converting components of EVs, electric motor faults are generally divided into two categories, namely, electric fault and mechanical fault [9]. It can also be subdivided into four main faults as following [11]-[14]: (1) Rotor-related fault; (2) Stator-related fault; (3) Bearing fault; (4) Eccentricity-related fault.

This paper aims to investigate the comparison of in-wheel motor drives for their fault-tolerant operations. By using time-stepping finite-element-analysis (TS-FEA), the performance comparison of three motor drives is presented. It demonstrates the torque performance of each motor drive under normal, faulty, and remedial operations. The rest of the paper is organized as follow. Section II gives a review of motor faults in EVs. Section III illustrates the operation principles of the hybrid-excitation in-wheel motor drives. Section IV compares the performances of three motor drive models for their fault-tolerant operation. And Section V gives the conclusion.

## 2 Review of Motor Faults for EVs

Figure 1 represents an exploded diagram of induction machine and the corresponding fault occurrence rates. The machine mainly consists of stator, rotor, bearing, and shaft. And the bar chart indicates that stator-related fault and bearing fault are the dominating faults in electric motors [15]-[17]. For further classification and exploration, Table 1 summarizes the motor drive faults by percentage, cause, feature, frequency, and diagnostic approach [18]-[25]. It can be found that the frequency components of the corresponding faults on electric motor can be expressed by common mathematical expressions [23]. In addition, the presence of these faults can be detected by applying motor current signature analysis.

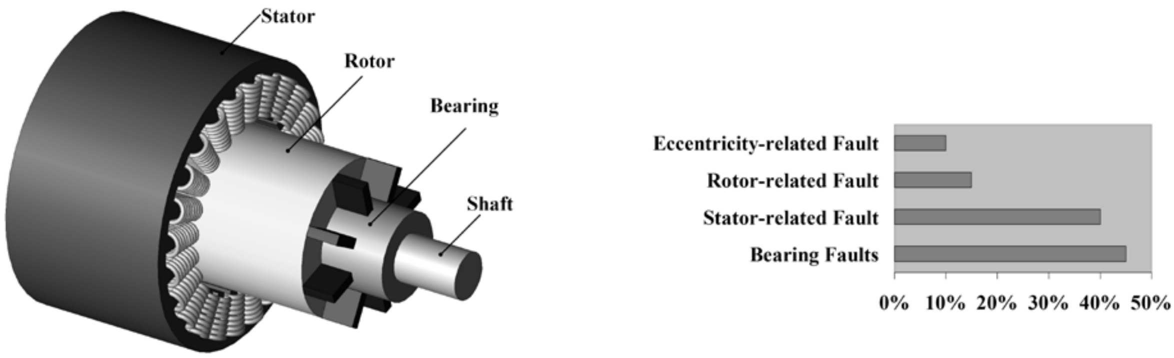


Figure 1: Exploded diagram of induction machine and the corresponding fault occurrence rates

Table 1: Power levels for charging (230V)

| | Electrical Faults | | Mechanical Faults | |
|---|---|---|---|---|
| | Rotor-related faults | Stator-related faults | Bearing faults | Eccentricity-related faults |
| Percentage | 5%-10% | 40%-50% | 40%-50% | 5%-10% |
| Cause | Thermal stress;<br>Magnetic stress;<br>Residual stress;<br>Dynamic stress;<br>Environmental stress;<br>Mechanical stress; | High temperatures;<br>Slack core lamination;<br>Contamination due to oil, moisture, and dirt;<br>Short circuit or starting stresses;<br>Electrical discharges; | Contamination and corrosion;<br>Improper lubrication;<br>Improper installation of bearing; | Unequal air gap between the stator and rotor; |
| Feature | Broken rotor bar;<br>Cracked rotor end rings;<br>Shorted rotor field windings; | Abnormal connection of stator windings;<br>Open or short circuit of stator windings; | Outer bearing race defect;<br>Inner bearing race defect;<br>Ball defect;<br>Train defect; | Bend shaft;<br>Static air-gap Irregularities;<br>Dynamic air-gap irregularities; |
| Frequency | $f_s = (\eta / p(1-s) \pm s) f$<br>Where $\eta / p$ =1,2,3, | $f_s = (n/ p(1-s) \pm k) f$<br>Where n=1, 2, k=1, 3, 5,.. | $f_{bea} = \lvert f \pm nf_v \rvert$<br>Where n=1, 2,..;<br>$f_v$ is vibration frequency | $f_{ecc} = [(N_r + n_d)(1-s)/ p \pm k$<br>Where $n_d$ is NO. of rotor bar; K=1,3,5,…. |
| Diagnostic approach | Spectrum analysis of motor current signature analysis;<br>FFT based; | Flux-based technique;<br>Motor current signature analysis;<br>Power decomposition; | Traditional spectrum analysis;<br>Envelop detection techniques | Spectrum analysis of motor current signature analysis; |

# 3 Hybrid-Excitation In-Wheel Motor Drive

The paper aims to investigate the hybrid-excitation fault-tolerant in-wheel motor drive. Figure 2 presents a schematic diagram of the hybrid-excitation in-wheel motor drive [26]. It mainly consists of a three-phase rectifier, a braking chopper, a three-phase full-bridge inverter, an H-bridge converter, and a three-phase hybrid-excitation in-wheel motor. As can be seen, the fault-tolerant operation of the motor drive is dependent of operation of the full-bridge inverter and the H-bridge converter. The three-phase full-bridge inverter aims to control the armature winding current independently, and the H-bridge converter has the capability of controlling the magnitude and direction of the DC field winding [27]-[28]. Hence, by controlling the three-phase full-bridge inverter and the H-bridge converter, the motor drive can perform the fault-tolerant operation.

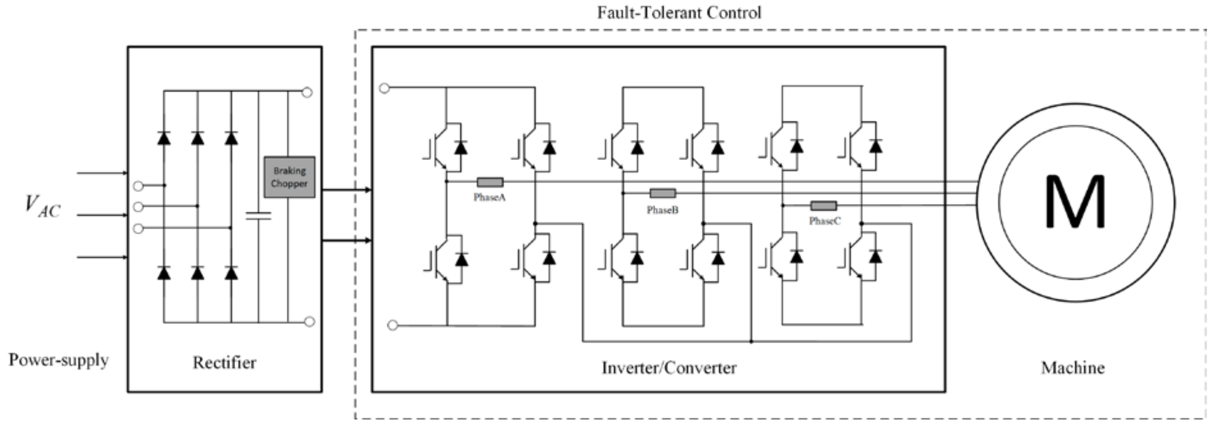


Figure 2: Hybrid-excitation in-wheel motor drive

Figure 3 shows the topologies of the proposed motors, which give a general presentation of the construction for the proposed machines. Three topologies are presented and compared in the study. Each topology has different construction in terms of rotor and stator. Type (a) is selected with the most common construction. While type (b) and type (c) are designed with in-wheel construction. Compared with type (c), it can be found that type (b) has double-lay stator construction, which consists of outer rotor, outer-layer stator, and inner-layer stator. Type (c) has only one outer-rotor and one stator.

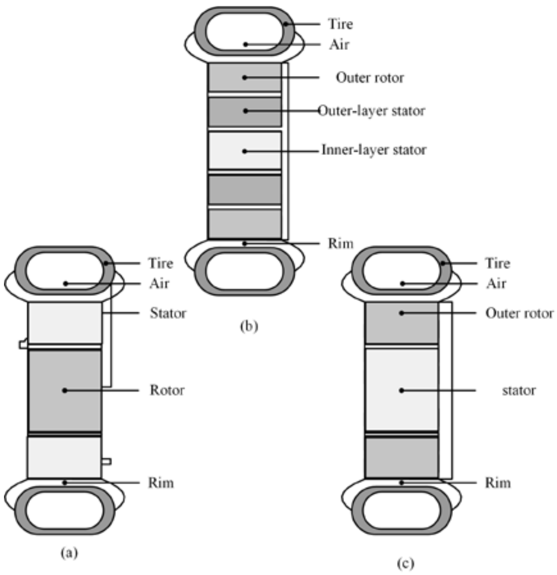


Figure 3: Motor topologies.

# 4 Performance Comparison of Fault-Tolerant Operation

As shown in Figure 4, the schematic diagrams of the proposed machines are presented [29]. It can be found that all proposed machines have DC windings as the hybrid field excitation. Furthermore, type (b) and type (c) have permanent-magnets (PMs) as the hybrid field excitation in addition to DC windings. Hence, with two sets of windings, the proposed machines possess the advantage of fault-tolerant capability.

## 4.1 Principle of Fault-Tolerant Operation

For the proposed machines, phase-current reconfiguration is applied to investigate the fault-tolerant operation. This approach aims to reconstruct the magnitude and phase angle of the phase currents to keep the magnetomotive force (MMF) constant after fault occurs. Open circuit fault is investigated in this study. In general, the three-phase current phasor is $120^{\circ}$ apart in space from each other with the same magnitude under normal operation. Under phase *A* open circuit fault, $i_a$ becomes zero, amplitudes of $i_b$ and $i_c$ are increased by 1.732, $i_b$ is lagged by $30^{\circ}$ and $i_c$ is led by $30^{\circ}$. The sum of MMF generated by three-phase current is given by:

$$\mathrm{MMF} = \mathrm{MMF_a} + \mathrm{MMF_b} + \mathrm{MMF_c} = Ni_a + aNi_b + a^2Ni_c \quad (1)$$

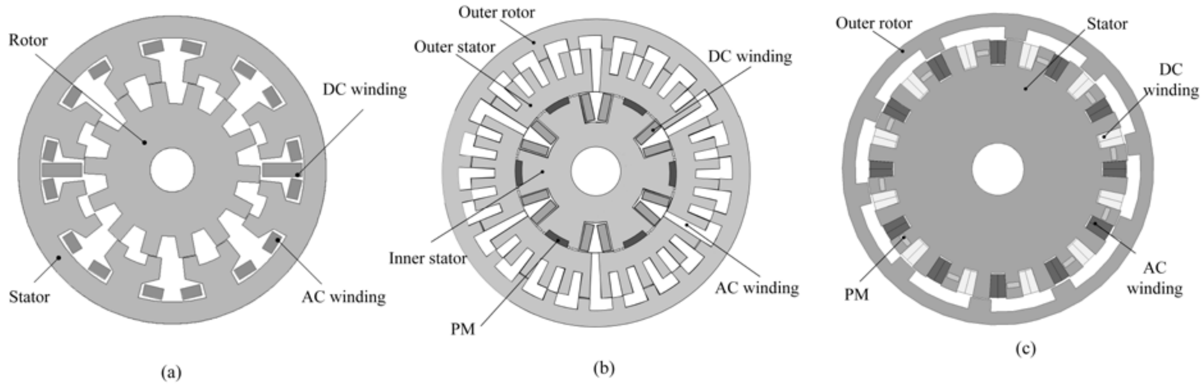


Figure 4: 2-D diagrams of proposed three machines

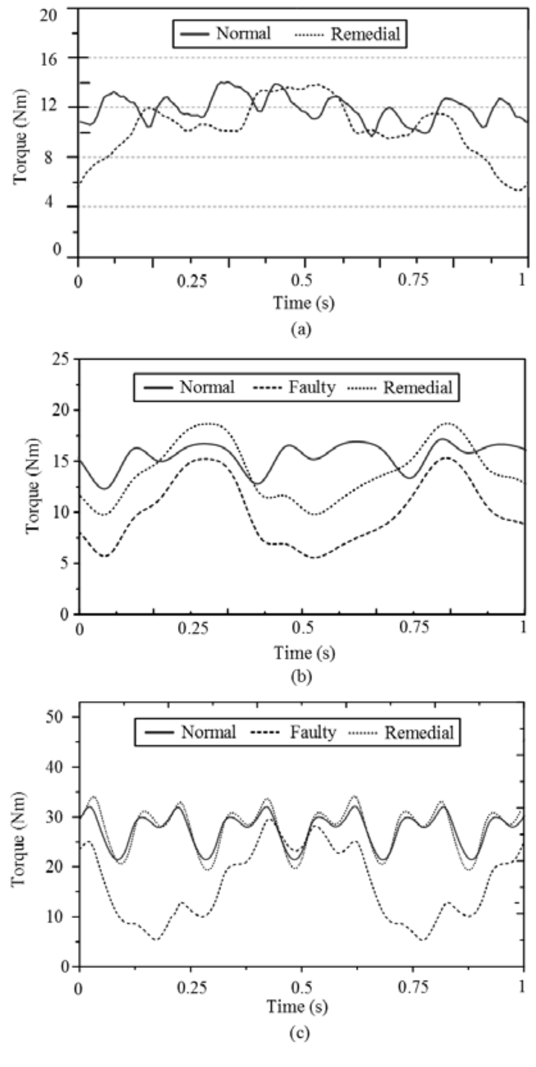


Figure 5: Fault-tolerant performance under normal, faulty, and remedial operation

## 4.2 Torque Performance Analysis

Table 2: Toque performance comparison

| Model | Operation modes | Torque ripple | Average torque |
|---|---|---|---|
| Type A | Normal | 34.5% | 12.2Nm |
| | Faulty | - | - |
| | Remedial | 82.4% | 11.9Nm |
| Type B | Normal | 32.5% | 15.1Nm |
| | Faulty | 87.6% | 10.5Nm |
| | Remedial | 58.6% | 14.5Nm |
| Type C | Normal | 39.1% | 27.4Nm |
| | Faulty | 96.3% | 17.9Nm |
| | Remedial | 41.8% | 27.3Nm |

By performing time-stepping finite element analysis (TS-FEA), the performances of the proposed operations can be calculated and analysed. The torque performance of the proposed machines under normal, faulty, and remedial operation are depicted in Figure 5. It can be found that the phase-current reconfiguration approach is able to remedy the open circuit fault and retrieve the torque level as the normal operation does.

The corresponding torque ripple rate and average torque results are quantitatively compared and summarized in Table 2. With type (a), the remedial operation can retrieve almost the same torque value as the normal operation, which shows around 12 Nm. But the torque ripple shows distinct fluctuation after remedial operation, which increases from 34.5% to 82.4 %. For type (b), the normal operation and remedial operation show almost the same average torque of around 15 Nm, the faulty average torque value is only 10.5 Nm. It is noted that the torque ripple drops from 87.7 % to 58.6 % after remedial phase-current reconfiguration. Similarly, type (c) successfully retrieves nearly the same average torque value with the remedial operation. And the torque ripple is 39.1% under normal operation and 41.8% under remedial operation. The faulty torque ripple is 96.3%. Hence, all the proposed machines have the capability of fault-tolerant operation. They are able to retrieve the torque level after phase-current reconfiguration. It should be noted that type (a) has slightly higher torque ripple than the other two modes, which is due to the reason that the other two machines have PMs as the hybrid field excitation in addition to DC windings.

# 5 Conclusion

In this paper, the performance comparison is conducted with three hybrid-excitation machines for fault-tolerant operation. The torque output is used as the fault indicator. By applying phase-current reconfiguration, the proposed machines are able to remedy the open-circuit fault and retrieve nearly the same torque level. By comparison, it reveals that machine type (a) has lower capability in controlling the torque ripple, which is owing to the lack of PM as the hybrid excitation source.

# Acknowledgments

This work was supported by a grant (Project No. HKU SFPBR 201210159060) from The University of Hong Kong, Hong Kong Special Administrative Region, China.

This work was also supported and funded by the grant of Basic Research Program (Project Code: CYJ20120831142942515), Science, Technology and Innovation Commission of Shenzhen Municipality (SZSTI), China.

# References

[1] C. Liu, K. T. Chau, J. Z. Jiang, L. Jian , "Design of a New Outer-Rotor Permanent Magnet Hybrid Machine for Wind Power Generation", *IEEE Trans. Magn.*, 44(6) 1494-1497, (2008).

[2] C. Liu, K. T. Chau, W. Li, "Comparison of Fault-tolerant Operation for Permanent-Magnet Hybrid Brushless Motor Drive", *IEEE Tran. Magn.*, 46(6) 1378-1381, (2010).

[3] S. Nandi, H.A. Toliyat, and X.D. Li, "Condition monitoring and fault diagnosis of electrical motors-a review," *IEEE Trans.Energy Convers.*, vol. 20, no. 4, pp. 719-729, Dec. 2005.

[4] B. Akin, C. Seungdeog, U. Orguner, and H. A. Toliyat, "A Simple Real-Time Fault Signature Monitoring Tool for Motor-Drive-Embedded Fault Diagnosis Systems," *IEEE Trans.Ind.Electron.*, vol. 58, no. 5, pp. 1990-2001, May 2011.

[5] G.J. Offer, V. Yufit, D.A. Howey, B. Wu, and N.P. Brandon, "Module design and fault diagnosis in electric vehicle batteries," *Journal of Power Sources*, vol. 206, pp. 383-392, May 2012.

[6] R.L. de Araujo Ribeiro, C.B. Jacobina, E.R. Cabral da Silva, and A M.N. Lima, "Fault detection of open-switch damage in voltage-fed PWM motor drive systems," *IEEE Trans.Power Electron.*, vol. 18, no.2, pp. 587-593, Mar 2003.

[7] M. El Hachemi Benbouzid, "A review of induction motors signature analysis as a medium for faults detection," *IEEE Trans.Electron.*, vol. 47, pp. 984-993, Aug/Sep 1998.

[8] C. Liu, K.T. Chau, and W. Li, "Loss analysis of permanent magnet hybrid brushless machines with and without HTS field windings," *IEEE Transactions on Applied Superconductivity*, vol. 20, no. 3, pp. 1077-1080, June 2010.

[9] M.A. Masrur, Z. Chen, and Y. Murphey, "Intelligent diagnosis of open and short circuit faults in electric drive inverters for real-time applications," *IET Power Electron.*, vol. 3, no. 2, pp. 279-291, Mar 2010.

[10] H.A. Toliyat, S. Nandi, and S. Choi, *Electric Machines: Modeling, Condition Monitoring, and Fault Diagnosis*: Taylor & Francis Group, 2012.

[11] W.X. Zhao, M. Cheng, K.T. Chau, and C.C. Chan, "Control and operation of fault-tolerant flux-switching permanent-magnet motor drive with second harmonic current injection," *IET Electric Power Applications.*, vol. 6, no. 9, pp. 707-715, Nov 2012.

[12] C. Liu and K.T. Chau, "A fault-tolerant permanent-magnet hybrid brushless motor drive for electric vehicles," Proceedings of IEEE Intermag, Sacramento, California, USA, Paper No. CW-01, May 2009.

[13] M. J. Devaney and L. Eren, "Detecting motor bearing faults," *IEEE Ins.Measurement Mag., IEEE*, vol. 7, no. 4, pp. 30-50, Dec 2004.

[14] C. Liu and K.-T. Chau, "Electromagnetic design and analysis of double-rotor flux-modulated permanent-magnet machines," *Progress In Electromagnetics Research*, vol. 131, pp. 81-97, 2012.

[15] C. Liu, K.T. Chau, and Z. Zhang, "Novel design of double-stator single-rotor magnetic-geared machines" IEEE Transactions on Magnetics, vol. 48, no. 11, pp. 4180-4183, November 2012.

[16] O. Duque, M. Perez, and D. Morinigo, "Detection of Bearing Faults in Cage Induction Motors Fed by Frequency Converter using Spectral Analysis of Line Current," *IEEE International Conference Electric Machines and Drives*, pp. 17-22, May 2005.

[17] X. Zhu, K.T, Chau, M.Cheng and C.Yu, “Designa and Control of a flux-controllable stator-permanenet magnet brushless motor drive,” *Journal of Applied Physics*, vol. 103, no. 7, pp. 1-3, paper no. 7F134, Apr 2008.

[18] K.T.Chau and Z. Wang, “Overview of power electronic drives for elecic vehicles,” *HAIT journal of Science and Engineering – B: Applied Sciences and Engineering*, vol. 2, no. 5-6, pp. 737-761, Dec 2005.

[19] S. Ibrahim, D.A. Asfani, and H. Takashi, "Simulation-based analysis of short circuit fault in parallel-series type hybrid electric vehicle," *Conference Advanced Power System Automation and Protection (APAP)*, pp. 2045-2049, Oct 2011.

[20] M. d. S. Aderiano, "Induction motor fault diagnostic and monitoring methods," Master, Electrical and Computer Enginnering, Marquette University, Milwaukee, Wisconsin, 2006.

[21] O. Ondel, E. Boutleux, and G. Clerc, "Thermal signatures for pattern recognition approach applied to induction motor diagnosis," *International Conference Condition Monitoring and Diagnosis (CMD).*, pp. 714-717, Sep 2012.

[22] C. Mo-Yuen and S.O. Yee, "Methodology for on-line incipient fault detection in single-phase squirrel-cage induction motors using artificial neural networks," *IEEE Trans.Energy Convers., no. 3*, vol. 6, pp. 536-545, Sep 1991.

[23] R. R. Schoen, T. G. Habetler, F. Kamran, and R. G. Bartfield, "Motor bearing damage detection using stator current monitoring," *IEEE Trans.Ind.Appl.*, vol. 31, no. 9, pp. 1274-1279, Nov/Dec 1995.

[24] C. Liu, K.T. Chau, W. Li, and C. Yu, “Efficiency optimization of a permanent-magnet hybrid brushless machine using DC field current control,” *IEEE Transactions on Magnetics*, vol. 45, no. 10, pp. 4652-4655, October 2009.

[25] B. Tabbache, M. E. H. Benbouzid, A. Kheloui, and J. M. Bourgeot, "Virtual-Sensor-Based Maximum-Likelihood Voting Approach for Fault-Tolerant Control of Electric Vehicle Powertrains," *IEEE Trans.Vehicle Tech.*, vol. 62, no. 3, pp. 1075-1083, Mar 2013.

[26] E. Sulaiman, T. Kosaka, N. Matsui, N., "High Power Density Design of 6-Slot–8-Pole Hybrid Excitation Flux Switching Machine for Hybrid Electric Vehicles," , *IEEE Transactions on Magnetics*, vol.47, no.10, pp. 4453-4456, Oct. 2011.

[27] M. T. Abolhassani and H. A. Toliyat, “Fault tolerant permanent magnet motor drives for electric vehicles,” in Proc. IEEE Int. Elec. Mach. Driv. Conf., pp. 1146–1152, May 2009.

[28] C. Liu, K. T. Chau, J. Z. Jiang, and L. Jian, “Design of a new outer-rotor permanent magnet hybrid machine for wind power generation,” IEEE Trans. Magn., vol. 44, no. 6, pp. 1494–1497, Jun. 2008.

[29] Y. Gong, K. T. Chau, J. Z. Jiang, C. Yu, and W. Li, “Design of doubly salient permanent magnet motors with minimum torque ripple,” IEEE Trans. Magn., vol. 45, no. 10, pp. 4704–4707, Oct. 2009.