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Design, Analysis and Control of a Double-Rotor Motor with Magnetic Differential for Electric Vehicles

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Abstract

In this paper, a double-rotor motor with magnetic differential, dubbed as magnetic differential (MagD) motor, is designed and analyzed to realize the differential function in electric vehicle. The proposed MagD motor adopts the magnetic steering (MS) field winding in the stator to regulate inversely the magnetic field in two rotors. Hence, the torques and speeds of two rotors can be differentiated during cornering by controlling the MS-field excitation. The proposed MagD motor and system take advantages of high compactness and lightless over conventional mechanical differential (MechD) system, and high safety and reliability over the two-or-more-motors direct-driven system or electronic differential (ElecD) system. The operation principle the proposed double-rotor MagD motor are first introduced, followed by the evaluation of the electromagnetic performances by finite-element analysis. Moreover, the MagD system model and control strategy are proposed based on the proposed MagD motor. Finally, the system operation performances are also simulated to further verify the MagD mechanism.

Keywords: Mechanical differential, electronic differential, magnetic differential, magnetic differential motor, magnetic steering.

1 Introduction

With ever-increasing concern on air pollution and environmental protection, electric vehicles (EVs), as the cleanest and greenest road transportation, have received a rapid development in recent years [1-6]. As one of the core parts of EVs, electric propulsion system conventionally adopts traction motor with a differential gear to drive the EV in straight and curvilinear movement, which is so called mechanical differential (MechD) [7, 8]. Besides, the electronic differential (ElecD) traction and steering system, which adopts independent control of two or more motors coupled to the driven wheels, is also put forward to replace the heavy and inefficiency MechD system [9]. Yet, some fatal accidents might occur in the ElecD system if there are any control, feedback or motor faults in the motors. In order to simultaneously retain the merits of high compactness and lightless of ElecD system, and high safety and reliability of MechD system, the magnetic differential (MagD) system is proposed recently [10], which adopts the magnetic steering (MS) field excitation to regulate the magnetic fields or torques in two rotors of the MS motor for driving and steering. The above three typical types of differential systems are illustrated in Fig. 1.

Meanwhile, as the core part of the MagD system, electrical machines are expected to operate with high efficiency, high torque density and high robustness [11-15]. Generally, permanent-magnet machines achieve most of above requirements due to the utilization of high-energy PM materials (PMs). Based on the location of PMs, the PM machines can be divided into three types, namely the rotor-PM machine, the stator-PM machine and the dual-PM machine [16-20]. Since the stator-PM machine enjoys the merits of high robustness and good heat dissipation capability compared with other two types, researchers have paid more and more attention in the stator-PM machine including topology design [21-25], control strategy [26-29] and principle analysis [30-33]. Among the stator-PM machine, the flux-switching PM machine (FSPM) has been the most promising and attractive candidate due to its higher torque density than other stator-PM machines such as the doubly-salient machine and the flux-reversal machine [34-36]. However, FSPM machine suffers from low cost-effectiveness with the usage of rare-earth PMs, poor flux-controllability and potential PM demagnetization risk [37-41]. To improve this situation, the flux-switching DC-field (FSDC) machine is proposed by replacing the DC-field windings with PMs in FSPM machine [42-44].

In this paper, extended from the FSDC machine topology, a double-rotor motor with magnetic differential, dubbed as magnetic differential (MagD) motor, is designed and analyzed with emphasis on its operation principle and electromagnetic performances. In particular, the MagD system model and control strategy are proposed based on the MagD motor. Consequently, the MagD system operation performances are simulated and evaluated based on the proposed system model and control strategy, hence verifying the MagD mechanism.

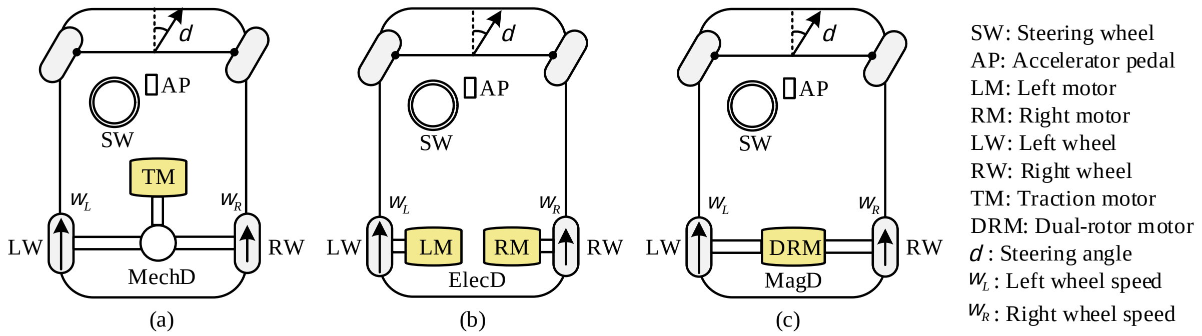

Fig. 1. Differential mechanism configurations: (a) Conventional MechD system. (b) Conventional ElecD system. (c) Proposed MagD system.

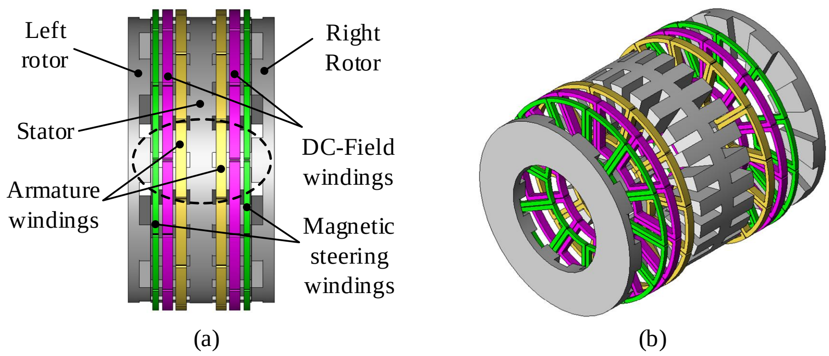

Fig. 2. Proposed double-rotor MagD motor. (a) Motor topology. (b) Exploded view.

2 Proposed Magnetic Differential Motor

2.1 Motor Topology

Fig. 2 shows the proposed double-rotor MagD motor with its motor topology and exploded view. It is derived from the profound three-phase 12r/10s flux switching DC (FSDC) machine [45-48]. However, the MagD motor adopts sandwiched-stator sided-rotors structure. It should be noted that two rotors are independently coupled to the wheels via shaft. Particularly, the magnetic steering (MS) windings are incorporated in the stator to inversely regulate the magnetic fields in two rotors so that the torques of two rotors can be differentiated during cornering by controlling the MS-field excitation.

2.2 Operation Principle

To further illustrate the operation principle of MagD motor, the magnetic flux patterns are depicted in Fig. 3. In straight motion, the MS windings are not injected with currents so that the DC-flux produced by DC-field windings symmetrically distributes in two rotors, and hence achieving equal torques in two rotors for straight motion. During cornering, the MS windings take effects to produce MS flux so that total magnetic flux in one rotor is strengthened while the other is weakened, and hence achieving torque difference between two rotors for cornering.

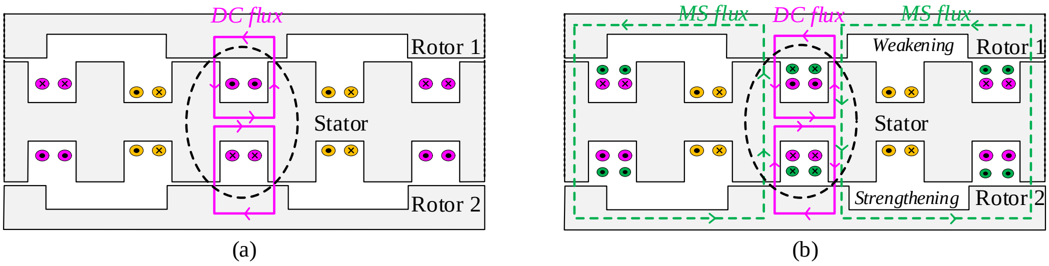

Fig. 3. Operation principle of MagD motor. (a) Without MS-field for straight motion. (b) With MS-field for cornering.

2.3 Electromagnetic Performance

To evaluate the electromagnetic performance of the proposed MagD motor, the electromagnetic field analysis is conducted in the FEM-based software – JMAG Designer. The key design parameters of the proposed MagD motor are listed in Table 1.

Table 1: Key Design Parameters of Proposed MagD Motor

Outside diameter: 381 mm	No. of rotor poles: 10
Inside diameter: 210 mm	Slot-filling factor: 0.4
Axial length: 195 mm	Armature winding coil turns: 65
Airgap length: 0.5 mm	DC-field winding coil turns: 65
No. of stator poles: 12	MS-field winding coil turns: 10

Firstly, the magnetic field distributions of proposed MagD motor under no-load condition is shown in Fig. 4. It can be seen that, without MS-field excitation, the magnetic flux symmetrically passes in the two rotors with same magnetic flux density. Meanwhile, when the MS-field is positively applied, the magnetic flux density of the left rotor is weakened while that of the right rotor is enhanced. The situation is reversed when the negative MS-field is applied. Thus, the simulated results well agree with the above theoretical analysis and verify the MS-field regulation effects.

Secondly, the no-load flux linkages and back-EMF of phase coils are also analysed and shown in Fig. 5 under the DC-field excitation alone of 6 A/mm^2 and rotation speed of 300 rpm. It can be seen that the flux linkages and back-EMFs of all phase windings are well balanced and symmetrical with bipolar characteristics, which well agree with those of the profound FSDC machine. Besides, the flux linkages and back-EMFs of two rotos are identical under only DC-field excitation condition, which well matches with previous theoretical analysis. Therefore, it can be predicted that when the MS-field is applied, the flux linkages and back-EMFs are inversely varied in two rotors, resulting in differential torque between two rotors for curvilinear movement.

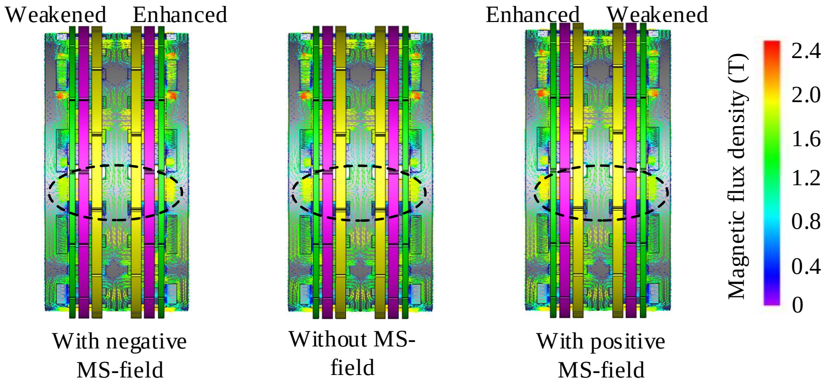

Fig. 4. No-load magnetic field distributions of MagD motor.

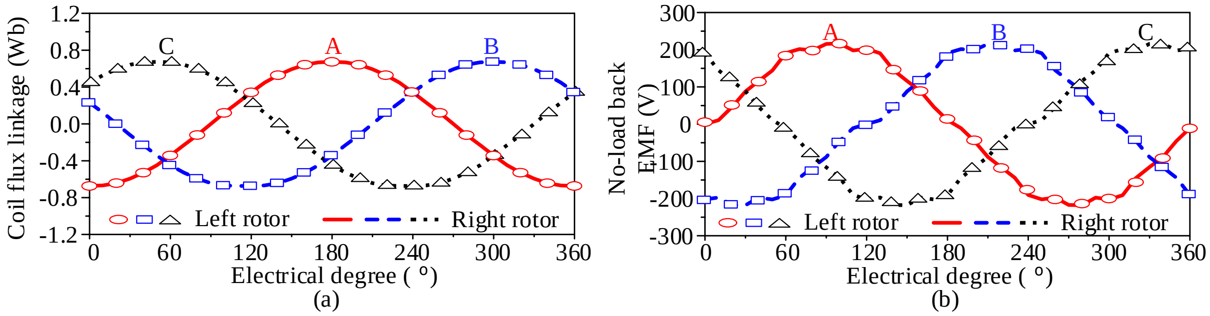

Fig. 5. No-load performance without MS-field. (a) Coil flux linkages waveforms. (b) Back-EMF waveforms.

Lastly, the torque performances of the proposed MagD motor under armature coil of 6 A/mm^2 are simulated as shown in Fig. 6. It can be seen that the steady torques of two rotors are identical and both about 175 Nm with DC-field excitation alone of 6 A/mm^2. Meanwhile, the torque ripples of two rotors are both about 13.5 % which is acceptable for EV application. Moreover, the differential torque between two rotors are simulated under different MS-field current densities. One can see that the differential torque can reach about 40 Nm under 6 A/mm^2. Therefore, with the utilization of the MS-field and differential torque, the speeds of two rotors can be differentiated at certain level to steer the EV with specified turning angle during cornering, which will further be introduced in the following system model.

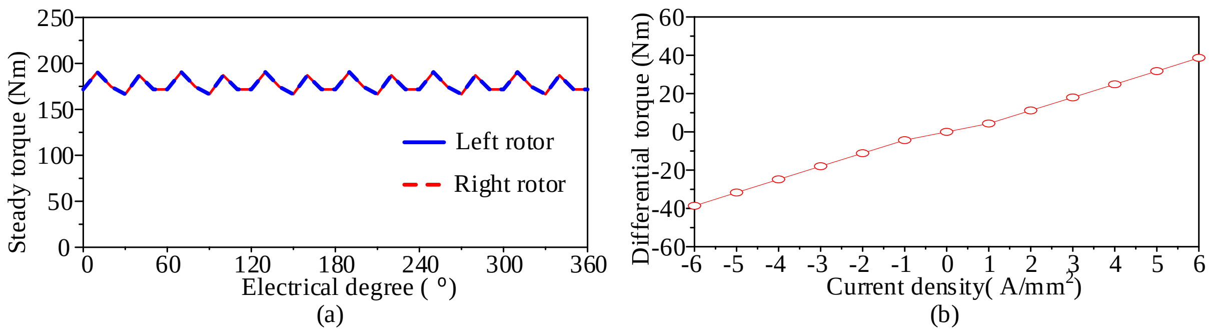

Fig. 6. Torque waveforms. (a) Steady torque without MS-field. (b) Differential torque with different MS-field current densities.

3 MagD System Modeling

According to the Ackerman-Jeantand model [49] and the proposed MagD model in Fig. 1(c), the electronic differential model can be simplified and derived. The angular speeds of two wheels can be expressed as:

$$\begin{cases} \omega_L = \dfrac{v_h}{r} + \dfrac{\Delta\omega}{2} \\ \omega_R = \dfrac{v_h}{r} - \dfrac{\Delta\omega}{2} \\ \Delta\omega = \dfrac{v_h \cdot d_w}{r} \dfrac{\tan\delta}{L_w} \end{cases} \tag{1}$$

where ω_L is left rotor angular speed, ω_R is right rotor angular speed, v_h is the vehicle speed, r is the radius of the curve, d_w is the width of vehicle, L_w is the length of vehicle, and δ is the steering angle. It should be mentioned that this above electronic differential model can be utilized to steer the EV both for ElecD and MagD systems. However, the proposed MagD system takes the advantages of lighter structure and higher reliability than the ElecD system as stated earlier.

Then, the vehicle dynamic model is also built and can be expressed as [50]:

$$\begin{cases} F_{res} = F_{sld} + F_{aero} + F_{slope} \\ F_{sld} = \mu M g \\ F_{aero} = \dfrac{1}{2} \rho C_x S v_h^2 \\ F_{slope} = Mg \sin\alpha \end{cases} \tag{2}$$

where F_{res} is the total resistance force, F_{aero} is the aerodynamic drag force, F_{slope} is the slope resistance, μ is the sliding friction coefficient, M is the total mass of the EV, ρ is the air density, C_x is the aerodynamic drag coefficient, S is the frontal area of the EV, v_h is the vehicle speed, and α is the slope of the road.

Furthermore, based on the differential model (1), the control strategy is proposed for the MagD system. Based on the classic PM brushless machine *d-q* coordination transformation, the torque equations for two rotors can be expressed as:

$$T_e = \frac{3}{2} p(\lambda_m i_q + (L_d - L_q) i_d i_q) = \frac{3}{2} p \lambda_m i_q = \frac{3}{2} p(\lambda_{DC} + \lambda_f) i_q \tag{3}$$

where λ_m is the resultant magnetic flux linkage, L_d and L_q are the *d-axis* and *q-axis* inductances (considered equal for the proposed MagD motor), i_d and i_q are the *d-axis* and *q-axis* component of armature currents, p is the pole-pair number, λ_{DC} and λ_f are the flux linkages produced by DC-field winding and MS-field windings, respectively. Thus, with MS-field excitation and same armature currents, λ_m in two rotors can be varied and hence different steady torque can be developed in two rotors during cornering.

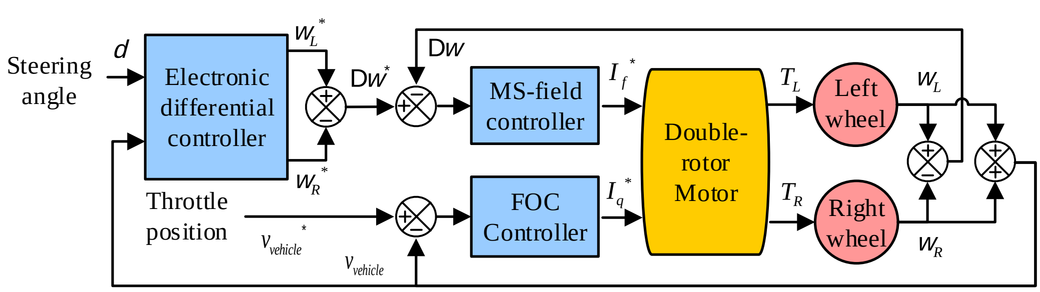

Fig. 7. Control diagram for MagD system.

Lastly, the whole system control diagram is proposed as shown in Fig. 7. The differential signal between speed differential reference $\Delta\omega^*$ which is given by the electronic differential controller based on (1), and speed differential feedback from two wheels, is fed into the MS-field controller to control the MS-field current I_f^* and regulate the differential torque. Meanwhile, the differential signal between vehicle speed reference $v_{vehicle}^*$ and vehicle speed feedback $v_{vehicle}$ is fed into the FOC controller to regulate armature windings i_q current and the average steady torque for motors. As a result, the left rotor toque T_L and right rotor torque T_R can be developed and differentiated so that the speeds of two rotors can be varied during cornering.

4 MagD System Performance

Based on (1) – (3) and Fig. 3, the straight and curvilinear motion of an EV can be simulated by using MATLAB/Simulink. The key parameters of the EV model are listed in Table 2 while the vehicular performances of the MagD system under various turning angles are simulated as shown in Fig. 8.

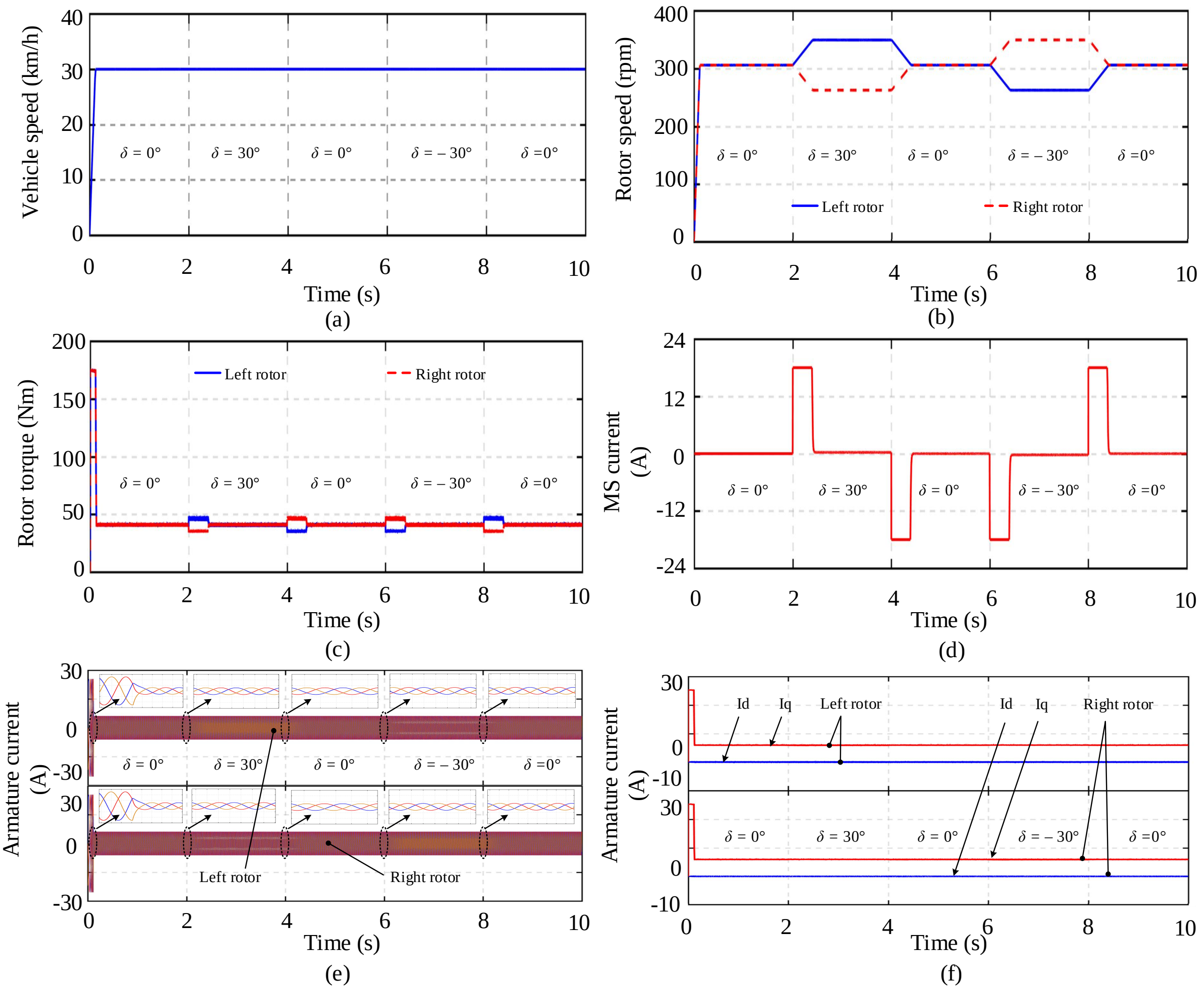

Fig. 8. Vehicular performances of MagD system under various turning angles. (a) Speed of EV. (b) Speeds of rotors. (c) Torques of rotors. (d) MS-field current. (e) Armature currents. (f) I_d and I_q of armature windings.

During the motion, it is assumed that the EV runs at a certain vehicle speed of 30 km/h after starting up, which also well agrees with the result in Fig. 8(a). At δ= 30º, the EV is turning right with an angle of 30º while δ= -30º, the EV is turning left with an angle of 30º instead. It can be seen that from Fig. 8(b)-(d) during cornering the speeds of two rotors are differentiated accordingly due to the differential torque between two rotors by controlling the MS-field currents. It should be noted that the MS-field current I_f serves as the single parameter to differential the torques between two rotors since the amplitudes of armature currents, I_d

and I_q keep constant during cornering, as shown in Fig. 8 (d)-(f). Actually, various turning angles can be also achieved by controlling the MS-field current I_f, provided that the speeds of two rotors reach the requirements in (1). Therefore, the operation performances well agree with the previous machine and system analysis, and hence verifying the proposed MagD motor, system and control strategy.

Table 2: Key Parameters of EV model

Total mass M : 1960 kg	Vehicle width d_w : 1.9 m
Sliding friction coefficient m: 0.015	Vehicle length L_w : 3.9 m
Air density r : 1.184 kg/m^3	Wheel radius R: 0.26 m
Aerodynamic drag coefficient C_x : 0.25	Slope angle a : 0
Frontal area: 2.2 m^2	Air temperature T: 25 ºC

5 Conclusion

In this paper, a double-rotor MagD motor is proposed while its system model and control strategy are also developed to realize the MagD mechanism for EVs. The key is to utilize the MS-field current to inversely regulate the magnetic field in two rotors. Consequently, the torques and speeds of two rotors can be differentiated with the control of MS-field current. Both the MagD motor electromagnetic performances and MagD system operation performances are evaluated, which well verifies the validity of the proposed MagD mechanism for EVs.

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References

[1] K. T. Chau, C. Jiang, W. Han, and C. H. T. Lee, "State-of-the-art electromagnetics research in electric and hybrid vehicles," *Progress in Electromagnetics Research*, vol. 159, pp. 139-157, 2017.

[2] K. T. Chau, C. C. Chan, and C. Liu, "Overview of permanent-magnet brushless drives for electric and hybrid electric vehicles," *IEEE Transactions on Industrial Electronics,* vol. 55, no. 6, pp. 2246-2257, Jun. 2008.

[3] Z. Q. Zhu and D. Howe, "Electrical machines and drives for electric, hybrid, and fuel cell vehicles," *Proceedings of the IEEE,* vol. 95, no. 4, pp. 746-765, Apr. 2007.

[4] C. H. T. Lee, K. T. Chau, and C. Liu, "Design and analysis of an electronic-geared magnetless machine for electric vehicles," *IEEE Transactions on Industrial Electronics,* vol. 63, no. 11, pp. 6705-6714, Nov. 2016.

[5] K. T. Chau and W. Li, "Overview of electric machines for electric and hybrid vehicles," *International Journal of Vehicle Design,* vol. 64, pp. 46-71, 2014.

[6] C. H. T. Lee, C. Liu, and K. T. Chau, "A magnetless axial-flux machine for range-extended electric vehicle," *Energies*, vol. 7, no. 3, pp. 1483-1499, Mar. 2014.

[7] Y. Zhou, S. Li, X. Zhou, and Z. D. Fang, "The control strategy of electronic differential for EV with four in-wheel motors," in *2010 Chinese Control and Decision Conference, IEEE,* pp. 4190-4195, May 2010.

[8] K. T. Chau, *Electric Vehicle Machines and Drives: Design, Analysis and Application*: John Wiley & Sons, 2015.[9] J. Kim, C. Park, S. Hwang, Y. Hori, and H. Kim, "Control algorithm for an independent

motor-drive vehicle," *IEEE Transactions on Vehicular Technology,* vol. 59, no. 7, pp. 3213-3222, Sep. 2010.

[10] C. H. T. Lee, K. T. Chau, and L. Cao, "Development of reliable gearless motors for electric vehicles," *IEEE Transactions on Magnetics*, vol. 53, no. 11, pp. 1-8, Nov. 2017.

[11] K. T. Chau, W. Li and C. H. T. Lee, "Challenges and opportunities of electric machines for renewable energy," *Progress In Electromagnetics Research B*, vol. 42, pp. 45-74, 2012.

[12] K. T. Chau, "Overview of renewable energy machines: existing and emerging technologies," *Studies in Science and Technology*, vol. 6, no. 1, pp. 5-14, Jun. 2017.

[13] M. Cheng, W. Hua, J. Zhang, and W. Zhao, "Overview of stator-permanent magnet brushless machines," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 11, pp. 5087-5101, Nov. 2011.

[14] C. H. T. Lee, K. T. Chau, C. Liu, D. Wu, and S. Gao, "Quantitative comparison and analysis of magnetless machines with reluctance topologies," *IEEE Transactions on Magnetics*, vol. 49, no. 7, pp. 3969-3972, Jul. 2013.

[15] C. Liu, K. T. Chau, and J. Jiang, "A permanent-magnet hybrid brushless integrated starter-generator for hybrid electric vehicles," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 12, pp. 4055-4064, Dec. 2010.

[16] H. Fan, K. T. Chau, C. Liu, L. Cao, and T. W. Ching, "Quantitative comparison of novel dual-PM linear motors for ropeless elevator system," *IEEE Transactions on Magnetics*, vol. 54, no. 11, pp.1-6, Jun. 2018,

[17] Q. Wang, S. Niu, and L. Yang, "Design optimization and comparative study of novel dual-PM excited machines," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 12, pp. 9924-9933, Dec. 2017.

[18] M. Cheng, K. T. Chau, and C. C. Chan, "Design and analysis of a new doubly salient permanent magnet motor," *IEEE Transactions on Magnetics*, vol. 37, no. 4, pp. 3012-3020, Jul. 2001.

[19] H. Fan, K. T. Chau, L. Cao, and C. Jiang, "Design and analysis of a new bipolar-flux DSPM linear machine," *IEEE Transactions on Energy Conversion*, vol. 33, no. 4, pp. 2081-2090, Dec.2018.

[20] P. Su, W. Hua, Z. Wu, P. Han, and M. Cheng, "Analysis of the operation principle for rotor-permanent-magnet flux-switching machines," *IEEE Transactions on Industrial Electronics,* vol. 65, no. 2, pp. 1062-1073, Feb. 2018.

[21] Y. Gong, K. T. Chau, J. Jiang, C. Yu, and W. Li, "Design of doubly salient permanent magnet motors with minimum torque ripple," *IEEE Transactions on Magnetics*, vol. 45, no. 10, pp. 4704-4707, Oct. 2009.

[22] C. Liu, K. T. Chau, J. Z. Jiang, and S. Niu, "Comparison of stator-permanent-magnet brushless machines," *IEEE Transactions on Magnetics,* vol. 44, no. 11, pp. 4405-4408, Nov. 2008.

[23] D. J. Evans and Z. Q. Zhu, "Novel partitioned stator switched flux permanent magnet machines," *IEEE Transactions on Magnetics*, vol. 51, no. 1, pp. 1-14, Jan. 2015.

[24] Y. Fan, K. T. Chau, and M. Cheng, "A new three-phase doubly salient permanent magnet machine for wind power generation," *IEEE Transactions on Industry Applications*, vol. 42, no. 1, pp. 53-60, Feb. 2006.

[25] M. Cheng, Y. Fan, and K. T. Chau, "Design and analysis of a novel stator-doubly-fed doubly salient motor for electric vehicles," *AIP Journal of Applied Physics*, vol. 97, no. 10, pp. 1-3, May 2005.

[26] X. Zhu, K. T. Chau, M. Cheng, and C. Yu, "Design and control of a flux-controllable stator-permanent magnet brushless motor drive," *Journal of Applied Physics,* vol. 103, p. 07F134, Apr. 2008.

[27] Y. Wang and Z. Deng, "Hybrid excitation topologies and control strategies of stator permanent magnet machines for DC power system," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 12 , pp.4601-4616, Dec. 2012.

[28] W. Zhao, M. Cheng, K. T. Chau, W. Hua, H. Jia, J. Ji, and W. Li, "Stator-flux-oriented fault-tolerant control of flux-switching permanent-magnet motors," *IEEE Transactions on Magnetics,* vol. 47, no. 10, pp. 4191-4194, Oct. 2011.

[29] M, Cheng, K. T. Chau, C. C. Chan, and S. Qiang, "Control and operation of a new 8/6-pole doubly salient permanent-magnet motor drive," *IEEE Transactions on Industry Applications,* vol. 39, no. 5, pp. 1363-1371, Sep. 2003.

[30] Y. Du, F. Xiao, W. Hua, X. Zhu, M. Cheng, L. Quan, and K. T. Chau, "Comparison of flux-switching PM motors with different winding configurations using magnetic gearing principle," *IEEE Transactions on Magnetics,* vol. 52, no. 5, pp. 1-8, May 2016.

[31] K. T. Chau, M. Cheng, and C. C. Chan, "Nonlinear magnetic circuit analysis for a novel stator-doubly-fed doubly-salient machine," *IEEE Transactions on Magnetics*, vol. 38, no. 5, pp. 2382-2384, Sep. 2002.

[32] J. Chen and Z. Zhu, "Winding configurations and optimal stator and rotor pole combination of flux-switching PM brushless AC machines," *IEEE Transactions on Energy Conversion*, vol. 25, no. 2, pp. 293-302, Jun. 2010.

[33] F. Li, K. T. Chau, C. Liu, and Z. Zhang, "Design principles of permanent magnet dual-memory machines," *IEEE Transactions on Magnetics*, vol. 48, no. 11, pp. 3234-3237, Nov. 2012.

[34] K. T. Chau, J. Jiang, and W. Yong, "A novel stator doubly fed doubly salient permanent magnet brushless machine," *IEEE Transactions on Magnetics*, vol. 39, no. 5, pp. 3001-3003, Sep. 2003.

[35] F. Yu, M. Cheng, K. T. Chau, and F. Li, "Control and performance evaluation of multiphase FSPM motor in low-speed region for hybrid electric vehicles," *Energies*, vol. 8, no. 9, pp. 10335-10353, Sep. 2015.

[36] Y. Gao, R. Qu, D. Li, J. Li, and G. Zhou, "Consequent-pole flux-reversal permanent-magnet machine for electric vehicle propulsion," *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 4, pp. 1-5, Jun. 2016.

[37] C. H. T. Lee, K. T. Chau, C. Liu, T. W. Ching, and F. Li, "A high-torque magnetless axial-flux doubly salient machine for in-wheel direct drive applications," *IEEE Transactions on Magnetics*, vol. 50, no. 11, pp. 1-5, Nov. 2014.

[38] C. H. T. Lee, K. T. Chau, and C. C. Chan, "Comparison of flux-switching machines with and without permanent magnets," *Chinese Journal of Electrical Engineering*, vol. 1, no. 1, pp. 78-84, Dec. 2015.

[39] W. Zhao, K. T. Chau, M. Cheng, J. Ji, and X. Zhu, "Remedial brushless AC operation of fault-tolerant doubly-salient permanent-magnet motor drives," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 6, pp. 2134-2141, Jun. 2010.

[40] Z. Q. Zhu, Z. Z. Wu, D. J. Evans, and W. Q. Chu, "A wound field switched flux machine with field and armature windings separately wound in double stators," *IEEE Transactions on Energy Conversion*, vol. 30, no. 2, pp. 772-783, Jun. 2015.

[41] C. H. T. Lee, K. T. Chau, and C. Liu, "Design and analysis of a dual-mode flux-switching doubly salient DC-field magnetless machine for wind power harvesting," *IET Renewable Power Generation*, vol. 9, no. 8, pp. 908-915, Nov. 2015.

[42] F. Lin, K. T. Chau, C. H. T. Lee, and C. Liu, "Fault signature of a flux-switching DC-field generator," *IEEE Transactions on Magnetics*, vol. 51, no. 11, pp. 1-4, Nov. 2015.

[43] Y. Fan and K. T. Chau, "Design, modeling, and analysis of a brushless doubly fed doubly salient machine for electric vehicles," *IEEE Transactions on Industry Applications*, vol. 44, no. 3, pp. 727-734, May 2008.

[44] Y. Tang, J. Paulides, T. Motoasca, and E. Lomonova, "Flux-switching machine with DC excitation," *IEEE Transactions on Magnetics*, vol. 48, no. 11, pp. 3583-3586, Nov. 2012.

[45] C. H. T. Lee, K. T. Chau, C. Liu, and C. C. Chan, "Overview of magnetless brushless machines," *IET Electric Power Applications*, vol. 12, no. 8, pp. 1117-1125, Aug. 2018.

[46] Y. Wang, J. Sun, Z. Zou, Z. Wang, and K. T. Chau, "Design and analysis of a HTS flux-switching machine for wind energy conversion," *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3, pp. 1-4, Jun. 2013.

[47] C. H. T. Lee, W. K. Lee, and K. T. Chau, "Development of partitioned stator flux-switching machines for electric vehicles," *Journal of International Council on Electrical Engineering*, vol. 7, no. 1, pp. 276-281, Jan. 2017.

[48] Y. Wang, M. Chen, T. W. Ching, and K. T. Chau, "Design and analysis of a new HTS axial-field flux-switching machine," *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 3, pp. 1-5, Jun. 2015.

[49] A. Draou, "Elect in-wronic differential speed control for twoheels motors drive vehicle," in *Fourth International Conference on Power Engineering, Energy and Electrical Drives*, pp. 764-769, May 2013.

[50] T. D. Gillespie, *Fundamentals of Vehicle Dynamics. Warrendale*, PA: Society of Automotive Engineers, Inc., 1992.

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