Hao LIU, Xinbo CHEN, Xinjian WANG

Department of Electric Drive System, Clean Energy Vehicle Engineering Centre, Tongji University

Overview and Prospects on Distributed Drive Electric Vehicles and Its Energy Saving Strategy

***Abstract**. Significant research has been directed towards developing the electric vehicle (EV) to reduce the energy consumption and exhaust emissions. Focusing on the distributed drive electric vehicles (DDEVs) offering flexible chassis arrangement and brief drive lines, this paper gives an overview about the basic topologies and characteristics. The energy saving strategy to increase driving range is also discussed. Existing problems and prospects for future research on improvements of topologies, optimized torque distribution and drive system efficiency are analysed as well.*

***Streszczenie.** W artykule zaprezentowano przegląd wiedzy na temat nowej generacji samochodów elektrycznych – samochodów z wieloma napędami elektrycznymi – DDEV (distributed drive electric vehicles). Omówiono topologię i charakterystyki tego typu pojazdów oraz strategie oszczędności energii. (**Nowa generacja samochodów elektrycznych z wieloma napędami – DDEV (distributed drive electric vehicles)**)*

Keywords: distributed drive electric vehicles, topologies, torque distribution, efficiency.
Słowa kluczowe: pojazdy elektryczne, pojazdy DDEV

Introduction

Along with the development of the society and the science technology, not only has vehicle become the indispensable transportation in people's daily life but also has led to excess energy consumption and environmental contamination, which attracts much more concerns of the world. The required cut in CO2 and other contaminant emissions may not be achievable solely through improvements to the traditional internal combustion engine vehicle (ICEV) or using alternative fuels like biofuels. New solutions need exploring and these problems can be solved by EV technology. [1-4]

Within various EV topologies, DDEVs [5-7] with characteristics of higher efficiency drive systems and control flexibility have been considered as promising vehicles with potentials in emissions and energy consumption reductions. The electric motors of DDEVs are not only information units providing speed and torque signals, but also control units regulating drive or brake torques. As a result, DDEV can achieve higher energy efficiency and motion control performance which are further beyond the capabilities of ICEV.

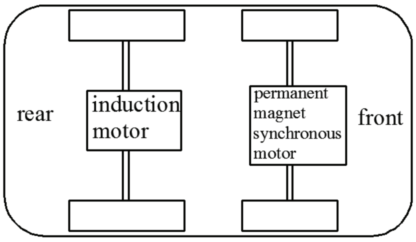
In order to make EV more widely used, many key techniques of the vehicle itself, such as quick charging management, increasing driving range, enhancing safety and driving performance, must be solved in acceptance of infrastructure establishment like charging stations. Besides, the drive system efficiency of DDEV which directly affecting the driving range is an essential factor needing in-depth studies.

Topologies and Characteristics of EV Drive System

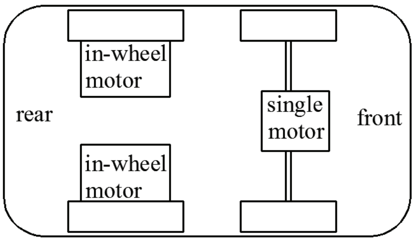
According to the topology of drive system, EV is divided into two types: the integrated drive electric vehicle (IDEV) and DDEV. IDEV is derived from ICEV and they are similar in transmissions, drive drafts, differentials and etc.

From the world wide aspect, IDEV is in the majority among EV platforms, such as E-MINI, Ford FCV P2000 and Nissan Leaf [8-10]. And we Clean Energy Vehicle Engineering Centre (CEVEC) in Tongji University also have done much research about IDEV recent years, such as Audi A6LE and BMW ECHO Project.

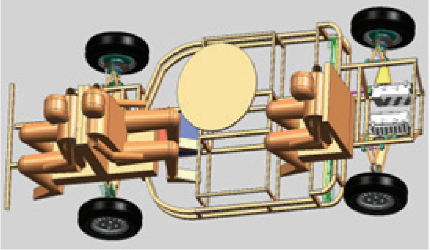
On the other hand, DDEV which is still in the prototyping and pre-market phases includes several topologies (as shown in Fig.1). Nobuyoshi Mutoh, et al. [7, 11-12] have developed a front and rear wheel independent drive type electric vehicle (FRID EV), by arranging a permanent magnet synchronous motor and an induction motor for driving the front and rear wheels respectively, which is possible to improve failsafe control and drivability. GM Sequel's "Electric AWD" architecture [13-15], which has a single electric motor (60kw) to drive the front wheels and in-wheel motors (2*25kw) to drive each of the rear wheels, makes the total power up to 110 kW. And with fuel cell and high voltage lithium ion battery system, Sequel provides satisfying acceleration ability and driving range for more than 300 miles on public roads under typical driving conditions without refueling. Meanwhile, all-wheel drive vehicles (IWDVs) are prevalent research objectives, for example, Luciole [16] and IZA [17], especially eight-wheel-motor-drive vehicles like KAZ [18] and Eliica [19], and also "Chun Hui" series which have been developed in CEVEC.



（a）FRID EV



（b）Sequel



（c）Chun Hui Explorer

Fig. 1 Topologies of DDEVs

From the above references it can be seen that, the choices and allocations of electric motors are very flexible in DDEV chassis arrangement, and there are several key features that clearly distinguish DDEV from ICEV and IDEV as well.

First of all, the electric motor technology allows fast and accurate torque control, compared with ICE, and the electric motor system is much more efficient than ICE system. The electric motor system, reduction gears, wheel bearing and mechanical brake can be assembled as a modular of aggressive power density and performance, which is to the benefit of enhancing vehicle drivability [20-21]. Moreover, DDEV especially IWDV has a compact and simple drivetrain due to the exclusion of transmissions and differentials which are indispensable in ICEV and IDEV, which is not only favor of energy loss reduction and system efficiency increase but also facilitates chassis arrangement and inspires new characteristics of vehicle body design that of explicit difference to ICEV or IDEV. Also, compared with ICEV and IDEV, ABS, TCS, ASR and DYC of DDEV can be more easily achievable by controlling the driving/braking torque of each wheel independently and precise measurements of the rotational speed of each wheel, which improving vehicle maneuverability and safety on different road conditions [23-30]. In addition, DDEV can maximize the regeneration of braking energy, which consequently improves the driving range [31].

Energy saving strategy of distributed drive electric vehicle

At present, the limited driving range of EV still remains a challenge for mainstream OEM car manufacturers and institutes due to reasons such as lower energy density and high price of battery packs and the drawback of charging time by the limitation of battery technology. With certain capacity of onboard battery, the driving range is highly related to energy efficiency of the vehicle. That is why strong emphasis is supposed to be placed on energy saving strategy research for DDEV.

I. Torque distribution for energy saving strategy

While much research on torque distribution strategy of DDEV have paid attention to active safety related object such as driving stability up to date, much fewer studies contribute to the optimized torque distribution (OTD) of driving/braking torque for reducing energy consumption and enhancing driving efficiency.

Nobuyoshi Mutoh and co-workers [7, 11-12] investigated into load transferring and slip rate control of FRID EV during acceleration and braking under various road conditions. They optimized distribution ratio of driving/braking torque on front and rear wheels, proving that the energy consumption could be reduced by 30% and the acceleration and braking performance were improved simultaneously. Fan JJ et al. [39] proposed an economical control method for an EV with three driving axles. The energy efficiency was increased by 13.98% from 59.11% up to 73% by using a distribution ratio optimized by complex method instead of the constant 1:1:1 ration. As to the more prevalent IWDV, Yu Zhuopin et al. [40] and Wang Bo et al. [41] have developed economical torque distribution strategies and simulation results showed that by OTD strategies, the electric motors worked closely to the highest efficiency region and the overall efficiencies could be increased by 3% and 6%, respectively. Unfortunately, all aforementioned methods which do not take cornering into consideration are only applicable to straight driving situations.

During cornering motions, the direction of tire traveling velocity is slightly differed from that of tire rolling velocity, which causes tire slip velocity (as shown in Fig. 2).

The slip velocity V^s can be defined as the difference between rolling velocity V^r and traveling velocity V, or

(1) $$V^s = V^r - V.$$

And the slip velocity causes friction loss on the surface between the tire and ground, defining the energy loss W due to the tire friction as

(2) $$W = Q^s \bullet V^s,$$

where: Q^s – the component of driving force Q on direction of slip velocity V^s.

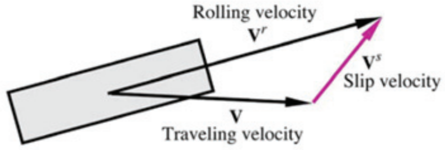


Fig. 2 Slip velocity on a wheel

Junya Yamakawa et al. [42] established a function based on the energy loss W and simulation models to analyze driving performance and energy consumption of DDEV with different drive systems during on slop and turning motions. Zhang HH et al. [36] proposed a coordinated torque distribution method to minimize slip power loss by optimizing rolling velocities of four wheels, and indicated that the vehicle had the lowest energy consumption while maintaining neutral steering characteristic during cornering by analyzing friction loss of vehicle cornering driving. Yan Chen and Junmin Wang [43, 44] considered IWDV as an over-actuated system and adopted a sliding mode controller to track the desired planar vehicle motions and an energy-efficient control allocation scheme based on the Karush-Kuhn-Tucker conditions to improve power consumption. The simulation results indicated that the proposed algorithm was much faster than the commonly-used active-set method. The research mentioned above may have well pointed out the way to further improve overall efficiency of DDEV but experiments verification is also necessary.

The aforementioned literatures have led the author to the conclusion that the research on energy saving strategy for DDEV is making progress, while not many of the studies take the approach of OTD to increase energy efficiency. Besides, the drive system efficiency which has much effect on overall vehicle efficiency has not been mentioned.

II. Drive system efficiency for energy saving strategy

Energy saving strategy for DDEV includes not only OTD but also improvements on drive system efficiency. Distributed drive system includes mainly two parts: electric motor system and drivetrain. Its potential in improving energy efficiency has not been fully explored. According to the study of Masayuki Terashima and co-workers [17], apart from the energy consumed by battery internal resistance, rolling resistance and air drag about 60.9% of the total energy is lost in motor and motor controller by an in-wheel drive system at four-mode-operation. That means either reducing motor loss or improving controller efficiency can make improvements to the overall energy efficiency [45-47]. Another way is the application of new kinds of motors. Tuyoshi Nonaka et al. [48] designed a variable magnetic flux motor (VMFM) with an efficiency superiority of 20% to the conventional steady-field-magnetic-flux motor. And axial-flux motors (Fig. 3 shows one example) which can be fitted into the wheel rim have been developed by J. F. Eastham [49], Khwaja M. Rahman [50] and S. L. Ho [51]. Also an outer-rotor permanent-magnet flux-switching machine [52] has been designed for EV propulsion (Fig. 4). The novel motors have the merits of not only lower unsprung mass but also higher torque density and less power loss.

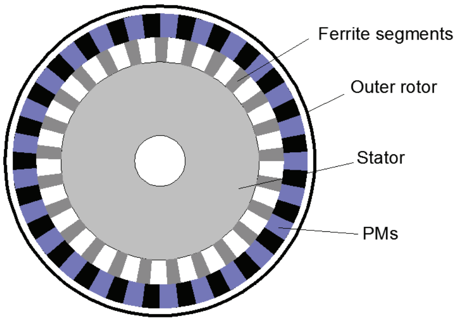


Fig. 3 An example of axial-flux motors

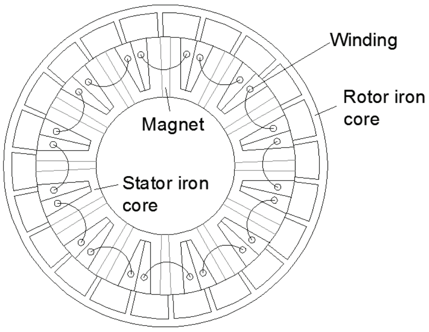


Fig. 4 Topology of an outer-rotor PMFS machine

Drivetrain efficiency is another important factor that cannot be ignored. The power loss map of the motor on electric buses (Fig. 5) [53] demonstrates a way to analyze drivetrain efficiency of DDEV.

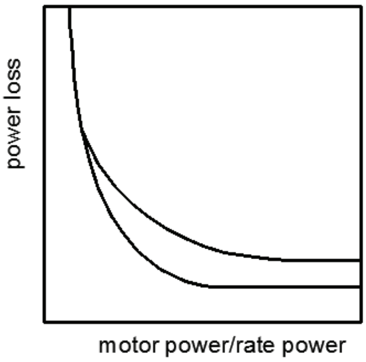


Fig. 5 Power loss map of the motor on electric buses

When it comes to the drive system of DDEV, it refers mainly to the reducer, universal joint and drive shaft. Similar to the drivetrain of ICEV, the power loss that involves toothing, bearing and churning losses mainly occurs in the reducer of distributed drive system [54-56]. As mentioned above, planetary gear and fixed axis gear trains are generally adopted as the reducers for DDEV. References [57-60] derived the calculation equations of mechanical efficiency in planetary gear trains and analyzed the power stream, but most of the methods ignored the influences of speed, load and acceleration/deceleration. In fact, the efficiency of gear trains in vehicles is sensitive to load. Mantriota, G. [61] putted up with a method that took account load dependent power losses and inertia effects for predicting efficiency of multi-degrees-of-freedom epicyclic gear trains, which is a valuable method to analyze the efficiency of reducers in DDEVs. Meanwhile, Cui Li [62] investigated the efficiency of planetary gears in an automatic transmission and indicated that different engaging efficiencies existed between accelerating and decelerating gears. And accurate calculation equations of engaging efficiencies of spur gears and spiral gears at either accelerating or decelerating situation are obtained. The above research which aimed on planetary gear trains laid a solid foundation for the design and analysis of the reducer in the distributed drive system. Liu Feng [63] analyzed test data of performance of constant velocity universal joint and obtained universal joint efficiencies with different working angles. The results can further guide the configuration of universal joint on DDEV.

In conclusion, higher overall efficiency of DDEV can be achieved if future research contributes to fundamental technical issues such as the electric motor and motor controller efficiency and the efficiency characteristic of drivetrain. Further study and design of drive system structures as well as OTD based on drive system efficiency need more exploring.

Conclusion

Although significant progress has been made in DDEV which plays a crucial role in the plan to improve the dynamic performance and energy efficiency, the complete potentials have not been realized so far in a mass-production vehicle. Since energy saving strategy of DDEV is the most important factor affecting driving range, this paper reviews the state-of-the-art research that has been accomplished to understand OTD and drive system efficiency. Further, the author reveals significant opportunities of research which are necessary to design novel/efficient distributed drive systems. Based on the aforementioned literature, the improvements to energy efficiency of DDEV have attracted attention in the past decade. However, OTD is not adequate for energy saving strategy and many existing problems need more exploring. Detailed knowledge on characteristics of electric motor system and drivetrain, at both driving and regenerative braking modes, are necessary for further research on improving DDEV operational energy efficiency. Especially characterizing the efficiency map of the drive system is a challenging work and deserves further in-depth studies.

ACKNOWLEDGMENT
The research is supported by National Basic Research Program of China (973 Program).

REFERENCES

[1] C. C. Chan. The state of the art of electric and hybrid vehicles. Invited Pater, Proceeding of IEEE, 2002, 90(2), 247-275.
[2] Steve Barrett. FCVs will be a key element in European vehicle powertrains portfolio to achieve 2050 goals. Elsevier, Fuel Cells Bulletin, 2011, 2011(1), 12-15.
[3] J. V. Mierlo, P. V. Bossche, and G. Maggetto, Models of energy sources for EV and HEV: fuel cells, batteries, ultracapacitors, flywheels and engine-generators. Elsevier, Journal of Power Sources, 2004, 128, 76-89.
[4] Mingfa Yao, Haifeng Liu, Xuan Feng. The development of low-carbon vehicles in China. Elsevier, Energy Policy, 2011, 39(9), 5457-5464.
[5] Yoichi Hori. Future vehicle driven by electricity and control--research on four-wheel-motored “UOT Electric March II” . IEEE Transactions on Industrial Electronics, 2004, 51(5), 954-967.
[6] Christopher Borroni-Bird, Mohsen Shabana. Chevrolet Sequel: Reinventing the automobile. SAE Paper, 2008-01-0421.
[7] Nobuyoshi Mutoh, Tadahiko Kato, Kazutoshi Murakami. Front-and-rear-wheel-independent-drive-type electric vehicle (FRID EV) taking the lead for next generation Eco-vehicles. SAE Paper, 2011-39-7206.
[8] WADA Masayoshi. Research and development of electric vehicles for clean transportation. Journal of Environmental Sciences, 2009, 21(6), 745-749.
[9] William F., Robert J. Natkin, Daniel M. Kabat, et al. Ford P2000 hydrogen engine design and vehicle development program. SAE Paper, 2002-01-0240.
[10] Nissan ZERO-EMISSION. http://www.nissan-zeroemission.com/EN/LEAF/.
[11] Nobuyoshi Mutoh, Takuro Kazama, Kazuya Takita. Driving characteristics of an electric vehicle system with independently

driven front and rear wheels. IEEE Transactions on Industrial Electronics, 2006, 53(3), 803-813.

[12] Nobuyoshi Mutoh, Yuichi Hayano, Hiromichi Yahagi, et al. Electric braking control methods for electric vehicles with independently driven front and rear wheels. IEEE Transactions on Industrial Electronics, 2007, 54(2), 1168-1176.

[13] Wikipedia. General Motors Sequel. http://en.wikipedia.org/wiki/General_Motors_Sequel.

[14] Douglas Cesiel, Michael C. Gaunt, Brian Daugherty. Development of a steer-by-wire system for the GM Sequel. SAE Paper, 2006-01-1173.

[15] Mohan Sundar, Dennis Plunkett. Brake-by-wire, motivation and engineering - GM Sequel. SAE Paper, 2006-01-3194.

[16] H. Shimizu, J. Harada, C. Bland, K. Kawakami, and C. Lam. Advanced concepts in electric vehicle design., IEEE Trans. Ind. Electron., 1997, 44, 14–18.

[17] M. Terashima, T. Ashikaga, T. Mizuno, and K. Natori. Novel motors and controllers for high-performance electric vehicle with four in-wheel motors. IEEE Trans. Ind. Electron., 1997, 44, 28–38.

[18] 清水浩.電気自動車用インホイールモーター. Patent, P2002-247713A . 2002.

[19] Hiroichi Yoshida, Hiroshi Shimizu. Development of high-performance electric vehicle “Eliica” . Koyo Engineering Journal English Edition, 2005, 168 (E).

[20] Yimin Gao, H. Maghbelli, Mehrdad Ehsani, et al. Investigation of proper motor drive characteristics for military vehicle propulsion. SAE paper, 2003-01-2296.

[21] Gilsu Choi, Zhuxian Xu, Ming Li, et al. Development of integrated modular motor drive for traction applications. SAE Paper, 2011-01-0344.

[22] Dirk van Gogh, Kikuo Emoto, and Hiroshi Shimizu. Form characteristics of an electric vehicle. Journal of Asian Electric Vehicles, 2004, 2(1),571-576.

[23] S.I. Sakai, H. Sado, and Y. Hori. Anti-skid control with motor in electric vehicle[J]. Proc.6th Int. Workshop on Advanced Motion Control, 2005, 317–322.

[24] E. Esmailzadeh, A.Goodarzi, G.R. Vossoughi. Optimal yaw moment control law for improved vehicle handling. Int. J. Mechatronics, 2003,13 (7), 659-675.

[25] Shin-ichiro Sakai, Hideo Sado, and Yoichi Hori. Motion control in an electric vehicle with four independently driven in-wheel motors. IEEE/ASME Transactions on mechatronics, 1999, 4(1), pp. 9-16.

[26] E. Esmailzadeh, G. R. Vossoughi, A. Goodarzi. Dynamic modeling and analysis of a four motorized wheels electric vehicle. Vehicle System Dynamics, 2001, 35(3), 163-194.

[27] He, P., Hori, Y., Kamachi, et al. Future motion control to be realized by in-wheel motored electric vehicle. The 31st Annual Conference of the IEEE Industrial Electronics Society, IECON 2005, Raliegh, South Carolina, USA.

[28] Yoichi Hori, Yasushi Toyoda and Yoshimasa Tsuruoka. Traction control of electric vehicle based on the estimation of road surface condition-basic experimental results using the test EV “UOT Electric March” . Power Conversion Conference, 1997, 1, 1-8.

[29] Yee-Pien Yang , Chun-Pin Lo. Current distribution control of dual directly driven wheel motors for electric vehicles. Elsevier, Control Engineering Practice, 2008, 16(11), 1285-1292.

[30] Fujimoto H., Fujii K., Takahashi, N. Traction and yaw-rate control of electric vehicle with slip-ratio and cornering stiffness estimation. IEEE Proceedings of the 2007 American Control Conference, 2007. ACC '07, 5742-5747.

[31] Rongrong Wang, Yan Chen, Daiwei Feng, et al. Development and performance characterization of an electric ground vehicle with independently actuated in-wheel motors. Elsevier, Journal of Power Sources, 2011, 3962-3971.

[32] Ning Guobao, Wan Gang. The Present research situation of the influences on vehicle vertical performances induced by direct wheel drives system. Automobile Technology, 2007, 1000-3703(2007)03-0021-0.

[33] D Purdy. A brief investigation into the effect on suspension motions of high unsprung mass. Journal of Battlefield Technology, 2004, 7(1).

[34] Go Nagaya, Yasumichi Wakao, Akihiko Abe. Development of an in-wheel drive with advanced dynamic-damper mechanism. JSAE Review, 2003, 24(4), 477-481.

[35] Ning Guobao. Research on vertical vibrating negative influences induced by in-wheel motor driving system and countermeasures. Shanghai: Tongji University, 2006.

[36] Zhang Huanhuan. Research on the torque coordinating control of in-wheel motor driving electric vehicle. Jilin: Jilin University, 2009.

[37] Zhong Zaimin, Chen Xinbo, Wang Xinjian. A novel topology of distributed drive system of EV. China Patent, 201120084385.6. 2011.

[38] Chen Xinbo, Liu Hao, et al. A novel in-wheel drive system with fixed gear train of power switch device.China Patent, 201120393987.X. 2011.

[39] FAN Jingjing, MAO Ming. A Study of driving force distribution strategy for three-axles electric driving vehicle based on economics. Vehicle & power Technology, 2007, 1009-4687(2007)01-0049-03.

[40] Yu Zhuoping, Zhang Lijun, Xiong Lu. Optimized torque distribution control to achieve higher fuel economy of 4wd electric vehicle with four in-wheel motors. Journal of Tongji University (Natural Science), 2005, 33(10).

[41] Wang Bo, Luo Yugong, Fan Jingjing, Li Keqiang. A study on driving force distribution of four-wheel-independent drive electric vehicle based on control allocation[J]. Automotive Engineering, 2010, 32(2), 128-132.

[42] Junya Yamakawa, Keiji Watanabe. A method of optimal wheel torque determination for independent wheel drive vehicles. Elsevier, Journal of Terramechanics, 2006, 43(3), 269-285.

[43] Yan Chen, Junmin Wang. Energy-efficient control allocation with applications on planar motion control of electric ground vehicles. American Control Conference (ACC), 2011, 2719-2724.

[44] Yan Chen, Junmin Wang. Fast and global optimal energy-efficient control allocation with applications to over-actuated electric ground vehicles. IEEE Trans. Control Syst. Technol., 2011, PP (99), 1-10.

[45] Jiang Shanlin. High-speed permanent magnet synchronous motor loss analysis and temperature field calculation. Harbin: Harbin Institute of Technology, 2010.

[46] N. Bianchi, S. Bolognani, F. Luise. Potentials and limits of high-speed PM motors. IEEE Transactions on Industry Applications, 2004,40(6), 1570-1578.

[47] M. Aoulkadi A. Binder, G. Joksimovic. Additional losses in high-speed induction machine-removed rotor test. Proc. of the 11th European Conference on Power Electronics and Applications, EPE, 11-14 Sept. 2005, Dresden, Germany, paper ID 610, 10 pages.

[48] Tuyoshi Nonaka, Shogo Makino, Masayuki Hirayama, et al. Efficiency evaluation of new variable magnetic flux motor-development of EV motor with wide range high-efficiency drive-. SAE International, 2011-39-7258.

[49] J. F. Eastham, M. J. Balchin, T. Betzer, et al. Disc motor with reduced unsprung mass for direct EV wheel drive. Industrial Electronics, ISIE '95, 1995, 2, 569–573.

[50] Khwaja M. Rahman, et al. Application of direct-drive wheel motor for fuel cell electric and hybrid electric vehicle propulsion system. IEEE Trans. on Industry Applications, 2006, 42(5), 1185-1192.

[51] S. L. Ho, Shuangxia Niu, and W. N. Fu. Design and analysis of a novel axial-flux electric machine. IEEE Transactions on Magnetics, 2011, 47(10), 4368-4371.

[52] W. Fei, P.C.K. Luk, J. Shen, et al. A novel outer-rotor permanent-magnet flux-switching machine for urban electric vehicle propulsion. 3rd International Conference on Power Electronics Systems and Applications, 2009, 1-6.

[53] National Standards of Peoples Republic of China. Drive motor system for electric buses (Draft) . Appendix A. 2010.

[54] Narita, K. and Priest, M. Metal-metal friction characteristics and the transmission efficiency of a metal V-belt-type continuously variable transmission. J. Engineering Tribology, 2007, 221(1), 11-26.

[55] G Lechner, H Naunheimer. Automotive transmissions: fundamentals, selection, design and application. Springer, 1999, 54-67.

[56] Nilabh Srivastava, Imtiaz Haque, 2009, “A review on belt and chain continuously variable transmissions (CVT): Dynamics and control. Elsevier, Mechanism and Machine Theory, Vol. 44, No. 1, pp.19-41.

[57] E. Pennestrı`, F. Freudenstein. The mechanical efficiency of epicyclic gear trains. ASME J. Mech. Des., 1993,115(3),645–651.

[58] Ettore Pennestrı`, Pier Paolo Valentini. A review of formulas for the mechanical efficiency analysis of two degrees-of-freedom epicyclic gear trains.ASME J. Mech. Des., 2003,125(3), 602–608.

[59] del Castillo, J. M. The analytical expression of the efficiency of planetary gear trains. Mech. Mach. Theory, 2002, 37 (2), 197-214.

[60] Chao Chen.Power flow analysis of compound epicyclic gear transmission. ASME J. Mech. Des.,2011,133(9), 094502 (5 pages).

[61] Mantriota, G., and Pennestrı`, E. ‘‘Theoretical and experimental efficiency analysis of multi degrees-of-freedom epicyclic gear trains. Multibody Syst. Dyn., 2001, 389-408.

[62] Cui Li. Study on efficiency of planetary gear train of automatic transmission. Chongqing: Chongqing University, 2005.

[63] Liu Feng. Constant velocity driving shaft kinematics and dynamics simulation and experiment analysis. Jilin: Jilin University, 2004.

***Authors**: Hao Liu，Ph.D. Candidate，Department of Electric Drive System, Clean Energy Vehicle Engineering Centre, NO.4800 Cao an Road, Shanghai 201804, China, E-mail: 09liuhao@tongji.edu.cn or 498773209@qq.com.*