# Driving Range Parametric Analysis of Electric Vehicles Driven by Interior Permanent Magnet Motors Considering Driving Cycles

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(Invited)

***Abstract*—This paper presents parametric analysis of driving range of electric vehicles driven by V-type interior permanent magnet motors aiming at maximum driving range, i.e., minimal total energy consumption of the motors over a driving cycle. Influence of design parameters including tooth width, slot depth, split ratio (the ratio of inner diameter to outer diameter of the stator), and V-type magnet angle on the energy consumption of the motors and driving range of electric vehicles over a driving cycle is investigated in detail. The investigation is carried out for two typical driving cycles with different characteristics to represent different conditions: One is high-speed, low-torque cycle - Highway Fuel Economy Test and the other is low-speed, high-torque cycle - Artemis Urban Driving Cycle. It shows that for both driving cycles, the same parameters may have different influence on the energy consumption of the motors, as well as driving range of electric vehicles.**

***Index Terms*—Driving cycle, driving range, electrical vehicle, interior permanent magnet motor.**

## I. Introduction

With development of economy and industry, resource shortage and environment pollution are getting more and more critic in our life. Thanks to their incomparable advantages in energy saving and emission reduction, electric vehicles (EVs) have been considered as an alternative to fuel vehicles [1], [2]. Interior permanent magnet (IPM) motor has the superiority of high power density and efficiency, and therefore provides a promising candidate for EV's propulsion system [3]-[6]. Many papers optimized the IPM motor for high torque density or efficiency at the rated condition. However, making full use of IPM motor's high efficiency area to improve driving range of the vehicle in actual operating cycles, is more meaningful [7], [8].

It is obvious that motors with different design parameters have different iron and copper losses characteristics. Since various driving cycles have different distribution of operating points [9], optimal designs of motor structure should be different for them in order to make their frequent operating points fall in high efficiency area.

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In [9], optimization of surface-mounted permanent magnet (SPM) motors for EVs were analyzed considering New European Driving Cycle (NEDC), Artemis Urban Driving Cycle (Artemis) and combined cycle with algorithm called Sequential Surrogate Optimizer. It shows that optimal designs for three cycles are different and Artemis requires more magnet and copper while NEDC is opposite. In [10], losses of several integer-/fractional-slot motors were compared with three cycles, i.e., Urban Dynamometer Driving Schedule, Highway Fuel Economy Driving Schedule, and the high acceleration aggressive driving schedule. In [11], pole number and split ratio were optimized for an IPM motor considering a given driving cycle. There are also some other studies on optimization of motors considering driving cycles [2], [12]-[16]. However, some of them were based on specific optimization algorithm or performance comparison, others were mostly based on a driving cycle or some operating points, etc. The influence of design parameters on the performance was not systematically revealed considering different driving cycles.

This paper discusses the relationship between motor design parameters and energy consumption of the motors, as well as driving range of EVs over different driving cycles. With fixed peak torque and turning point, four motor parameters, including tooth width, slot depth, split ratio, and V-type magnet angle, are analyzed to compare energy consumptions and driving ranges over the two driving cycles, Highway Fuel Economy Test (HWY) and Artemis. Based on this, the optimization trend of the four parameters to improve driving ranges over different driving cycles is investigated.

## II. Motor Model and Driving Cycles

The basic structure of the model is shown in Fig. 1 and four parameters, i.e., tooth width $H_t$, slot depth $H_s$, split ratio $\lambda$, and V-type magnet angle $\theta$, are explained in Fig. 2. It should be noted here that the split ratio is the ratio of stator inner radius $R_{si}$ to stator outer radius $R_{so}$. Initial design parameters are given in Table I. Speed and shaft torque curves of two typical driving cycles are illustrated in Fig. 3. HWY is a typical cycle with frequent high-speed and low-torque operating points whereas Artemis is opposite.

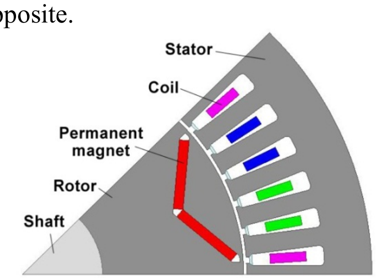



Fig. 1. Structure of the interior permanent magnet motor.

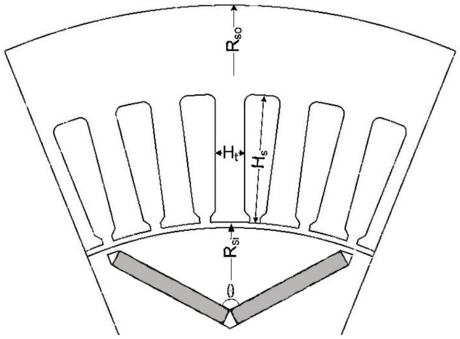
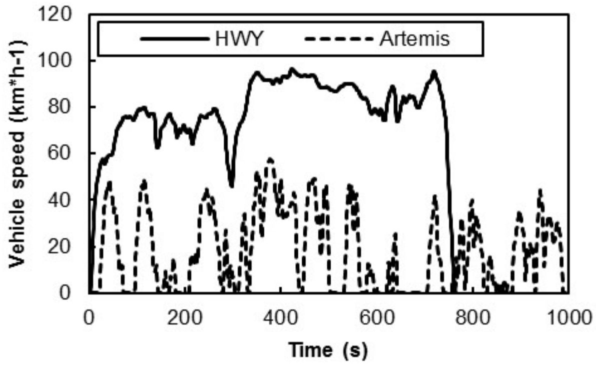


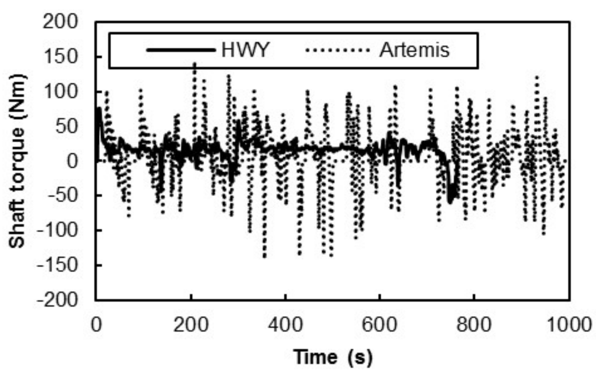

Fig. 2. Designation of parameters in the motor.

TABLE I
PARAMETERS OF THE MODEL

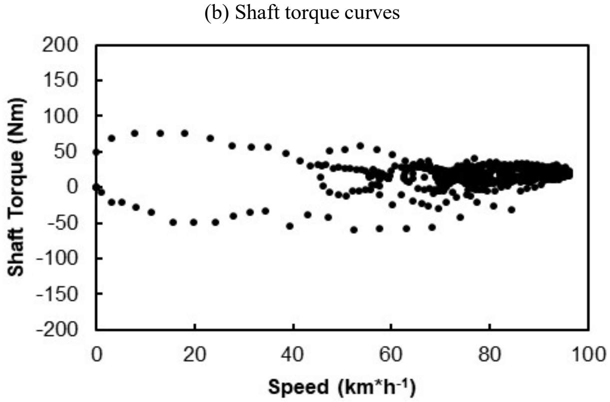
| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Pole/slot number | 8/48 | Airgap (mm) | 1 |
| Stator outer diameter (mm) | 218 | Core length (mm) | 135 |
| Stator inner diameter (mm) | 140 | Turns per coil | 6 |
| Parallel branches number | 2 | Tooth width, $H_t$ (mm) | 5.45 |
| Magnet thickness (mm) | 3 | Slot depth, $H_s$ (mm) | 23 |
| V-type magnet angle, $\theta$ (°) | 125 | Split ratio, $\lambda$ | 0.642 |



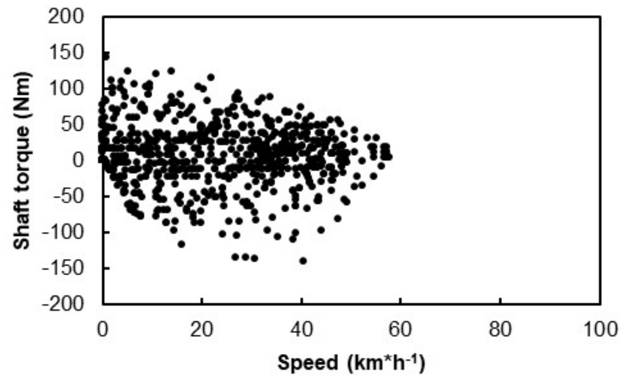

(a) Speed curves




(b) Shaft torque curves




(c) Torque-speed dot figure with HWY




(d) Torque-speed dot figure with Artemis

Fig. 3. Driving cycles.

## III. PARAMETRIC ANALYSIS CONSIDERING DRIVING CYCLES

Electric motors mainly have copper, iron, mechanical, and stray losses, etc. For a certain driving cycle, mechanical loss is the same for different designs and stray loss shares only a very small proportion, which will not be discussed.

In the following analysis, flux density distribution and motor efficiency map can be attained by Finite Element Method. Each parameter is scanned in a certain range of values, while other parameters are kept constant. The energy consumption and driving range are calculated for two driving cycles, respectively. All designs should satisfy vehicle's dynamic performance demand, e.g., the maximum torque 210Nm, maximum speed 13000rpm and base speed 3650rpm. The stator outer diameter and axial active length are constraints. The number of turns per slot is fixed to ease investigation, although the motor voltage is limited and the number of turns is also optimized instead in practice. The motor will run with the control strategy to achieve maximum efficiency. The efficiency of the converter is assumed to 97%. A 50kWh battery is used and regenerative brake capability is assumed to be 25% as a percentage of recovered braking energy.

### A. Tooth Width

The tooth width can influence the tooth mass, slot area and flux density. Using the method mentioned in [17], the representative operating points of two cycles can be obtained, which are 6894rpm-21.26Nm for HWY and 2589rpm-50.23Nm for Artemis, with only motoring operating points and only one subregion considered. It should be noted that in the following discussion, the current and flux density over a driving cycle are analyzed at the representative point, but the energy consumption and driving range are calculated for the entire-cycle analysis.

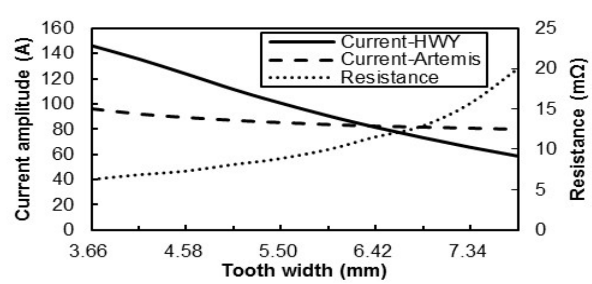
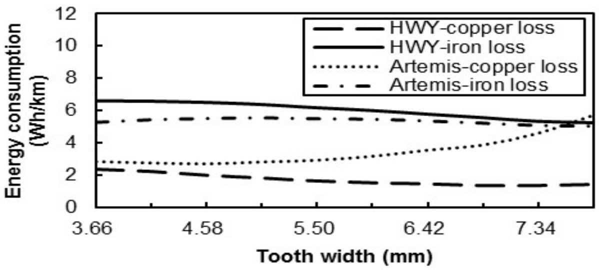
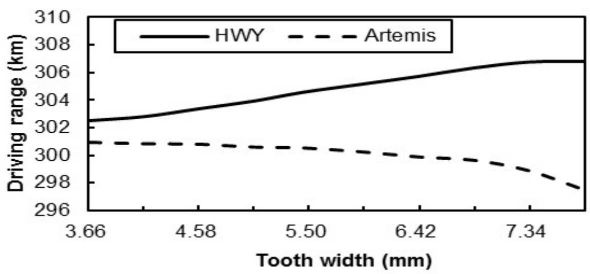



Fig. 4. Variation of current and winding resistance with tooth width.

The current and winding resistance are shown in Fig. 4, while the copper/iron loss energy consumption and driving range over one driving cycle are shown in Fig. 5. The influence of tooth width on driving range is opposite for HWY and Artemis. It is mainly because the variation of copper loss energy consumption is opposite as the tooth width increases. For the larger tooth width, the winding resistance is also larger and the copper loss energy consumption tends to increase, which explains the copper loss energy consumption increase for Artemis. However, the flux weakening current required over HWY decreases very fast with increasing tooth width, which tends to reduce copper loss energy consumption. This effect is more significant than the increased resistance, which results in smaller copper loss energy consumption.




(a) Energy consumption.




(b) Driving range.

Fig. 5. Variation of energy consumption and driving range with tooth width.

## B. *Slot depth*

The slot depth is a main parameter that influences stator yoke mass, slot area and flux density. The current and winding resistance are illustrated in Fig. 6. The energy consumption and driving range over the driving cycles are shown in Fig. 7.

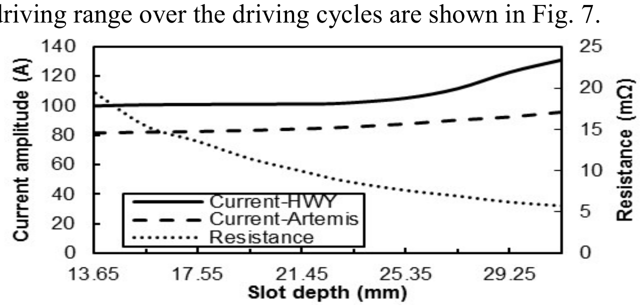
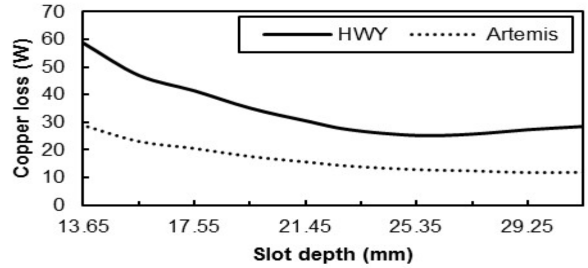
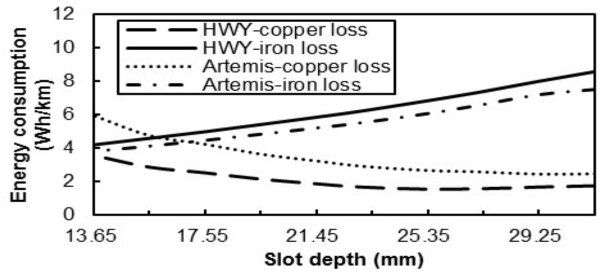



Fig. 6. Variation of current and winding resistance with slot depth.

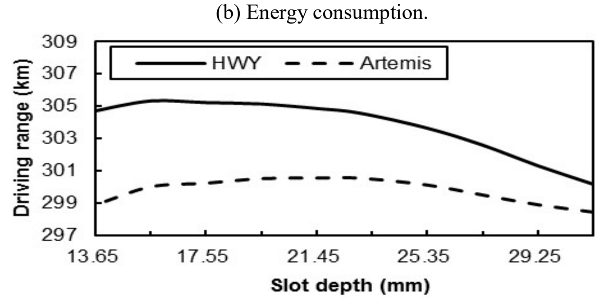
There are optimal values of slot depth to maximize driving range over both cycles. But the optimal slot depth for HWY is 15.60mm, smaller than that for Artemis, 21.45mm. There is a balance between copper and iron loss energy consumptions to improve driving range. When the slot depth decreases, the iron loss energy consumption decreases in similar rate over both cycles, while the copper loss energy consumption increases distinctively. From Fig. 6, it can be found that overall, the required currents over both driving cycles decrease in similar way. However, although the copper loss increases faster over HWY than that over Artemis, the increase amount of copper loss energy consumption over HWY is smaller than Artemis when the slot depth decreases, as shown in Fig. 7. This is because HWY has much longer one-cycle distance, almost 4 times of Artemis. Besides, HWY lasts nearly four-fifths time of Artemis.




(a) Average copper loss.




(b) Energy consumption.




(c) Driving range.

Fig. 7. Variation of copper loss, energy consumption and driving range with slot depth.

## C. *Split ratio*

Decreasing split ratio can cause less magnet consumption, larger slot area with constant stator tooth width and yoke height. The current and winding resistance are shown in Fig. 8. The energy consumption and driving range are illustrated in Fig. 9. It can be found that decreasing split ratio can increase driving range over both cycles but the increase over Artemis is very little when split ratio is lower than 0.688. This is mainly because the variation trend of copper loss energy consumption is different. Decreasing split ratio can reduce the required current over HWY and the winding resistance, which reduces copper loss energy consumption over HWY. However, decreasing split ratio can increase the current over Artemis, which tends to increase the copper loss energy consumption. Two effects of increasing current and decreasing winding resistance are almost cancelled and the copper loss energy consumption only shows slight increase as the split ratio reduces. Combined with slight reduction of iron loss energy consumption over Artemis, the total energy consumption and driving range remain essentially flat when the split ratio is lower than 0.688.

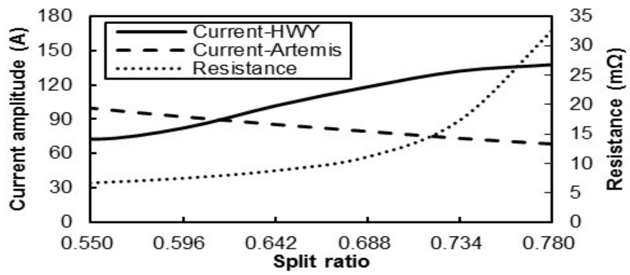
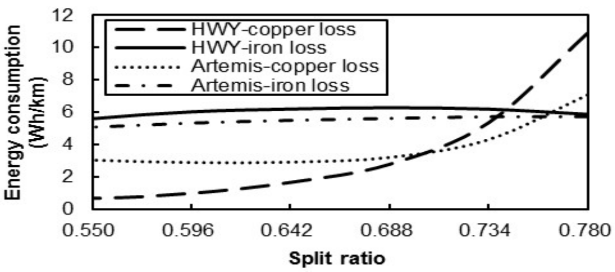
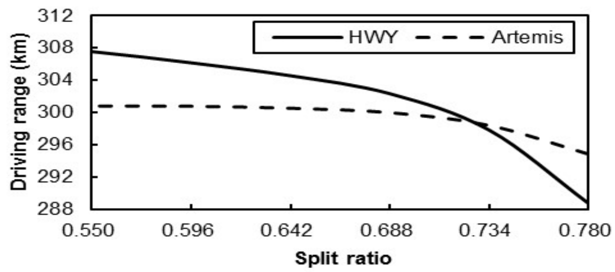



Fig. 8. Variation of current and winding resistance with split ratio.




(a) Energy consumption.




(b) Driving range.

Fig. 9. Variation of energy consumption and driving range with split ratio.

### *D. V-type magnet angle*

The variation of V-type magnet angle can change airgap flux density due to flux focus effect. It has dramatically different influence on the performance for both driving cycles, Figs. 10-11. As shown in Fig. 10, the larger V-type magnet angle results in less PM flux, which requires smaller current for HWY due to reduced d-axis current, but larger current for Artemis because of increased q-axis current. Hence, the copper loss energy consumption reduces for HWY but increases for Artemis. On the other hand, the iron loss energy consumption shows the same decrease trend for both driving cycles. Therefore, the total energy consumption of HWY significantly reduces with the increase of V-type magnet angle, but the variation trends of copper and iron loss energy consumptions are cancelling over Artemis. Due to these effects, the comparison between two driving cycles in Fig. 11 shows that the driving range increases much faster over HWY, while it becomes stable over Artemis when the angle is larger than 125°.

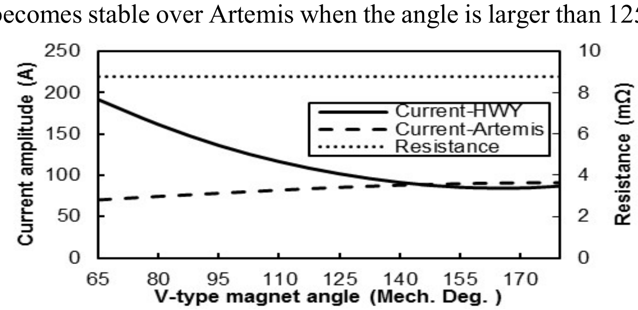
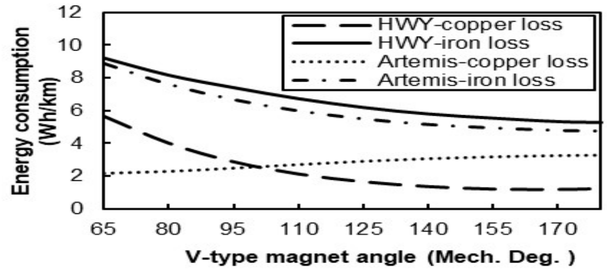
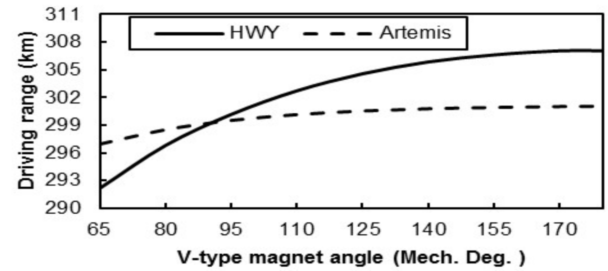



Fig. 10. Variation of current and winding resistance with V-type magnet angle.




(a) Energy consumption




(b) Driving range.

Fig. 11. Variation of energy consumption and driving range with V-type magnet angle.

## IV. Conclusion

For the two driving cycles, HWY and Artemis, the same parameters have different influence on copper/iron loss energy consumptions of IPM motors and driving ranges of EVs. The driving range over HWY increases with the tooth width while that over Artemis is decreased. The maximum driving range occurs when the slot depth is 15.60mm for HWY and 21.45mm for Artemis. It means that a smaller slot depth is preferred for HWY while a slightly larger slot depth is more suitable for Artemis. Decreasing the split ratio can increase driving range over both cycles but the driving range is almost constant over Artemis when the split ratio is smaller than 0.688. Increasing the V-type magnet angle can increase the driving range over both cycles but the driving range over Artemis becomes stable when the angle is larger than 125°. Different effects of the four parameters on driving ranges are mainly due to different variation trend of copper loss energy consumption.

It can be concluded that for the model proposed in this paper, optimization for the maximum driving range over HWY tends to larger tooth width and V-type magnet angle, smaller slot depth and split ratio. However, for optimization over Artemis, smaller tooth width, modest slot depth, split ratio and V-type magnet angle may be a better set of design parameters, which is distinctively different from the optimization for HWY.

## Reference

[1] C. C. Chan, "An overview of electric vehicle technology," *Proceedings of the IEEE,* vol. 81, pp. 1202-1213, 1993.

[2] D. M. Kim, K. S. Cha, M. S. Lim, and J. P. Hong, "Rare-Earth-Free Electric Motor Design for EV Traction Comparing Overall Vehicle Efficiency Considering Driving Cycle," in *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)*, 2016, pp. 1-5.

[3] Z. Q. Zhu and D. Howe, "Electrical Machines and Drives for Electric, Hybrid, and Fuel Cell Vehicles," *Proceedings of the IEEE,* vol. 95, pp. 746-765, 2007.

[4] Z. Q. Zhu and C. C. Chan, "Electrical machine topologies and technologies for electric, hybrid, and fuel cell vehicles," in *2008 IEEE Vehicle Power and Propulsion Conference*, 2008, pp. 1-6.

[5] H. C. Jung, G. J. Park, D. J. Kim, and S. Y. Jung, "Optimal Design and Validation of IPMSM for Maximum Efficiency Distribution Compatible to Energy Consumption Areas of HD-EV," *IEEE Transactions on Magnetics,* vol. 53, pp. 1-4, 2017.

[6] B. Stumberger, G. Stumberger, M. Hadziselimovic, T. Marcic, P. Virtic, M. Trlep, *et al.*, "Design and Finite-Element Analysis of Interior Permanent Magnet Synchronous Motor With Flux Barriers," *IEEE Transactions on Magnetics,* vol. 44, pp. 4389-4392, 2008.

[7] T. Finken and K. Hameyer, "Design of Electric Motors for Hybrid-and Electric-Vehicle Applications," *Int.conf.electrical Machines Syst,* 2009.

[8] Q. Li, T. Fan, Y. Li, Z. Wang, X. Wen, and J. Guo, "Optimization of external rotor surface permanent magnet machines based on efficiency map over a target driving cycle," in *2017 20th International Conference on Electrical Machines and Systems (ICEMS)*, 2017, pp. 1-5.

[9] L. Chen, J. Wang, P. Lazari, and C. Xiao, "Optimizations of a permanent magnet machine targeting different driving cycles for electric vehicles," in *2013 International Electric Machines & Drives Conference*, 2013, pp. 855-862.

[10] C. Gilsu and T. M. Jahns, "Design of electric machines for electric vehicles based on driving schedules," in *2013 International Electric Machines & Drives Conference*, 2013, pp. 54-61.

[11] Q. Li, T. Fan, X. Wen, Y. Li, Z. Wang, and J. Guo, "Design optimization of interior permanent magnet sychronous machines for traction application over a given driving cycle," in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, 2017, pp. 1900-1904.

[12] A. G. Sarigiannidis, M. E. Beniakar, and A. G. Kladas, "Fast Adaptive Evolutionary PM Traction Motor Optimization Based on Electric Vehicle Drive Cycle," *IEEE Transactions on Vehicular Technology,* vol. 66, pp. 5762-5774, 2017.

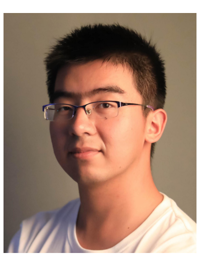
[13] X. Zhu, Z. Xiang, L. Quan, W. Wu, and Y. Du, "Multimode Optimization Design Methodology for a Flux-Controllable Stator Permanent Magnet Memory Motor Considering Driving Cycles," *IEEE Transactions on Industrial Electronics,* vol. 65, pp. 5353-5366, 2018.

[14] C. T. Krasopoulos, M. E. Beniakar, and A. G. Kladas, "Multicriteria PM Motor Design Based on ANFIS Evaluation of EV Driving Cycle Efficiency," *IEEE Transactions on Transportation Electrification,* vol. 4, pp. 525-535, 2018.

[15] Y. Shi, A. Athavale, and R. D. Lorenz, "Shaping Induction Machine Rotor Slots for Driving Cycle Loss Reduction," in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2018, pp. 1619-1626.

[16] M. Salameh, I. P. Brown, and M. Krishnamurthy, "Driving Cycle Analysis Methods Using Data Clustering for Machine Design Optimization," in *2019 IEEE Transportation Electrification Conference and Expo (ITEC)*, 2019, pp. 1-6.

[17] P. Lazari, J. Wang, and L. Chen, "A Computationally Efficient Design Technique for Electric-Vehicle Traction Machines," *IEEE Transactions on Industry Applications,* vol. 50, pp. 3203-3213, 2014.



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