2021-01-0784 Published 06 Apr 2021

The Effect of Tuning PMSM Torque to Track Engine Torque on Speed Fluctuation of Range Extender

Weiqi Ding, Minglong Li, Xingyu Zeng, Dengke Yuan, Zongjie Hu, and Liguang Li Tongji Universtiy

Citation: Ding, W., Li, M., Zeng, X., Yuan, D. et al., "The Effect of Tuning PMSM Torque to Track Engine Torque on Speed Fluctuation of Range Extender," SAE Technical Paper 2021-01-0784, 2021, doi:10.4271/2021-01-0784.

Abstract

REEV (Range-Extended Electric Vehicle) can avoid the mileage anxiety of BEV (Battery Electric Vehicle). Nevertheless, RE (Range Extender) for passenger cars prefers to use ICE (Internal Combustion Engine) with smaller displacement and lower cylinder number, which is usually with a worse vibration performance at low speeds. As RE only outputs electricity, it provides the possibility to optimize NVH (Noise, Vibration, and Harshness) of the engine by PMSM (Permanent Magnet Synchronous Motor). By real-time control, the electromagnetic torque of PMSM can track the shaft torque fluctuation during engine strokes, especially the combustion stroke. When the instability and rolling torque of RE could be suppressed, NVH performance of RE can be improved.

This paper presents simulation research on speed fluctuation suppression for RE engine based on dynamic torque compensation by controlling a PMSM. First, the simulation models of a three-cylinder ICE, a PMSM, and their control strategies were built and verified by GT-Power and Simulink. Second, a joint simulation was carried out to compare the effects of different PMSM torque patterns on the speed fluctuation of the RE. Then an FFT (Fast Fourier Transformation) analysis of the shaft speed was conducted to analyze the inhibitory effect in the frequency domain. Under 2000r/min and 0.7MPa BMEP (Brake Mean Effective Pressure) condition, the speed fluctuation value (the difference between the maximum and minimum speed in a cycle) of optimized torque patterns is decreased by 25.4% ~ 49.0%, and the speed variance is decreased by 54.2% ~ 79.2% when control frequency of the system is multiple frequency of engine speed fundamental frequency.

Introduction

BEV (Battery Electric Vehicle) and HEV (Hybrid Electric Vehicle) are regarded as environmental-friendly vehicles and gradually accepted by the public when faced with the problem of environmental deterioration. REEV (Range-Extended Electric Vehicle) has a more extended driving range compared with BEV, which solves mileage anxiety [1]. Compared with other types of HEV, REEV has the strengths of simple structure and low cost. Therefore, RE (Range Extender) can be used as the powertrain for compact cars [2]. Compared with conventional ICE (Internal Combustion Engine) vehicles, REEV has a low fuel consumption because the engine of REEV generally works under high-efficient conditions [3].

Because of the lower cylinder number, higher engine working speed, and more start-stop conditions, the ICE of REEV has a poor NVH (Noise, Vibration, and Harshness) performance compared with conventional ICE. As a type of HEV, the public's demand for function and performance of REEV is different from that of conventional ICE vehicles. Trattner and Pertl [4] put forward the evaluation index and its ranking in the development process of REEV, and NVH performance ranked second. Similarly, Martin et al. [5] investigated that, affected by the NVH performance of BEV, consumers had higher expectations for the NVH performance of REEV. Therefore, it is essential to optimize the NVH performance in the design of REEV.

The differences of cylinder pressure among four strokes in one cycle may lead to the fluctuation of speed and rolling torque, which can directly affect the NVH performance of the engine [6]. Unlike conventional ICE with flywheel, in REEV, the engine shaft can be coaxially connected with the rotor shaft of PMSM (Permanent Magnet Synchronous Motor). Therefore, the whole system only has electric energy output instead of kinetic energy output. The torque ripple compensation strategy of PMSM can optimize the working status of the engine. If electromagnetic torque of PMSM follows and compensates for the in-cycle torque ripple of shaft, the speed fluctuation of the engine will be suppressed, and NVH performance will be improved [6]. Zhu and Pritchard [7] sent torque commands to the generator to switch the engine operating point in RE, and Dadam et al. [8] used a virtual idle technique to suppress the decline of engine speed during engine pull-down, which indicated the feasibility to control engine by tuning motor torque. Liu et al. [9] investigated a series of torque patterns to counteract speed

DC voltage fluctuates more seriously. Compared with the P-N patterns, DC voltage fluctuation value is reduced by more than 22.6%, and variance is reduced by more than 50% in O-P patterns with the same frequency. Considering that the average DC voltage is 332.2V, the DC voltage fluctuation value and variance of O-P patterns are acceptable.

Conclusions

In this study, simulation models of the engine, PMSM, and control strategy of PMSM, which constitute a RE system, were respectively built by GT-Power and Simulink. After verifying the accuracy of the models, a joint simulation was carried out to investigate the inhibitory effect of tuning PMSM torque on engine shaft speed fluctuation.

A series of PMSM torque patterns in different control frequencies were designed. With higher control frequency, PMSM torque can track engine torque ripples better. In addition, the speed fluctuation value and variance of most patterns are less than those of the reference group, which means the purpose of restraining speed fluctuation is achieved. The results of FFT analysis indicate that the reduction of speed amplitude at fundamental frequency is more than 76.7% when control frequency is multiple frequency of the engine speed fundamental frequency, and there is a positive correlation between the inhibitory effect on speed fluctuation and control frequency. On the contrary, when the control frequency is not multiple frequency of the fundamental frequency, the inhibitory effect on speed fluctuation can be weakened.

The stability of PMSM power generation process was also optimized. In O-P patterns, PMSM torque no longer switches between positive and negative values. Compared with P-N patterns, DC voltage fluctuation value is reduced by more than 22.6%, and variance is reduced by more than 50% in O-P patterns with the same frequency, which is acceptable for the stability of the power generation process.

Finally, compared with the reference group, the speed fluctuation value of O-P patterns decreases by 25.4% ~ 49.0%, and the speed variance of O-P patterns decreases by 54.2% ~ 79.2% in simulation research when control frequency is multiple of the fundamental frequency.

References

1. Xu, X., Wang, H., Zhang, N., Liu, Z. et al., “Review of the Fault Mechanism and Diagnostic Techniques for the Range Extender Hybrid Electric Vehicle,” *IEEE Access*14234-14244, 2017, doi:10.1109/ACCESS.2017.2725298.
2. Besch, M., Covington, A., Johnson, D., Fowler, N. et al., “Effects of EGR Addition onto Combustion Stability and Alternator Performance Variability of a Small, Single-cylinder Diesel Generator,” SAE Technical Paper 2016-32-0063, 2016, https://doi.org/10.4271/2016-32-0063.
3. Song, K., and Zhang, T., “Instantaneous Optimization Energy Management for Extended-Range Electric Vehicle Based on Minimum Loss Power Algorithm,” SAE Technical Paper 2013-24-0073, 2013, https://doi.org/10.4271/2013-24-0073.
4. Trattner, A., Pertl, P., Schmidt, S., and Sato, T., “Novel Range Extender Concepts for 2025 with Regard to Small Engine Technologies,” *SAE Int. J. Alt. Power.* 1(2):566-583, 2012, doi:10.4271/2011-32-0596.
5. Pischinger, M., Tomazic, D., Wittek, K., Esch, H. et al., “A Low NVH Range-Extender Application with a Small V-2 Engine - Based on a New Vibration Compensation System,” SAE Technical Paper 2012-32-0081, 2012, https://doi.org/10.4271/2012-32-0081.
6. Ayana, E., Paul, P., and Krzysztof, W., "Active Torque Cancellation for Transmitted Vibration Reduction of Low Cylinder Count Engines." in *2009 IEEE Vehicle Power & Propulsion Conference*, USA, Sept. 7-11, 2009, doi:10.1109/VPPC.2009.5289833.
7. Zhu, D., and Pritchard, E., “NCSU Year Three Final Technical Report,” SAE Technical Paper 2014-01-2907, 2014, https://doi.org/10.4271/2014-01-2907.
8. Dadam, S.R., Jentz, R., Lenzen, T., and Meissner, H., “Diagnostic Evaluation of Exhaust Gas Recirculation (EGR) System on Gasoline Electric Hybrid Vehicle,” SAE Technical Paper 2020-01-0902, 2020, https://doi.org/10.4271/2020-01-0902.
9. Liu, D., Rodrigues, L., Brace, C., Akehurst, S. et al., “A Study on Dynamic Torque Cancellation in a Range Extender Unit,” SAE Technical Paper 2016-01-1231, 2016, https://doi.org/10.4271/2016-01-1231.
10. Hu, Y., Yang, F., Du, L., Ouyang, M. et al., “Simulation Research on Engine Speed Fluctuation Suppression Based on Engine Torque Observer by Using a Flywheel ISG,” SAE Technical Paper 2019-01-0787, 2019, https://doi.org/10.4271/2019-01-0787.
11. Ding, S., Cui, Z., Wu, Q., Chang, X. et al., “Simulation Research of Permanent Magnet Synchronous Motor FOC Strategy Based on SVPWM,” *Foreign Electronic Measurement Technology* 33(06):81-85, 2014, doi:10.19652/j.cnki.femt.2014.06.026.
12. Wei, Y., Li, M., Qiao, Q., and Liu, G., “Variable Frequency Speed Regulating System of Asynchronous Motor Based on Simulink Simulation,” *Electronics Quality* 27-32, Sept. 2020.
13. Zhao, H., and Hu, R., “Space-Vector Pulse Width Modulation and it's Simulation Based on Simulink,” *Transactions of China Electrotechnical Society* 30(14):350-353, 2015, doi:10.19595/j.cnki.1000-6753.tces.2015.14.047.
14. Yin, X., Yuan, D., Zhen, Y., Shao, Z. et al., “Direct Torque Control Technology for Permanent Magnet Synchronous Motor Based on SVPWM,” *Journal of System Simulation* 31(11):2535-2542, 2019, doi:10.16182/j.issn1004731x.joss.19-fz0279.
15. Liu, Y., Jia, H., Zhang, P., and Geng, T., “Research of Vector Control System of BLDCM Based on SVPWM,” *Journal of Mechanical & Electrical Engineering* 31(09):1177-1181, 2014, doi:10.3969/j.issn.1001-4551.2014.09.017.
16. Zhang, L., Kan, Y., Meng, D., and Yu, Z., “Torsional Vibration Modeling and Analysis of Internal Combustion Engine as a Range Extender,” *Automotive Engineering* 40(09):1101-1109, 2018, doi:10.19562/j.chinasae.qcgc.2018.09.015.

Contact Information

Weiqi Ding
Ph.D. candidate
School of Automotive Studies, Tongji University
Jiading District, Shanghai, China
keytoss@sina.com

Zongjie Hu
Associate Professor
Zongjie-hu@tongji.edu.cn

Liguang Li
Professor
liguang@tongji.edu.cn

Acknowledgments

This study was supported by two projects from Fundamental Research Founds for National University of Tongji University. One is "Study on vibration characteristics optimization with co-control of the range extender". The other one is "Study on in-cycle speed characteristics at starting/stopping conditions of range extender".

Abbreviations

APU - auxiliary power unit
BMEP - brake mean effective pressure
BEV - battery electric vehicle
DC - direct current
EGR - exhaust gas recirculation
FFT - fast Fourier transformation
FISG - flywheel integrated starter generator
FOC - field-oriented control
FPGA - field programmable gate array
GDI - gasoline direct injection
HEV - hybrid electric vehicle
ICE - internal combustion engine
IGBT - insulated-gate bipolar transistor
MCU - motor control unit
NVH - noise, vibration, and harshness
PID - proportional-integral-derivative
PMSM - permanent magnet synchronous motor
PWM - pulse width modulation
RE - range extender
REEV - range-extended electric vehicle
SVPWM - space vector pulse width modulation

ISSN 0148-7191