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Optimization of Speed Fluctuation of Internal Combustion Engine Range Extender by a Dual Closed-Loop Control Strategy

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Abstract

With the increasing concern on environmental pollution and CO_2 emission all over the world, range-extended electrical vehicle (REEV) has gradually got more attention because it could avoid the mileage anxiety of the battery electrical vehicles (BEV) and get high energy efficiency. Nevertheless, NVH performance of internal combustion engine range extender (ICRE) is a critical problem that affects the driving experiences for REEV. In this paper, a two-cylinder PFI gasoline engine and a permanent magnet synchronous motor (PMSM) are coaxially mounted to run as an ICRE. The ICRE control system was established based on Compact RIO hardware and LabVIEW, who has the functions of the intake throttle PID closed-loop control, autonomous ICRE operation control, and speed PID closed-loop control. In this paper, the gasoline engine was first driven to the idle condition by PMSM in speed-control mode. To study the speed fluctuation control of ICRE, the PMSM control mode was then switched from the speed-control mode to the torque-control mode after the steady idle condition. The steady states of a low-power and a high-power working condition were optimized by a new dual closed-loop control strategy to reduce the ICRE speed fluctuations. The switching process between the two steady states was further optimized by the dual closed-loop control strategy. The characteristics of ICRE speed fluctuation and charging process of batteries were also investigated. The results show that the speed fluctuation amplitude could be reduced by 30% at the low-power operating condition and 41.7% at the high-power operating condition with the optimal PI parameters of the dual closed-loop control strategy. During the switching process from low-power condition to high-power condition, the speed response time and overshoot rate can be reduced to 2.1s and 2.7% respectively.

Introduction

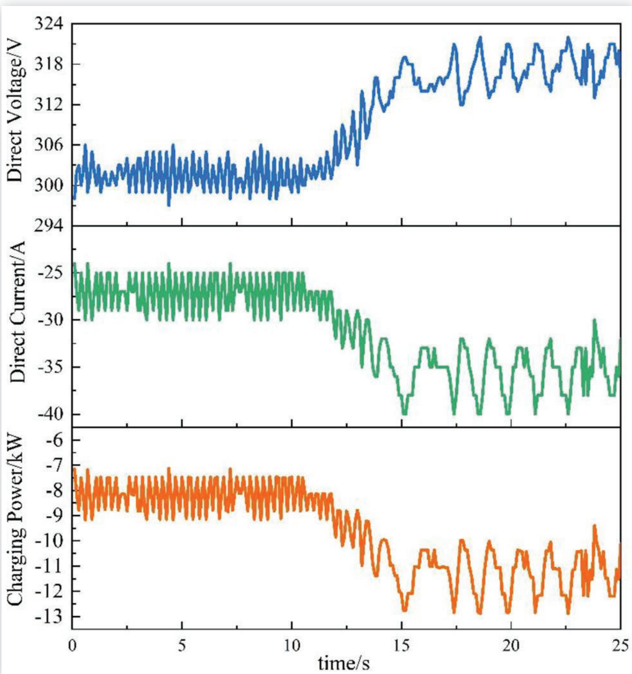
With the stricter harmful emission regulations and increasing CO_2 concern, battery electrical vehicles (BEV) have received more and more attention. However, the short mileage is still one of the bottlenecks restricting the development of BEVs, and the range extender electrical vehicle (REEV) is currently one of the more reasonable solutions [1]. Since the range extender mainly uses internal combustion engines (ICEs) with small displacement and cylinder number, the firework frequency is relatively low, which is likely to cause obvious NVH (Noise, Vibration and Harshness) and seriously deteriorates the driving experience. So the research on NVH of range extender has more critical significance. And normally for engines with 3 or less cylinder number, one or two balancer shafts would be used to compensate the speed fluctuation, but the high-power motor could assist to suppress the fluctuation in an internal combustion engine range extender (ICRE) system. Zhu and Pritchard [2] sent torque commands to the generator to switch the engine operating point in RE during brake period, which indicated the feasibility to control engine by tuning motor torque.

Wang Xiaole [3] explained the NVH characteristics from perspectives of the operating mode, ICE structure and working principle of REEV, described the main sources and causes of vibration and noise, proposed optimized control strategies which would sacrifice fuel economy but improve NVH performance. Guo Rong [4] et al. proposed a method to improve NVH performance through active control, and established a control-oriented nonlinear start-stop vibration analysis model. The engine torque was predicted in the model, and a compensation torque was actively applied accordingly to reduce the torque and speed fluctuations of the REEV during the start and stop processes. Liu D et al. [5] applied different load torque patterns of the motor to suppress the range extender torque fluctuation by simulation and achieved a 21.9% reduction in terms of speed fluctuation amplitude. M. Morandin et al. [6] proposed three different methods to suppressing torque fluctuations for range extenders: traditional proportional-integral (PI) control, feedforward control and multi-resonance compensation control, and it was found that the feedforward control would be the best solution. M. Assett [7] et al. introduced the dynamic motor torque

TABLE 5 The effects of PID parameters on the switching process.

PID	K_p	1	2	3	1	1	1
	K_i	0.008	0.008	0.008	0.008	0.008	0.008
	K_d	0	0	0	0.001	0.005	0.01
t_s /s		3.2	2.1	5.5	3.8	3.4	6.5
Mp /%		5.26	2.70	3.52	3.17	4.00	4.26

FIGURE 13 The electrical output of range extender during the transient condition with the optimal dual closed-loop control strategy.



amplitude is lower at low-power condition. This phenomenon is similar to the differences of ICRE speed fluctuation at two working conditions as shown in Figure 12.

Conclusions

In this paper, an ICRE system is established, which is mainly comprised of a V2 PFI engine, a PMSM and a co-control system. A dual closed-loop control strategy consisted of ITCC in MCU and SCC in co-control system, is developed to reduce the speed fluctuation of ICRE. The PID parameters of SCC are optimized under low-power condition, high-power condition and switching process. The conclusions are as followed.

1. With the dual closed-loop control strategy, speed fluctuation of the ICRE could be decreased effectively.
2. For the low-power condition, the engine speed is 2000r/min and TPS is 20%, the optimal PID parameters for SCC are K_p=1, K_i=0.008, K_d=0, and the speed fluctuation amplitude could be reduced by 30% compared with that without SCC. For the high-power conditions, the engine speed is 2300r/min and TPS is 30%, the optimal PID parameters are K_p=2, K_i =0.008, K_d =0, and the amplitude of the speed fluctuation could be reduced by 41.7%.
3. For the switching process from the low-power operating condition to the high-power condition, when PID parameters for SCC are K_p=2, K_i=0.008, K_d=0, the response time and speed overshoot error could be reduced to be 2.1s and 2.7% respectively.
4. The speed fluctuation affects the electrical output of ICRE. The fluctuation frequency of direct voltage and charging power is closely related to the speed fluctuation.

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