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Optimum Matching of Electric Vehicle Powertrain

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Abstract

Optimum matching of a target vehicle powertrain was formulated as a nonlinear constrained optimization problem. The dynamic and economic objective functions were respectively set up by maximum grade ability and driving range. In addition, the simulated annealing genetic algorithm (SAGA) was used to solve the optimum problem. In order to evaluate the effects of the optimized powertrain on vehicle performance, simulation models of the target and optimized vehicles were established in CRUISE software and verified by test results. It is helpful to achieve dynamic performance improvement, energy consumption reduction and driving range increase.

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Keywords: Electric vehicle powertrain; parameter matching and optimization; modeling and simulation.

1. Introduction

With lower noise, less pollution and zero tail pipe emissions, electric vehicles represent an important concept to meet the challenges like environmental pollution, energy security and depletion of fossil fuels [1, 2]. However, the development and popularization of electric vehicles are limited by the long charging time and short driving range. The powertrain in electric vehicles describes the main components that generate power and deliver it to the road surface, which includes the battery pack, electric motor, gearbox, drive shafts, final drive and the differentials. Range of electric vehicles depends on the voltage and energy of the battery pack, the ratio and the number of the gearbox, power of the electric motor and the ratio of the final drive. Powertrain should not only meet range requirement in the specified driving cycles, but

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also have enough dynamic performance. It is very difficult to determine the parameters of main components in powertrain because they are conditioned by each other. Up to now, many researchers have aimed at studying electric vehicle powertrain. There are several ways to address the optimal matching of electric vehicle powertrain. The researchers in [3-7] only paid attention to optimizing components in electric vehicle powertrain, respectively. In this paper the parameters of the target vehicle powertrain are determined by an integrated optimization approach to satisfy different requirements. The effects of optimized powertrain on vehicle performance are evaluated by the developed simulation model.

Nomenclature

I_b	Base speed ratio of the motor (-)
$[i_{max}]$	Requirement of maximum grade ability (-)
S	Mileage of per NEDC (km)
$[S_{NEDC}]$	Range requirement of NEDC (km)
t_N	Time of per NEDC (s)
u_c	Climbing velocity (km/h)
$[u_{max}]$	Requirement of maximum velocity (km/h)
η_c	Controller efficiency (-)
η_m	Motor efficiency (-)
η_T	Driveline efficiency (-)
ω	Penalty factor (-)

2. Optimization Method and Simulation Model

2.1. Optimization matching of powertrain

In order to achieve global optimization of electric vehicle powertrain, a double-speed gearbox is applied to the target vehicle and the optimization variables are chosen as follows.

$$\bar{x} = (x_1, x_2, x_3, x_4, x_5, x_6, x_7)^T = (U, C, P_{max}, n_b, i_o, i_{g1}, i_{g2})^T \tag{1}$$

The dynamic objective function is established by the absolute value of the difference between the target and actual maximum grade abilities.

$$f_1(\bar{x}) = \left| [i_{max}] - \tan\left[\arcsin\left(\frac{D - f\sqrt{1 - D^2 + f^2}}{1 + f^2}\right)\right] \right| \tag{2}$$

Where, $D = \frac{1}{mg}\left(\frac{9550 x_3 x_5 x_6 \eta_T}{r_r x_4} - \frac{C_D A u_c^2}{21.15}\right)$.

The economic objective function is set up by the absolute value of the difference between the target and actual driving ranges under New European Driving Cycle (NEDC).

$$f_2(\bar{x}) = \left| [S_{NEDC}] - \frac{x_1 x_2 \xi}{W} \right| \quad (3)$$

Where, $W = \int_0^{t_N} \frac{mgf + C_D A u^2 / 21.15 + \delta m a}{3.6 \eta_m \eta_c \eta_T} u dt \Big/ S$.

Acceleration time is used for constraints comprising [t_1] for 0 to 50 km/h in and [t_2] for 50 to 80 km/h.

$$g_1(\bar{x}) = [t_1] - \frac{1}{3.6} \int_0^{50} \frac{\delta m}{1000 \eta_T x_3 / u - (mgf + C_D A u^2 / 21.15)} du \geq 0 \quad (4)$$

$$g_2(\bar{x}) = [t_2] - \frac{1}{3.6} \int_{50}^{80} \frac{\delta m}{1000 \eta_T x_3 / u - (mgf + C_D A u^2 / 21.15)} du \geq 0 \quad (5)$$

The maximum velocity is limited by minimum gear ratio, base speed ratio and maximum speed.

$$g_3(\bar{x}) = [u_{max}] - 0.377 I_b r_r \frac{x_4}{x_5 x_7} \leq 0 \quad (6)$$

In order to avoid gearshift difficulty, the gear ratios of adjacent gears should be always less than 1.8.

$$g_4(\bar{x}) = 1 - x_6 / x_7 \leq 0 \quad (7)$$

$$g_5(\bar{x}) = x_6 / x_7 - 1.8 \leq 0 \quad (8)$$

The objective functions and related constraints would be transformed into a fitness function by the penalty function algorithm.

$$F(\bar{x}, \omega) = f_1(\bar{x}) + f_2(\bar{x}) + \omega \sum_{k=1}^{5} \left| g_k(\bar{x}) \right| \quad (9)$$

The specifications and requirements of the target vehicle are used to determine the powertrain parameters, as shown in Table 1.

Table 1. The specifications and requirements of the target vehicle

Parameter	Value	Requirement	Value
Curb mass (kg)	1370	Maximum velocity (km/h)	≥120
Frontal area (m^2)	2.10	Acceleration time (0-50km/h) (s)	≤6
Rolling radius (m)	0.29	Acceleration time (50-80km/h) (s)	≤8
Aerodynamic drag coefficient (-)	0.32	Maximum grade ability (-)	≥25%
Rolling resistance coefficient (-)	0.012	Range under NEDC (km)	≥120

2.2. The establishment and verification of simulation model

Fig. 1 and Fig. 2 show simulation models of the target and optimized vehicles which are respectively established in CRUISE software. The structure differences between the target and optimized vehicles are these with and without gearbox and clutch.

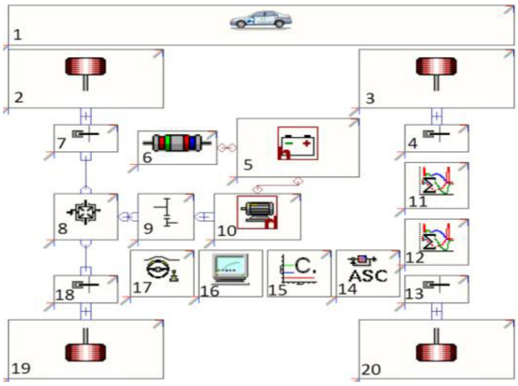

Fig. 1. Simulation model of the target vehicle

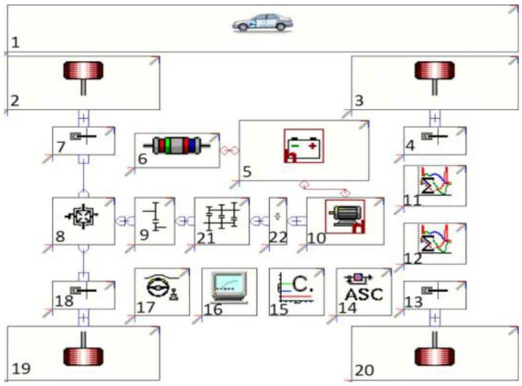

Fig. 2. Simulation model of the optimized vehicle

Note: 1. Electric vehicle 2, 3, 19 and 20. Wheels 4, 7, 13 and 18. Brakes 5. Battery pack 6. Electrical consumer 8. Differential 9. Final drive 10. Motor 11. Motor control system 12. Brake control system 14. ASC 15. Constants 16. Online monitor 17. Cockpit 21. Gearbox 22. Clutch

For the verification of the developed simulation model, the tests are performed by the target vehicle in accordance with the national standards [8, 9]. Additionally, the test velocity profile (Fig. 3) is used as the input of the simulation model (Fig. 1) and the solution procedures are completed by CRUISE software.

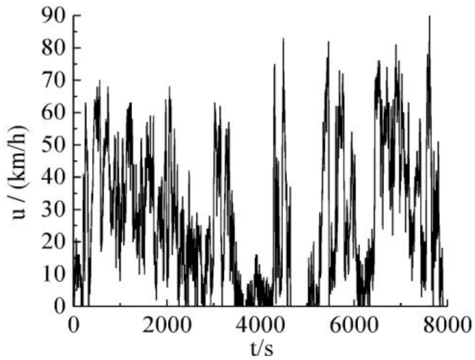

Fig. 3. Test velocity profile (Beijing)

3. Results and Discussions

The optimal problem is solved by SAGA based on the developed fitness function features. In addition, the battery pack, motor, double-speed gearbox and final drive are selected by market supply. The optimum and round results are listed in Table 2.

Table 2. The optimum and round results

Component	Variable	Optimum value	Round value
Battery pack	Rated voltage (V)	364.6232	360
	Capacity (Ah)	67.7437	66
Motor	Peak power (kW)	46.1586	45
	Rated speed (r/min)	2915	3000
Final drive	Gear ratio (-)	7.7015	7.75
Gearbox	Maximum gear ratio (-)	1.5896	1.593
	Minimum gear ratio (-)	1.0342	1.0

Fig. 4 to Fig. 6 describe the acceleration times and the SOC of battery pack. The results are summarized in Table 3 listing the relative driving range, energy consumption and acceleration time for the simulation and test.

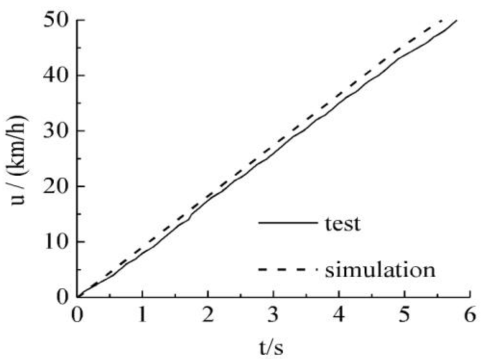

Fig. 4. Acceleration time (0-50km/h)

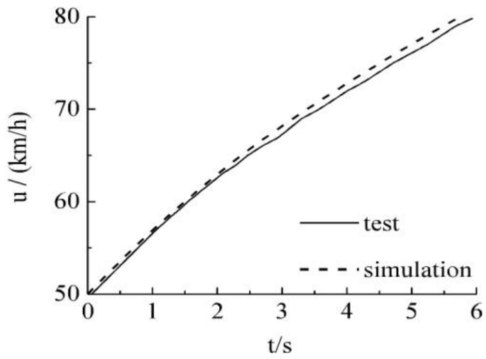

Fig. 5. Acceleration time (50-80km/h)

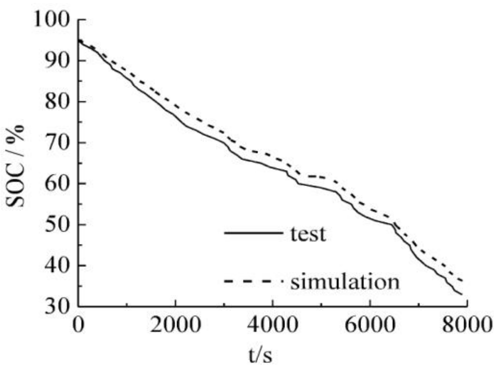

Fig. 6. SOC of battery pack

Table 3. The simulation and test results

Evaluation index	Simulation result	Test result	Relative error/%
Driving range (km)	99.68	96.80	2.98
Energy consumption (kWh/100km)	21.57	22.21	2.88
Acceleration time (0-50km/h) (s)	5.70	5.86	2.73
Acceleration time (50-80km/h) (s)	5.86	6.14	4.56

As shown in Fig. 4 to Fig. 6, the simulation results agree well with the test results. The relative errors between the simulation and test results are less than 5% which shows that the accuracy of the simulation model can be accepted.

The influences of the optimized powertrain on electric vehicle performance are evaluated by the developed simulation model with the help of specified driving cycles. The simulation results of the target and optimized vehicles are listed in Table 4.

Table 4. Simulation results of the target and optimized vehicles

Evaluation index	Cycle	The target vehicle	The optimized vehicle
Driving range (km)	NEDC	116.37	135.46
	FTP75	109.94	131.56
	JC08	108.56	126.65
Energy consumption (kWh/100km)	NEDC	18.49	17.54
	FTP75	19.57	18.06
	JC08	19.82	18.76
Acceleration time (s)	0-50km/h	5.70	4.49
	50-80km/h	5.86	5.74
Maximum velocity (km/h)		126.26	126.96
Maximum grade ability (-)		24.51%	37.34%

It is noted that the optimized vehicle obtains comprehensive performance improvement. The driving ranges of the optimized vehicle under NEDC, FTP75 and JC08 are respectively increased 19.09km, 21.62km and 18.09km relative to the target vehicle. Additionally, the energy consumptions over NEDC, FTP75 and JC08 fall by 5.42%, 8.36% and 5.65%, respectively. The Energy consumption reduction of the optimized vehicle comes from the optimum driveline. Accordingly, the driving ranges increase. Acceleration times from 0 to 50 km/h and 50 to 80 km/h decrease by 1.21s and 0.12s. The maximum grade ability grows from 24.51% to 37.34%. The dynamic performance improvements result from the optimal combination of powertrain components. However, the maximum velocity between the target vehicle and the optimized vehicle is almost equal on account of the minimum gear ratio remains almost unchanged. Although the time delay for gearshift is considered in the acceleration time from 50 to 80 km/h it obtains less reduction. Unfortunately, this paper ignores cost increase caused by the gearbox. Processing difficulties of high speed gearbox are not taken into account.

4. Conclusions

Optimum matching of electric vehicle powertrain is performed by the integrated optimization method. The influences of optimized powertrain on electric vehicle performance are evaluated by the developed simulation model. It is beneficial to achieve dynamic performance improvement, energy consumption reduction and driving range increase.

5. Copyright

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References

[1] JL Torres, R Gonzalez, A Gimenez, J Lopez. Energy management strategy for plug-in hybrid electric vehicles. A comparative study. *J Appl Energy* 2014; 113: 816-24.

[2] IL Sarioglu, B Czapnik, E Bostanci, OP Klein, H Schröder, F Küçükay. Optimum design of a fuel-cell powertrain based on multiple design criteria. *J Power Sour* 2014; 266: 7-21.

[3] M Redelbach, ED Özdemir, HE Friedrich. Optimizing battery sizes of plug-in hybrid and extended range electric vehicles for different user types. *J Energy Policy* 2014; 73: 158-68.

[4] Z Song, J Li, X Han, L Xu, L Lu, M Ouyang, et al. Multi-objective optimization of a semi-active battery/supercapacitor energy storage system for electric vehicles. *J Appl Energy* 2014; 135: 212-24.

[5] MG Read, RA Smith, KR Pullen. Optimisation of flywheel energy storage systems with geared transmission for hybrid vehicles. *J Mech Mach Theory* 2015; 87: 191-209.

[6] I Hofman, P Sergeant, AV Bossche. Drivetrain design for an ultra light electric vehicle with high efficiency. In: 2013 Electric Vehicle Symposium and Exhibition, EVS 27; 2013.p. 1-6.

[7] G Wager, MP McHenry, J Whale, T Bräunl. Testing energy efficiency and driving range of electric vehicles in relation to gear selection. *J Renew Energy* 2014; 62: 303-12.

[8] China Automotive Technology & Research Center. *GB/T 18385-2005 Electric vehicles-Power performance-Test method*. Beijing: Chinese Standard Press; 2005.

[9] China Automotive Technology & Research Center, Tsinghua University. *GB/T 18386-2005 Electric vehicles-Energy consumption and range-Test procedures*. Beijing: Chinese Standard Press; 2006.

Biography

Yong Chen is currently a Professor in Beijing Information Science and Technology University. He is also a researcher in Collaborative Innovation Center of Electric Vehicles in Beijing. His research interests include modeling, simulation and control of new energy source vehicles, vehicle system dynamics.