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Strategy for Improving Electric Propulsion System Efficiency with Weight Method Considering Vehicle Driving Schedule

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Abstract

This paper presents a method of improving efficiency of the electric propulsion system over specific driving schedule. The electric propulsion system's usage profile is firstly mapped on its efficiency map with the hardware-in-the-loop (HIL) test over emulated urban dynamometer driving schedule (UDDS). Then the usage ratings of specified operating ranges could be calculated and represented in terms of weighting factors. Based on the weighting results, regions that highly sensitive to the efficiency over UDDS could be identified and the efficiency in those regions could be the targets for the optimal design. A case study is given in this paper, the dimensions of a 50-kW permanent magnetic motor is redesigned with the proposed method. The results show that the average motor efficiency over UDDS cycle has been improved 2.6% compared to the original level.

Keywords: Electric Vehicle, Propulsion System, Driving Schedule, Efficiency Improvement

1 Introduction

To achieve more cruising range and better energy consumption performance of the electric vehicles, the propulsion system efficiency is one of the important factors. Generally, we usually evaluate the electric propulsion system efficiency with its peak performance, such as the peak efficiency with respect to a single operating point, which is based on the steady-state test. Nevertheless, the vehicle speed and load often vary with driver's intention, road condition, and so on. It would be ineffective to improve a single-point efficiency that may be rarely operated during driving. Instead, it is more realistic to identify what are the most-frequently operating regions and improve the efficiency performance over these regions, to overall enhance the average efficiency level of the propulsion system that is beneficial to longer cruising range.

In this paper, we proposed the improvement strategy to obtain the optimal design for the propulsion system for electric vehicle. The hardware-in-the-loop (HIL) test is carried out for understanding the usage profile of the propulsion system, identifying the most operating ranges over urban dynamometer driving schedule (UDDS) in terms of weighting factors. To improve the efficiency performance at the identified ranges will be theoretically the most

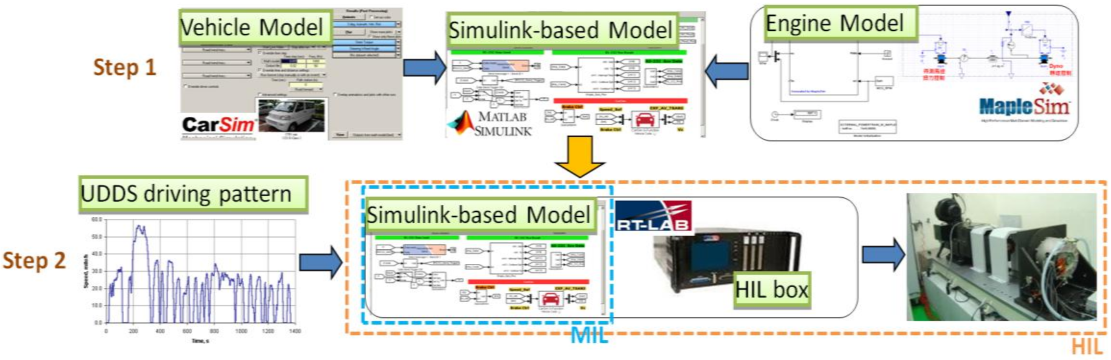


Figure 1: Analysis flowchart for virtual vehicle HIL platform

effective way to enhance the efficiency over vehicle usage condition. These identified ranges could be the target setting for the optimal design to upgrade the original design. A design flow and relevant experimental data are proposed.

The proposed method is carried out on a commercial passenger electric vehicle (CPEV) which is a EV platform built by ITRI. The traction motor design has been modified, and the average efficiency has been improved 2.6% over UDDS cycle compared to the original level. The proposed procedure could be applied to improve the performance, on different kind of electric vehicles over specified driving cycle not limited to the UDDS.

2 Electric Propulsion System-in-the Loop Efficiency Test

2.1 HIL Test for Efficiency Performance over UDDS

In order to improve the system efficiency and reduce the costs, some CAE tools are integrated with Matlab® /Simulink® for evaluating the vehicle/subsystem performance and validating the vehicle/motor control strategies. By adopting forward simulation technique, HIL system is able to accommodate both the real-time simulation and the high model accuracy. For the key development of technique, the integrated work acts as test platform of real-time simulation for electric vehicles, active dynamometer, characteristic measurement of motor system, and analysis flowchart for virtual vehicle HIL platform as shown in Figure 1.

2.2 Electric propulsion system usage profile and weighting factors

The analysis flowchart for virtual vehicle HIL platform is integrated with the characteristics of vehicle dynamics and real propulsion system. The HIL platform could provide customized solutions for the electric vehicle and propulsion system according to the driving cycle.

To obtain the motor efficiency map, the testing 50kW motor is setup on dyno testing stage, then do the steady states test, which shows the motor is operated in several areas of different torques and angular velocities, and the IPC records the sensing data which include battery voltage, battery current, driver voltage, driver current, motor torque and motor angular velocity at the same time; according to this log data, the T-N-E curve can be drawn, as shown in figure 2.

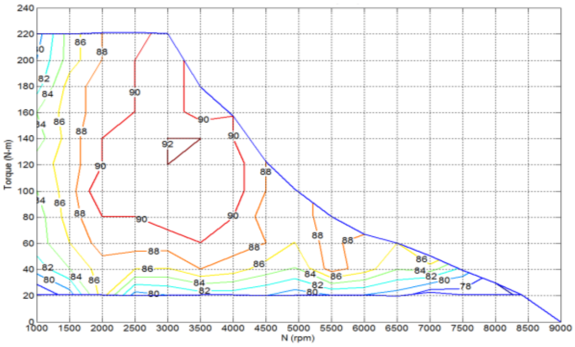


Figure 2: Steady state test of 50kw motor: (a)the T-N commands, (b)the T-N-E curve.

The relationship between the system efficiency and the operation points of propulsion system is identified by the vehicle model: CPEV and an objective evaluation method, the picture and specifications of CPEV are shown in Figure 3 and Table 1. From the evaluation method, we have segments graphical distribution for propulsion system performance of a 50-kW motor system at UDDS (FTP-72) driving cycle, as shown in Figure 4.

The operating point weighting factors for virtual vehicle HIL platform was shown in Table 2. The weighting factors are compared with various amounts of segment area and maximum amount of segment area. Therefore, designer and developer can be optimized to improve electrical motor characteristic for system efficiency. The HIL system can execute a specific driving cycle of prototype design according to electric vehicle requirement due to focus on a special task.

Figure 3: CPEV platform

Table 1: Weighting factor of each operating range

NAME		Commercial Vehicle
DRIVETRAIN		2 Rear Wheel Drive
DIMENSION	Overall Length (mm)	4090
	Overall Width (mm)	1570
	Overall Height (mm)	1940
	Wheelbase (mm)	2610
	Track Width F/R(mm)	1375/1380
	Curb Weight (kg)	1410
	Passengers/Payload (p/kg)	5/440
PERFORMANCE	Min. Turning radius (m)	4.8
	Range @city (km)	100
	Top Speed (km/hr)	100
BATTERY	Type	Lithium-ion
	Voltage (V)	324
	Capacity (kWh)	22.6
MOTRO	Type	PMSM
	Rated Power (kW)	35
	Peak Power (kW/rpm)	50/2500~4000
	Peak Torque (Nm/rpm)	210/0~2500
REDUCTION GEAR	Overall Ratio	7.874

Table 2: Weighting factor of each operating range

	Na	Nb	Nc	Nd	Ne	Nf	Ng	Nh
Td	0	0	0	0	0	0	0	0
Tc	0	0.01	0.029	0.02	0	0	0	0
Tb	0.12	0.16	0.22	0.09	0.03	0.01	0	0
Ta	1	0.26	0.76	0.68	0.15	0.12	0.18	0

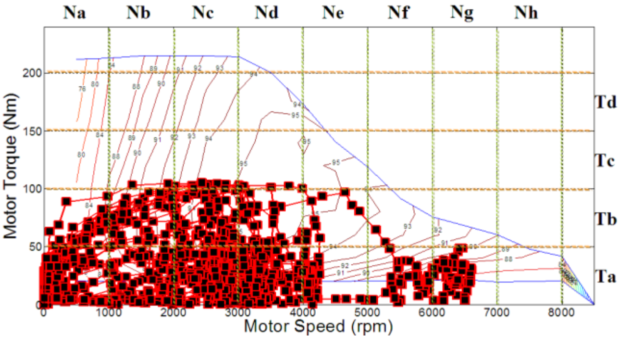


Figure 4: Graphical distribution for propulsion system performance of a 50kW motor system over UDDS driving cycle.

After steady state test, the power consumption over UDDS driving cycle can be obtained by using the HIL system introduced in figure 1. Figure 5 illustrates the architecture of the HIL system, block A-J indicate different functions of the RT model, as described below:

A. Receive control signals from CarSim RT.
B. According to command signals, selecting different torque controlling methods, which include open-loop controlling method (steady state driving test) and close-loop controlling method (dynamic state driving test).
C. Resolve the command signals according to selected controlling mode and CAN bus communication protocol.
D. Output the torque commands to motor driver by using soft CAN card.
E. Feedback signal data to RT model from dyno sensors.

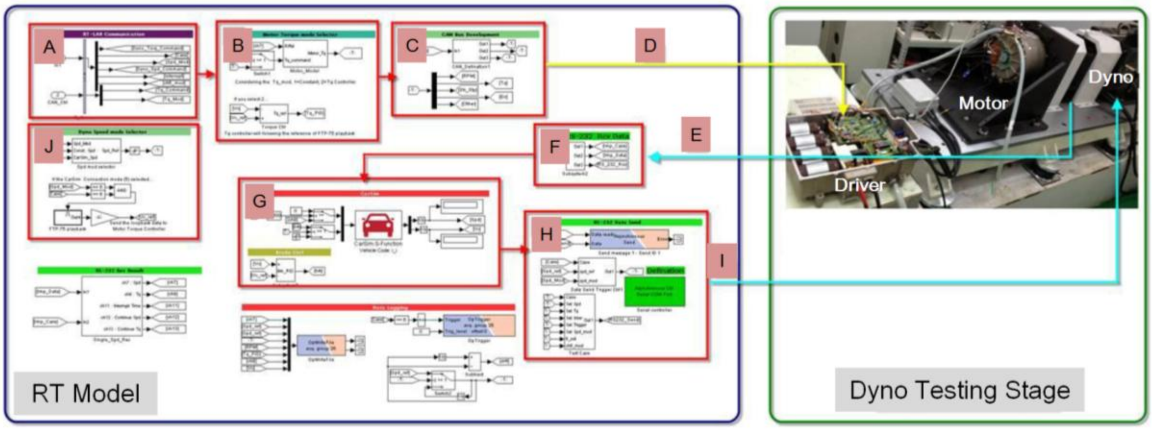


Figure 5: Architecture of the HIL system

F. Receive and process signal data from dyno sensors, then output the data to RT model.
G. Simulate and output the results, which include motor angular velocity and vehicle velocity.
H. Encode the simulation results, then output to dyno testing stage.
I. Output the motor angular velocity to achieve the speed controlling loop of dyno.
J. Dyno controlling model, which can be modified to fit the testing requirements.

Besides, other blocks are data log parts and data processing units.

Simulation results of HIL system of UDDS driving test show the energy sum of UDDS is 3193Wh, therefore the power consumption per kilometer is 266 Wh. To calculate the accuracy of HIL system, we also do UDDS driving test by using chassis dyno, and the testing data of chassis dyno show the energy sum of UDDS is 2763Wh, the power consumption per kilometer is 230.25 Wh. According to the comparison between test data of HIL system and chassis dyno, the accuracy of HIL system can be obtained 86.5%, as show in Figure 6.

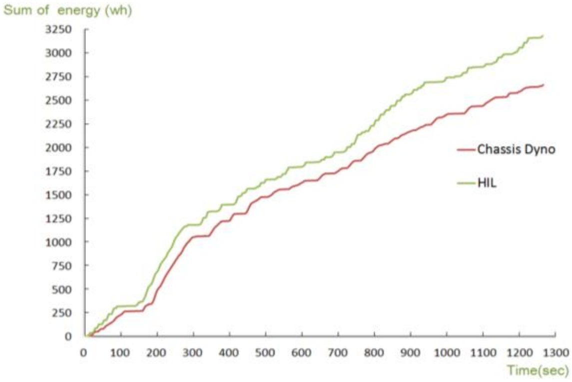


Figure 6: Energy consumption comparison between chassis dyno and HIL over UDDS driving cycle

3 Efficiency Improvement by Process Integrated Optimal Design

In Figure 7, a design flow is proposed for improving the electric propulsion system performance over UDDS that specifically fulfilling the requirement for vehicle use. Briefly, we input the vehicle performance requirements as max acceleration, grade ability and top speed, and we could come out the adequate motor T-N curve. Then we design some motor efficiency map and use driving patterns like UDDS, NEDC to calculate the average efficiency. According to vehicle performance, we can get motor torque and speed from UDDS driving pattern. We divide UDDS driving pattern time to 100 equal parts, and show these 100 points on motor efficiency map by motor torque and speed (Figure 4). Furthermore we can calculate motor average efficiency and know motor operating distribution on efficiency map. We chose best design in Table 2, then we analysed by coupling Optimus® and Maxwell® to get optimized design. The optimization model is as shown in Figure 8.

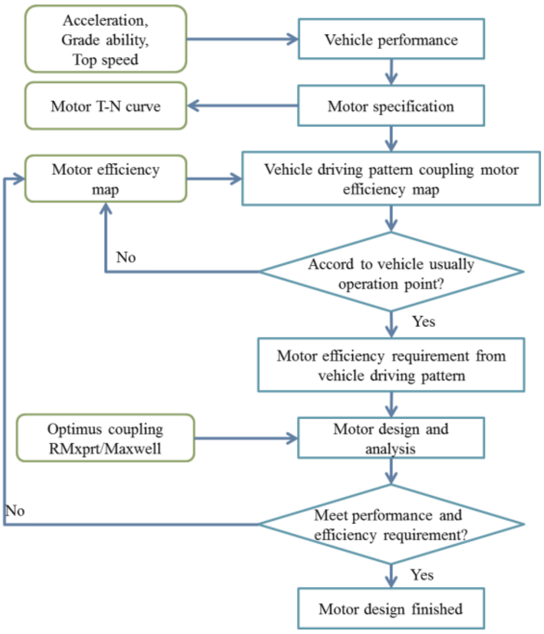


Figure 7: Design process for high efficiency motor

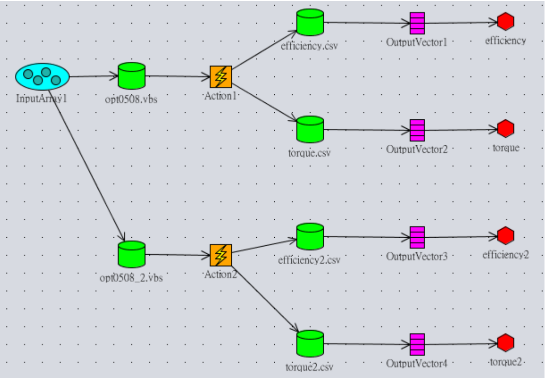


Figure 8: Optimus® coupled with RMxprt®

In this paper, we choose 50kW PM motor and vehicle model: CPEV from ITRI to develop and validate this process. Figure 9 shows 50-kW motor original design model and the specifications are shown in Table 3. Herein the 8 variables are set to do optimization, including slot opening, teeth height, magnet thickness…etc. The experimental design method of Optimus® is used to achieve the optimization process. Table 4 shows the optimized results which calculated by Optimus® and coupled with the software Maxwell® .

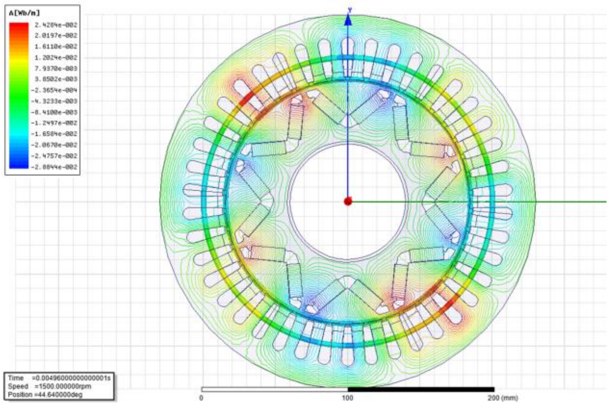


Figure 9: Optimized motor design

Table 3: 50kW motor design results

Dimensions	unit	original design	optimization design
slot opening	mm	3	2.82
air gap diameter	mm	170	165.7
slot depth	mm	21.77	21.86
slot opening depth	mm	1	0.87
rotor inner diameter	mm	83.6	83.95
magnet open degree	mm	11	11.91
magnet bridge thick	mm	5	4.73
magnet thick	mm	9.2	9.14
efficiency @Zone Na-Ta	%	89.22	89.44
torque @Zone Na-Ta	Nm	34.57	34.93
efficiency @Zone Nc-Ta	%	92.02	92.30
torque @Zone Nc-Ta	Nm	34.57	34.94
1* Na-Ta +0.76* Nc-Ta		159.16	159.59

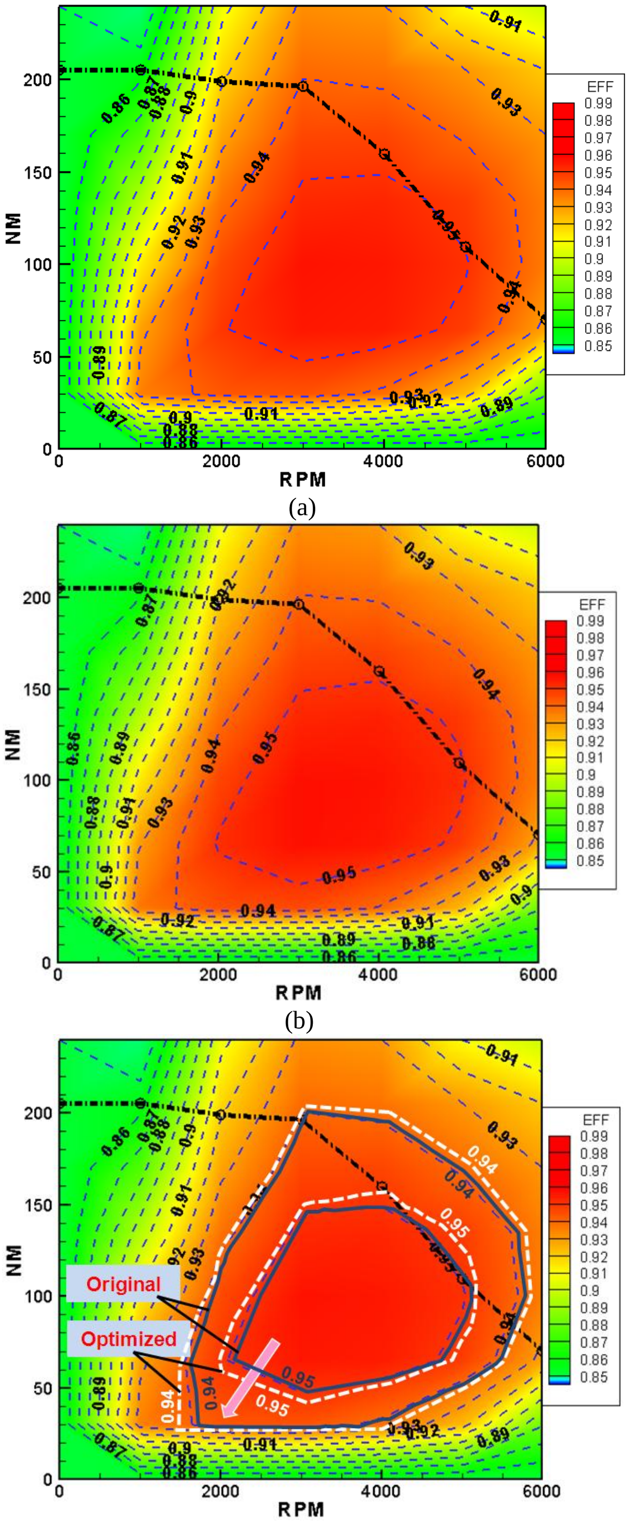
The motor with optimized specifications are simulated by Maxwell, as shown in Figure 9, and the simulation results are listed in Table 4, which shows the weighting factor point efficiencies before and after motor optimization. Table 5 shows the comparison motor efficiencies over UDDS test of original design analysis, experiment efficiency and optimized design analysis. Figure 9 shows the efficiency maps of original and optimized design. We can observe that optimized efficiency map has wider high efficiency area than original efficiency map in Fig. 9(c), and the vehicle can be usually operated over UDDS test in the higher efficiency areas to achieve better performance.

Table 4: efficiency comparison of weighting factor point

Weighting factor point	Before optimization	After optimization
50A@1000rpm	93.45	93.60
50A@3000rpm	94.41	94.57

Table 5: motor efficiencies comparison

Driving Cycle	Original design	Optimized design
UDDS	86.4	89.0



(a)

(b)

(c)

Figure 9: efficiency maps: (a) original design, (b)optimized design, (c)comparison between the two maps.

As optimized results shown in Figure 9 (c), it could be observed that the high efficiency region has been expanded, thus the overall efficiency could be enhanced. The optimized motor UDDS average efficiency is 2.6% higher than original motor design.

Conclusions

In this paper, a design method to improve the electric propulsion system efficiency over UDDS is proposed. The proposed method is practical to design or refine propulsion system for vehicle use over preferable driving conditions.A case study of improve a 50-kW motor is presented. The usage profile of the motor which is applied on an electric van over the UDDS is identified. The most frequently operating conditions are set as the target points for optimal efficiency improvement. The optimal design is carried out by Optimus® , and the results show that the average motor efficiency over UDDS is improved 2.6% compare with the original level.

References

[1] Y. Cheng, F. Duan and S. Cui, "*The Design Principle of Electric Motors and Drive Systems for Electric Vehicles*," ICEMS, Vol. 1, pp. 802–805, Sept. 2005.

[2] R. Maia, M. Silva, R. Ara´ujo, and U. Nunes, "*Electric Vehicle Simulator for Energy Consumption Studies in Electric Mobility Systems*," FISTS, pp. 227-232, 2011.

[3] J. J. Poon, M. A. Kinsy, N. A. Pallo, S. Devadas and I. L. Celanovic, "*Hardware-in-the-Loop Testing for Electric Vehicle Drive Applications*," 2012 Twenty-Seventh Annual IEEE Conference, pp. 2576 – 2582, 2012.

[4] R. M. Schupbach and J. C. Balda, "*A Versatile Laboratory Test Bench for Developing Powertrains of Electric Vehicles*," IEEE, Vol. 3, pp. 1666-1670, 2002.

[5] S. S. Williamson, S. M. Lukic and A. Emadi, "*Comprehensive Drive Train Efficiency Analysis of Hybrid Electric and Fuel Cell Vehicles Based on Motor-Controller Efficiency Modeling*," IEEE, Vol. 21, pp. 730-740, May 2006.

[6] W. Xu, J. Zhu, Y. Guo, Y. Li and Y. Wang, "*Performance Analysis of Electric Machine Drives for Plug-in Hybrid Electric Vehicles*," ASEMD, pp. 60-63, Sept. 2009.

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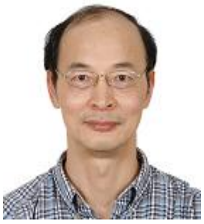

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