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Fuel Economy of Series Hybrid Electric Bus by Matching the Gear Ratio of Different Capacity Traction Motors

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Abstract

This paper investigated the different gear ratio matching effect on the series hybrid electric bus especially for the 90 kW & 150kW traction motors on the fuel economy. The 90 kW & 150 kW traction motors make the system use more efficient operating points; thus, the system is more efficient than when the 240 kW single unit is used. Furthermore, matching the different gear ratios allows the nonlinear characteristics in the traction motor efficiency to be used more efficiently; thus the standard for how to select the gear ratios was proposed. The fuel economy selection was optimized by the hybrid optimization methodology using RSM and the univariate search method, both of which are well known for their straightforward concepts and adequate performances; thus, the new suggested matching theory noticeably improved the system efficiency. The work presented here has profound implications for future studies for the design of the hybrid electric vehicle, as well as the plug-in hybrid and the electric vehicles and was carried out on the AMEsim-Simulink Co-simulation platform.

Keywords: Series Hybrid Electric Vehicle, Traction Motor Sizing, Reduction Gear Ratio, Hybrid Optimization

1 Introduction

Fuel economy improvement and emission reduction are the main issues related to hybrid electric vehicles and several methodologies for achieving these goals have been developed [1-3]. However there is an insufficient amount of research on the traction motor unit in the series hybrid electric vehicle. Figure1 shows the drive-train of the series hybrid electric vehicle. As shown in the figure, the main traction is carried out by the traction motors; thus, how to distribute energy in the traction motor unit is more important in this type of vehicle than in the parallel type hybrid vehicle. Although the energy flow from the battery or the engine to the traction motor unit was very efficient, this energy cannot be transferred to the wheels without an appropriate component matching or energy distribution strategy. Therefore, the study for the energy flow in the traction motor unit was required.

In previous studies, the matching for the 240 kW traction motor capacity was compared with those for the 240 kW single and 90 kW & 150 kW combinations. This comparison showed that the 90 kW & 150 kW combinations have the better fuel economy with the same line-up permanent magnet (PM) traction motors. That is because the general motor efficiency characteristics are in Figure2 and equipping the 90 kW & 150 kW traction motors allows to use the high efficiency region whenever the low torque is required (90 kW only is used), the middle torque is required (150 kW only is used) or the high torque is required (both are used) which is not available when the 240 kW single is used. However, considering only the traction motor capacity matching was insufficient because the gear ratio also has an effect on the system efficiency [4,5].

This paper studies the optimal gear ratio point with a new optimization methodology. The research focus is determining the best gear ratio with the different gear ratios of the 90 kW and 150 kW traction motors. These motors do not have the same maximum velocity limitations and the efficiency tendencies in their torque vs. rpm (T-N) curves are different. Thus, determining the gear ratio was optimized by the hybrid optimization methodology using the response surface methodology (RSM) with the central composite design (CCD) and the univariate search method, both of which are well known for the straightforward concepts and adequate performances [6,7]. Therefore, the power transferred to the traction motor unit can be given to the wheels efficiently without affecting the existing power distribution strategy.

This research was carried out on the AMEsim-Simulink Co-simulation platform, where the AMEsim portion accounts for the target plant model and the Simulink portion accounts for the hybrid control unit (HCU) controller. The work presented here has profound implications for future studies for the design of the hybrid electric vehicle, as well as the plug-in hybrid and electric vehicles because the proposed methodology can be applied to all of these cases.

2 Simulation Model

The simulation model in this research is a series hybrid urban bus, which equips dual power traction motors. The energy of the traction motors comes from either the engine or the battery. Figure3 shows the simulation model, where (a) refers to the plant model with the dynamics and (b) is the HCU which controls the plant model. The plant model and HCU controller were constructed by AMEsim and Simulink respectively, where the signal is sent and received each other.

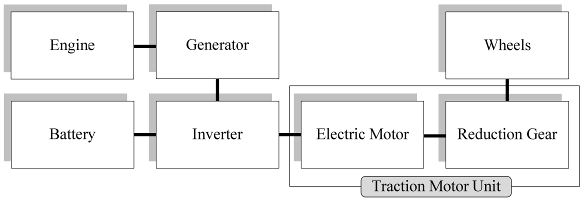


Figure1: Series hybrid electric vehicle drive-train

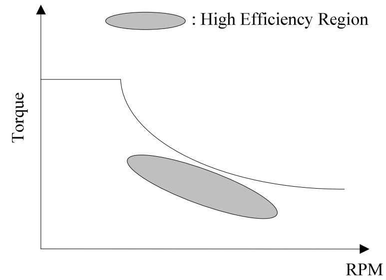
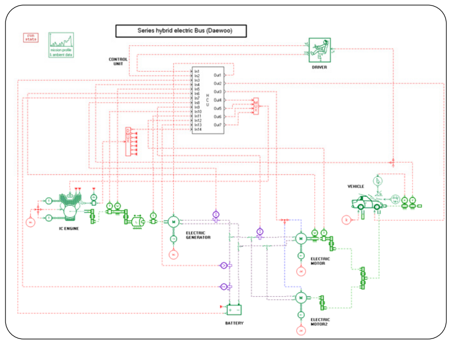
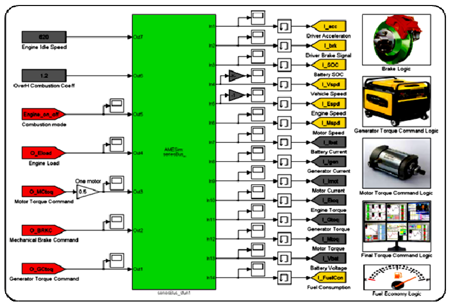


Figure2: Motor efficiency characteristics



(a) Plant model(forward model)



(b) HCU(Hybrid Contorl Unit)

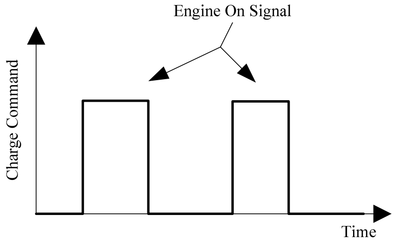
Figure3: Simulation model

2.1 Model Specification

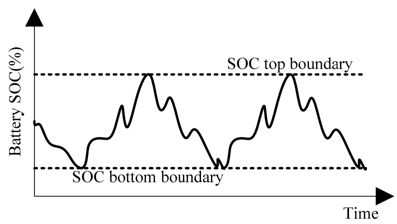
Table 1 shows the model specification used in the forward simulation model. The bus equips a traction motor with a total capacity of 240 kW, consisting of the 90 kW & 150 kW motors. The bsfc map was established by the experiment and the gear efficiency in the traction motor unit was assumed to be constant.

Table1: Vehicle specification

Item	Value
Type	Series hybrid electric bus
Total Mass	15,500 kg
Engine	CNG Type 8,000 cc 180 kW
Generator	PM Type 180 kW
Motor	PM Type 240 kW (dual)
Battery	NiMH Type 240 kW



(a) Thermostat strategy command signal



(b) Battery SOC of thermostat strategy

Figure4: Thermostat Strategy

2.2 Battery-SOC-sustaining strategy

A thermostat strategy is a battery SOC control strategy that decides whether the engine-generator unit should be turned on by the battery's SOC condition. Figure4-(a) shows the typical thermostat strategy on/off command signal, and Figure4-(b) shows the SOC tendency, including the top and bottom boundaries. When the SOC arrives at the bottom boundary, the engine charges the battery, and the engine operation rpm and the torque move to the most efficient operating point in the bsfc map until the SOC arrives at the upper boundary point. If the SOC hits the upper boundary, the engine-generator unit stops rotating so that the mechanical energy in the engine-generator unit does not convert to electrical energy; thus, the battery is used as the main power source.

The thermostat strategy is very useful for evaluating the fuel efficiency because it uses a single operating point; thus, the interferences of the engine bsfc operating point scattering can be removed. However, the repeated on/off of the engine reduces the ride quality

Equations (1)-(3) show the basic standards and conditions for the thermostat strategy. Eng_{on}, Pow_{eng}, Pow_{batt} and Pow_{req} refer to the engine on/off command signal, the generating power in the engine, the providing power in the battery and the power required by the vehicle, respectively. SOC_{before}, SOC_{top} and SOC_{bottom} refer to the most recent SOC, the SOC top boundary and the SOC bottom boundary, respectively.

$$Eng_{on} \begin{cases} 0 \ \ when\ 'SOC_{before} \geq SOC_{top}' \\ 1 \ \ when\ 'SOC_{before} \geq SOC_{bottom}\ \&\ Eng_{on\_before} = 0' \end{cases} \tag{1}$$

$$Pow_{eng} \begin{cases} 0 & when\ 'Eng_{on} = 0' \\ Pow_{bb} & when\ 'Eng_{on} = 1' \end{cases} \tag{2}$$

$$Pow_{batt} \begin{cases} 0 & when\ 'SOC < SOC_{bottom}' \\ Pow_{req} - Pow_{eng} & when\ 'SOC_{bottom} < SOC < SOC_{top}' \\ Pow_{req} & when\ 'SOC > SOC_{top}' \end{cases} \tag{3}$$

2.3 Speed Profile

This research uses the fuel economy test profile of the Braunschweig city driving cycle in Figure5. The cycle was developed at the Technical University of Braunschweig and includes frequent stops; thus, it reflects a transient driving schedule that is appropriate for simulating urban buses. The characteristics of the cycle show that the duration time is 1740 s, the average speed is 22.9 km/h and the maximum speed is 58.2 km/h, with a total driving distance of 11 km.

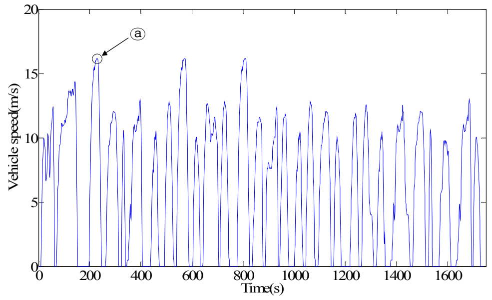
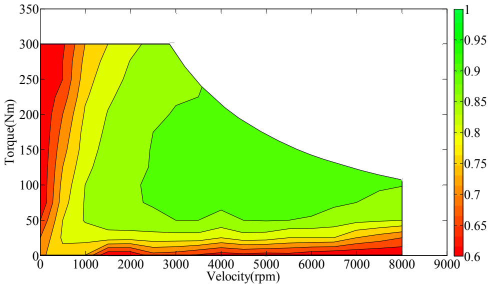


Figure5. Braunschweig cycle

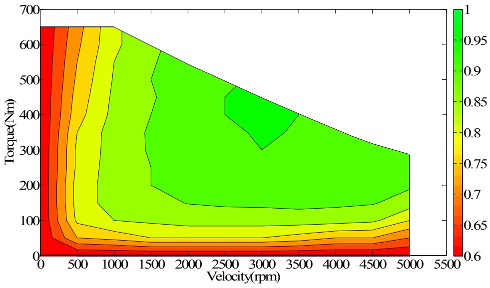
3 Gear Ratio Matching Algorithm

This section discusses why gear ratio matching is required on the basis of the motor efficiency characteristics and proposes a hybrid optimization algorithm for determining the optimal gear ratio.

3.1 Motor efficiency effects with the gear ratio



(a) 90 kW motor efficiency map



(b) 150 kW motor efficiency map

Figure6: Motor efficiency map

Figure6 shows the efficiency maps of the 90 kW and 150 kW combination traction motors with the maximum limitation rpms, 8000 rpm and 5000 rpm. The efficiency of the 150 kW motor is typically better than that of the 90 kW motor and the efficiencies over 90 % are 34 % and 41 % in each the T-N curve maps. If the gear ratio each motor in the traction motor unit is the same and is set to use the 150 kW motor map's maximum rpm (5000 rpm) in the simulation as a basic standard, the 90 kW motor's maximum rpm of 8,000 cannot be used; instead, the maximum velocity that can be used in the 90 kW motor is also 5,000 rpm. Thus, in Figure7, the dotted line is the maximum rpm limitation of the 90 kW motor and the more efficient operating points that might be used if the maximum rpm of 8,000 is available move to the lower efficiency region as in Figure8. Therefore, the different gear ratios that make use of the higher efficiency region in both of the motors cannot be used.

On the other hand, using the maximum rpms of both motors is not always the optimal solution. The points in Figure9, for example, are the operating points of 90 kW motor when the maximum rpm of 8,000 is used after the driving cycle simulation. The gray area indicates that the region has an efficiency of greater than 90%. Thus, the system is more efficient if there are more operating points in the gray area. If the majority of the operating points are near the maximum rpm region, then an rpm limit lower than 8,000 should be used because those points would not be in the gray area when using a limit of 8,000 rpm. In contrast, if the majority of the points are in the lower rpm region, such as 5,000 rpm, then the maximum rpm should be used to put the operating points into the gray area as much as possible. Therefore, the gear ratio must be optimized to improve the vehicle's efficiency.

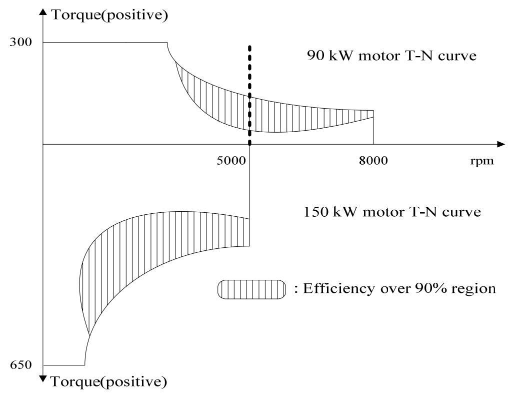


Figure7: Comparison of the 90 kW and 150 kW motors' T-N curves

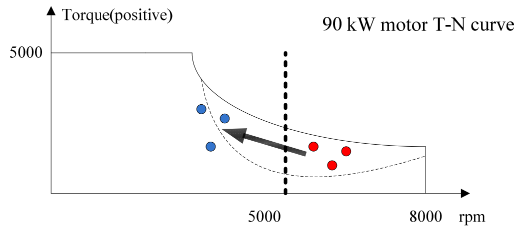


Figure8: Operating point movement

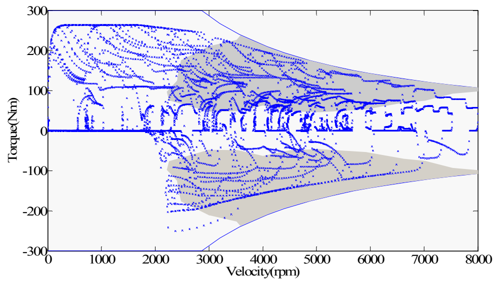


Figure9: Operating points above the 90 % efficiency region

3.2 Proposed Optimization Methodology

The proposed methodology is a hybrid algorithm using the response surface methodology (RSM) and the univariate search method to determine the optimal point without a significant amount of effort.

3.2.1 Design Variables and Object Function

The design variables are the maximum operating rpms in both motors. When the bus is running in the Braunschweig cycle, the maximum operating points are decided by the gear ratios of the 90 and 150 kW motors; thus, the 90 kW and 150 kW motors' maximum operating rpms were the design variables; this case typically happens in ⓐ (230 s) in Figure5. In other words, if the gear ratio for the 90 kW motor's full rpm (8,000 rpm) is G_{full90}, then the gear ratio for the 150 kW motor's full rpm (5,000 rpm) $G_{full150}$ is as follows:

$$G_{full90} = G_{full150} \times 1.6 \quad (4)$$

And the required full operating rpms of the 90 kW and 150 kW motors can be adjusted as shown below.

$$G_{req90} = G_{full90} / (RPM_{target} / 8000) \quad (5)$$

$$G_{req150} = G_{full150} / (RPM_{target} / 5000) \quad (6)$$

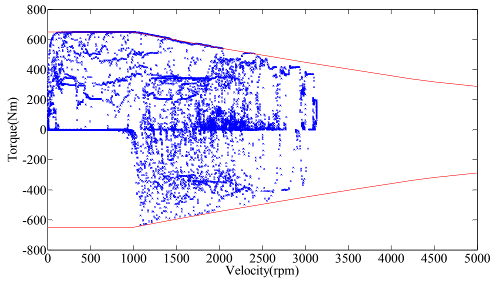
where G_{req90} and G_{req150} are the required gear ratios for the target rpm, RPM_{target}. Thus, the desired maximum operating rpm can be achieved. Table 2 shows the range of each design variable, and Figure10 shows the design variable cases when the 150 kW motor's rpm is 3,125 and 5,000. The object function minimizes the fuel consumption.

3.2.2 Hybrid Algorithm

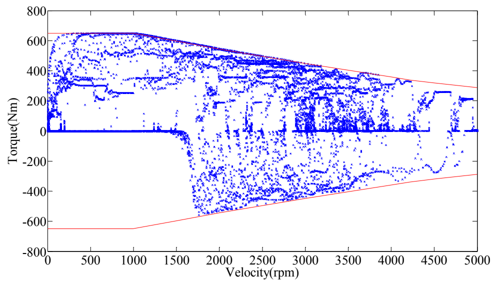
The proposed algorithm in this research is a hybrid algorithm that uses both the RSM and univariate method. The RSM is used to establish the best point of the objective function in the design variable domain, and the univariate search method reestablishes the optimal point near that best point. Although the RSM is well known for finding the optimal point in a straightforward and quick manner, a more precise objective function value searching was required. Thus, the hybrid algorithm using the RSM and univariate search method was adopted. The univariate method finds the optimal point by fixing all of the variables except for one variable and determines the optimal point for the one variable; this process is repeated for all of the other variables. Figure11 shows the flow of the proposed algorithm.

Table 2: Design variables

Design variables	Range
90 kW motor's maximum operating rpm	5,000 ~ 8,000 rpm
150 kW motor's maximum operating rpm	3,125 ~ 5,000 rpm



(a) Maximum operating rpm: 3,125 rpm



(b) Maximum operating rpm: 5,000 rpm

Figure10: 150 kW motor design variable cases

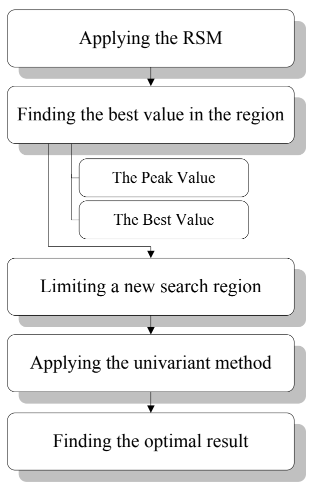


Figure11: Hybrid algorithm flow

4 Simulation Results and Discussion

To apply the RSM, the central composite design (CCD) was adopted; the sample points were chosen with alpha 1.414, and Figure12 shows the RSM result with equation (7).

$$f(x,y) = 4288.45 + 5.66\times10^{-3}x - 3.45\times10^{-1}y + 7\times10^{-6}x^2 + 5.14\times10^{-5}y^2 - 2.3\times10^{-5}xy \quad (7)$$

However, the peak value of the curve was found outside of the region, and the best value inside of the region was at (*x*, *y*) = (7,812, 5,000). The univariate search method with the best point as a center was then applied to the cross-domain that was the same size of the design variable area for a more exact solution, as shown in Figure13. When applying the univariate search method, the first fixed variable was *y* (150 kW motor's maximum operating rpm) because the peak point is over 5,000 rpm; thus, the gear ratio that makes the 150 kW motor's maximum rotating rpm 5,000 is sensible. Then, the univariate search method found the optimal value in region *x* (90 kW motor's maximum operating rpm). The best point was determined to be 7,500 rpm. Thus, the variation along the *y*-axis was repeated. The result of this analysis is given in Figure15.

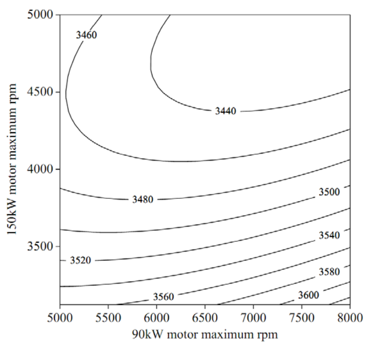


Figure12: RSM of the problem

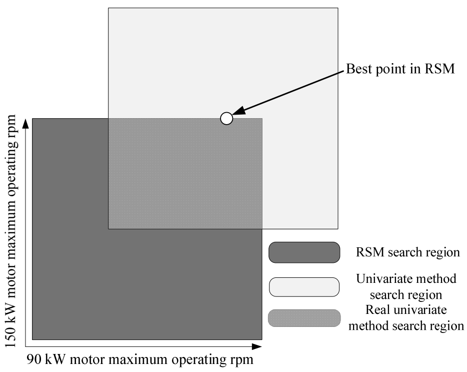


Figure13: Hybrid algorithm application

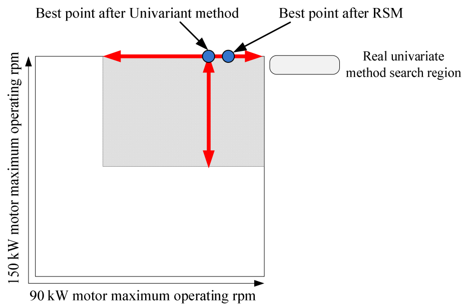
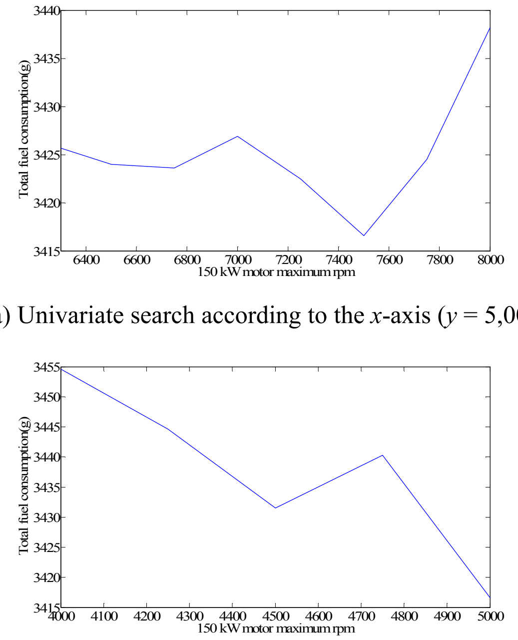


Figure14: Univariate search method's searching region



(a) Univariate search according to the *x*-axis (*y* = 5,000)

(b) Univariate search according to the *y*-axis (*x* = 7,500)

Figure15: Univariate search method result

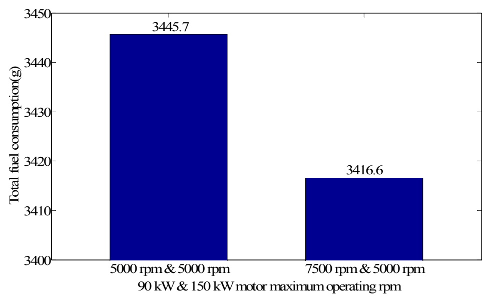


Figure16: Total fuel consumption

Figure14 shows the search direction of the univariate method, where the optimal result was found at (*x*, *y*) = (7,500, 5,000). Therefore, the gear ratio that makes the 90 kW and 150 kW motors use the maximum operation rpms of 7,500 and 5,000, respectively, was the best. Figure16 shows the final result compared with the cases in which both motors use the same maximum rpm of 5,000 and when the 90 kW motor uses 7,500 RPM and the 150 kW motor uses 5,000 RPM. Thus, the total fuel consumption was reduced by 0.84 %.

Conclusion

This paper studies the gear ratio effects of matching different motors in the series hybrid vehicle. In the case of the series hybrid bus, the traction motor capacity is typically very large so the motor can be operated with dual motors but the vehicle traction motor efficiency by the gear ratio was not considered. Thus, this paper investigates how the gear ratio should be established when designing the series hybrid electric vehicle by taking the fuel economy of the system into account. Thus, the hybrid algorithm using the RSM and univariate search method was adopted to determine the gear ratio; this algorithm is straightforward and more exact than using the RSM alone. Thus, the result resulted in a fuel consumption reduction of 0.84 %. The proposed strategy can be adopted for any vehicles with dual motor tractions, including the hybrid electric, electric, and plug-in hybrid electric vehicles.

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