Efficiency Optimization and Control of Auxiliary Power Unit for Extended Range Electric Vehicles

Gengchen Liu*, Jianwu Zhang

National Engineering Laboratory for Automotive Electronic Control Technology, School of Mechanical Engineering, Shanghai Jiao Tong University

*lgcsjtu@sina.com

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Abstract. How to determine the target engine operation point is a key issue of APU (Auxiliary Power Unit) control, which has a significant influence on fuel consumption of the system. Conventionally, engine operation point was decided by ensuring that the engine works in its maximum efficiency area. However, System efficiency of APU equals the product of engine efficiency and generator efficiency. Conventional method did not pay special attention to the generator efficiency. Based on analysis of how generator efficiency and engine efficiency influence fuel consumption of the system, a fuel optimal control method with consideration of both engine and generator efficiencies is proposed. Numerical models of generator efficiency and engine efficiency are established based on experiment data. An backward optimization algorithm is proposed to calculate optimal engine operation points in order to achieve highest overall efficiency of the engine-generator system. A simulation model is established to validate the optimal algorithm, simulation results indicates that the fuel consumption of the system is reduced by more than three percent after optimization.

1 Introduction

Drivers of Electric Vehicles (EV) often worry that the batteries may run out before reaching their destinations[1,2]. Extended Range Electric Vehicle (EREV) eliminates the problem of range anxiety by using an Auxiliary Power Unit (APU) as backup when batteries are depleted. Schematic diagram of EREV is shown in Fig. 1, an Internal Combustion Engine (ICE) is connected to a generator by an axis. The combination of the two is defined as the APU. There’s no mechanical connection between the APU and the drive shaft, and the APU is connected to the drive motor and battery pack via an electrical power bus, and usually, via some kind of coupling device with varying degrees of complexity. In simpler implementations, when SOC of the battery pack drops below a pre-defined threshold, the APU starts to work, and supplies extra electrical power to the drive motor and battery pack, making the driving range of EREVs comparable to conventional ICE vehicles [3,4].

Figure 1. Schematic diagram of EREV.
Control strategy of the APU partly determines system fuel economy. Conventional control strategies of the APU improve fuel economy by ensuring that the engine works in its high efficiency area\([5]\). However, this strategy paid no attention to the efficiency of the generator. As the engine is connected to the generator by an axis, the overall efficiency of the APU equals the engine efficiency multiplied by the generator efficiency. The generator efficiency ranges from 70% to 96% within its feasible working area\([6,7,8]\), which also has considerable influence on overall fuel consumption of the system. Therefore, in order to minimize fuel consumption under a certain driving condition, we must also take the efficiency of the generator into consideration. Because the engine output shaft and the generator input shaft are connected on the same axis, the efficiencies of the two cannot be adjusted independently. Thus, it is difficult to determine the target engine operation point under different vehicle operating conditions, to achieve maximum overall efficiency. To solve this problem, a backward optimization algorithm is proposed. In the algorithm, calculations of the target engine operating speed and torque under any given working condition are described. Simulation models are established based on experiments, to validate the optimization algorithm.

### 2 Influence of engine efficiency and generator efficiency on fuel consumption

Under a given electric power output demand, the target of the control strategy is to minimize fuel consumption. If engine power is represented as \( P_e \), fuel consumption of the engine can be represented as:

\[
 g_f = b_e P_f
\]

(1)

Where

- \( g_f \) — Fuel consumption of engine,
- \( b_e \) — Brake specific fuel consumption (BSFC),
- \( t \) — Working Time.

If we represent the electric power output demand of the APU as \( P_i \), efficiency of the generator as \( \eta_w \), the output power demand of the engine can be represented as:

\[
 P_e = P_i / \eta_w
\]

(2)

The relationship between \( b_e \) and engine efficiency \( \eta_e \) can be represented as\([9,10]\):

\[
b_e = 3600000 / (\eta_e R) = k / \eta_e
\]

(3)

Where \( k = 3600000 / R \), \( R = 46000 \) kJ/kg (caloric value of gasoline). Fuel consumption of the engine can be solved from Eqs. (1)–(3):

\[
 g_f = k P_i / \eta_e \eta_w
\]

(4)

In typical APU configurations, the engine is connected directly to the generator via an axis, thus, both \( \eta_e \) and \( \eta_w \) change with respect to the working speed and torque of the engine. Overall system efficiency of APU can be represented as \( \eta_{sw} = \eta_e \eta_w \). It is seen from equation (4) that under the same electric power output demand \( P_i \), fuel consumption of the engine \( g_f \) is determined by overall system efficiency of the APU.

### 3 Numerical model of engine and generator Efficiency

The optimization algorithm was carried out on an EREV system to evaluate its effectiveness. Numerical models of the engine and generator efficiencies were established by experiment.
3.1 Numerical model of engine efficiency

As shown in equation (3), the relationship between $\eta_e$ and $b_e$ is $\eta_e = \frac{3600000}{(b_e R)}$. Brake specific fuel consumption of the engine under different engine speed and torque is obtained by experiment[11], and engine efficiency under different engine speed and torque is then calculated from equation (3). Experiment results of the engine efficiency under different engine speed and torque is shown in fig. 2, where the efficiency of the engine can be represented as $\eta_e = f(n_e, T_e)$.

3.2 Numerical model of generator efficiency

Generator efficiency changes with respect to its working speed and torque, and can be represented as $\eta_g = f(n_g, T_g)$. Experiment results of generator efficiency under different input speed and torque is obtained by experiment and shown in fig. 3.

For the convenience of optimization, relations between $\eta_g$, $n_g$ and $T_g$ could be converted to relations between $\eta_g$, $\eta_e$ and $P_i$, i.e. $\eta_g = f(n_g, P_i)$. As the engine and generator were connected by one axis, i.e. $n_g = n_e$, $\eta_g$ could be represented as $\eta_g = f(n_e, P_i)$.

![Figure 2. Numerical model of engine efficiency.](image)

![Figure 3. Numerical model of generator efficiency.](image)

4 Optimization of engine working speed and torque for maximum system efficiency

4.1 Definition of optimization

According to the analysis:

$$g_f = \frac{kP_f}{\eta_e \eta_g} = \frac{kP_f}{f_1(n_e, T_e)f_2(n_e, P_i)}$$

(5)

The optimization can be summarized as follows: Under a given APU electric power demand $P_i$, find the optimal engine working speed and torque to get maximum system efficiency of APU.

Objective function of the optimization is: $\max(\eta_{sys})$, where $\eta_{sys} = \eta_e \eta_g$.  

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Constraints of the optimization:

\[
\begin{align*}
T_e & \leq T_{\text{emax}}(n_e) \\
T_e & \leq T_{\text{ge}}(n_e) \\
n_{\text{emin}} & \leq n_e \leq n_{\text{emax}} \\
(T_e \cdot n_e) / 9550 & = P_i / \eta_{\text{ge}}(n_e, P_i)
\end{align*}
\]

Where

- \(P_i\) — Electric power output demand of APU,
- \(T_{\text{emax}}\) — Maximum engine torque under given engine speed,
- \(T_{\text{ge}}\) — Maximum input torque of generator under given input speed,
- \(n_{\text{emin}}\) — Minimum engine speed,
- \(n_{\text{emax}}\) — Maximum engine speed,
- \(\eta_{\text{ge}}(n_e, P_i)\) — Efficiency of generator under \(n_e\) and \(P_i\).

4.2 Optimization algorithm

In the APU, the engine and generator are connected by one axis, both engine efficiency and generator efficiency change with respect to engine speed and torque, which makes the optimization problem difficult to solve. A backward-facing algorithm is proposed to tackle the problem. Progress of the backward-facing algorithm is shown in Figure 4. The general idea of the backward-facing algorithm can be summarized as follows: In the EREV system, \(P_i\) changes from 0 to 45kw using \(\Delta P\) as a fixed step. Under each value of \(P_i\), engine speed \(n_e\) changes from minimum to maximum using fixed step \(\Delta n_e\), system efficiency at every engine speed was calculated. When system efficiency gets its maximum value, use the specific engine speed and torque as target engine speed and torque under current \(P_i\).

As shown in Fig.4, system efficiency \(\eta_{\text{sys}}\) under certain \(P_i\) and \(n_e\) can be calculated as follows:

1) Generator efficiency \(\eta_{\text{ge}}\) under current \(P_i\) and \(n_e\) can be obtained from the numerical model of generator efficiency.

2) Engine output power can be calculated from \(P_i\) and \(\eta_{\text{ge}}\), relations between the three parameters can be represented as:

\[P_e = P_i / \eta_{\text{ge}}\]  

(7)

3) Engine output torque can be calculated as follows:

\[T_e = (P_e \cdot 9550) / n_e\]  

(8)

4) Maximum output torque of engine under certain \(n_e\), i.e. \(T_{\text{emax}}\), can be obtained from external characteristic curve of engine. Maximum input torque of generator under certain \(n_e\), i.e. \(T_{\text{ge}}\), can be obtained from external characteristic curve of generator.

5) Check if the calculated engine torque \(T_e\) satisfies the constraints \(T_e < T_{\text{emax}}\) and \(T_e < T_{\text{ge}}\). If the above conditions were not satisfied, which means \(T_e\) exceeds the capability of engine or generator, then go to next \(n_e\). If the above conditions were satisfied, then go to step 6.

6) Engine efficiency under current \(n_e\) and \(T_e\), i.e. \(\eta_{\text{sys}}\), can be obtained from the numerical model of engine efficiency. System efficiency of the APU can be calculated using the follow equation:

\[\eta_{\text{sys}} = \eta_e \eta_{\text{ge}}\]  

(9)

Follow the above steps to calculate system efficiency at all discrete engine speeds. When system efficiency gets its maximum value, use the specific engine speed and torque as target engine speed and torque under the calculating \(P_i\). Control the engine throttle to reach the target engine speed, and control the excitation current of generator to reach the target engine torque, then the APU is able to work at maximum system efficiency point under various electric power demands.
4.3 Results of the optimization

Set $\Delta P_e = 1$, $\Delta n_t = 10$, results of the optimization were shown in Fig. 5-8. Fig. 5 shows the optimized target engine speed and torque when system efficiency gets its maximum value. In real control, use fig.5 to determine target engine speed and torque, control the engine throttle to reach the target engine speed and control the excitation current of generator to reach the target engine torque. Using this method, the APU can be guaranteed to working at its maximum efficiency point under any electric power demand.

Figure 4. Illustration of the optimization algorithm.
Figure 5. Comparison of target engine speed and torque before and after the optimization.

It can be seen from Fig.5 that, target engine speed after optimization is higher than target engine speed before optimization. Target engine torque after optimization is lower than target engine torque before optimization. We can plot engine work point at each output power on the universal characteristic diagram of the engine, as shown in Fig.6. In Fig.6, line ‘a’ represents the external characteristics of engine torque. Line ‘b’ represents the external characteristics of generator input torque. ‘c’ is a set of line each represents a certain output power. ‘d’ is a set of line each represents a certain engine efficiency. Line ‘E’ represents engine working point at each output power before optimization. Line ‘S’ represents engine working point at each output power after optimization.

As engine and generator were coaxially connected, on stable working conditions, generator has the same speed and torque with engine, i.e. \( n_g = n_e \), \( T_g = T_e \). As we know the target engine speed and torque at different electric power demand, we can plot generator work point at each output power on the efficiency characteristic diagram of the generator, as shown in Fig.7.

We can see from Fig.6 and Fig.7 that, before optimization, engine works on its maximum efficiency working point, but generator efficiency is low, which results in a low overall system efficiency. After optimization, engine works at a higher speed and lower torque under same output power, engine efficiency was lower than before, but generator efficiency is much higher, thus leading to a higher over all efficiency.
Figure 6. Engine target working point at different output power before and after optimization.

Figure 7. Generator target working point at different output power before and after optimization.

Engine efficiency at different electric power demand before and after optimization is shown in Fig. 8(a). Generator efficiency at different electric power demand before and after optimization is shown in Fig. 8(b). Fig. 8(c) is the overall system efficiency of APU at different electric power demand before and after optimization. We can see from these figure that, under a given electric power demand, after the optimization, the engine efficiency and generator efficiency are not necessarily each at their own respective highest value, but the product of the two is at the highest, therefore the overall efficiency of sytem is higher after optimization. Fig. 8(d) shows the difference of system efficiency after and before optimization. It can be seen from the figure that system efficiency of the APU increased by 0%-5% at different electric power demands.
5 Simulation and analysis

5.1 Schematic diagram of the simulation program

In order to follow the optimized engine speed and torque, APU must be properly controlled, schematic diagram of APU control structure was shown in Fig.9. As in Fig.9, the vehicle control module export electric power demand \( P_i \) based on power following control strategy, using target vehicle speed, actual vehicle speed and current SOC as its input. The electric power demand \( P_i \) is transferred to the APU control module. The APU control module exports target engine speed and torque under \( P_i \) using the optimized data. Engine throttle was controlled to reach the target engine speed, and excitation current of generator was controlled to reach the target engine torque. With this control method, engine and generator can work along the optimized working line where system efficiency gets its maximum value.

In Fig.9, the power combiner module calculates charge and discharge power of the battery, i.e. \( P_{bb} \), using output current of the generator \( I_g \), output voltage of the generator \( U_g \) and electric power consumed by the drive motor \( P_m \). Charge and discharge power of the battery \( P_{bb} \) was transfer to battery module. The battery module calculates current SOC and feeds it back to the vehicle control module. The drive motor module controls the drive torque \( T_m \) based on target drive power \( P_m \) given by vehicle control module and actual motor speed \( n_m \) given by vehicle dynamic module. Vehicle

Figure 8. Analysis of the system efficiency before and after optimization.
dynamic module calculates the actual vehicle speed $v$ and actual drive motor speed $n_m$ based on vehicle dynamics, using drive torque $T_m$ and braking torque $T_r$.

5.2 Analysis of the simulation results

Control strategy before and after optimization were simulated and compared. In this section, we take the UDDS cycle as an example to analyse the simulation results. Control strategies of EREV require using electric power as much as possible, and the APU only start to work when SOC drops below a certain threshold. With the particular vehicle we used in this research, the energy consumption of one UDDS cycle isn't enough to get the SOC lower than the threshold, so 3 UDDS cycles were used in the simulation. The 3 UDDS cycles were connected one after another, making the distance of the driving cycles long enough to start the APU.

![Simulation results of three continuous UDDS cycle.](image)

Figure 10. Simulation results of three continuous UDDS cycle.
Figure 11. Simulation results of engine and generator operating point with conventional and optimal control algorithm.
Results of the simulation were shown in Fig.10-12. Fig.10 illustrates some of the simulation results. It can be seen from Fig.10 that, curves of SOC remain almost the same before and after optimization control algorithm is used. Electric power demand from APU is basically the same too. The reason for this is that the electric power demand is mostly determined by the drive cycle used. Fig.11 illustrates simulation results of engine and generator operating points, with conventional and optimal control algorithm respectively. We can see from Fig.7 and Fig.11 that simulation results of engine and generator operating points fluctuate in the vicinity of target operating line. Simulation results illustrate that the control structure and control algorithm are effective. Fig.12 shows simulation results of system efficiency with different control algorithms. We can see from the figure that engine efficiency under optimal control algorithm is lower than that of conventional control algorithm. However, generator efficiency under optimal control algorithm is much higher than that of conventional control algorithm, which leads to a higher overall system efficiency under optimal control algorithm. Simulation results illustrate that overall efficiency of the system increased by 2-6% after optimization.

6 Conclusion

(1) Conventionally, engine operation point is determined by ensuring that the engine works in its maximum efficiency area. However, system efficiency of the APU equals the product of engine efficiency and generator efficiency, and conventional method paid no attention to the generator
efficiency. Based on the analysis of how generator efficiency and engine efficiency affect fuel consumption of the system, a fuel optimal control method with consideration of both efficiencies is proposed.

(2) Numerical models of the engine efficiency and generator efficiency are established based on experiment data. An algorithm is proposed to calculate optimal engine operation points in order to achieve highest overall efficiency of the engine-generator system.

(3) Simulation model is established to validate the optimal algorithm. The results indicate that fuel consumption of the system is reduced by 3% - 4% after optimization.

References


