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# Multi-objective optimization study of energy management strategy and economic analysis for a range-extended electric bus

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## HIGHLIGHTS

- SOH loss model is built for predicting the life of battery pack.
- Multi-objective optimization method is proposed to match the battery SOH and APU fuel consumption.
- DP is applied in control strategy design for solving the multi-objective problem.
- Influences of battery capacity and battery SOH penalty coefficient on total cost of REEB.

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## ABSTRACT

A method of multi-objective optimal energy management is proposed to match the APU fuel consumption and the battery state of health (SOH) in the power system of a range-extended electric bus (REEB). Models are established for the calculation of an auxiliary power unit (APU) system fuel consumption and battery SOH loss. The APU fuel consumption and battery SOH are selected as the optimization objectives, and a performance functional of the multi-objective optimization is provided. The dynamic program (DP) algorithm is applied in the control strategy design for solving the multi-objective problem. Under the conditions of the Modified New European Drive Cycle (MNEDC) and Chinese Typical Urban Drive Cycle (CTUDC), which have been used to evaluate the performance of the proposed methodology, the matching-relation between SOH penalty coefficients of battery pack and APU fuel consumption, the SOH of a battery pack can be analysed. Taking the costs of a battery pack and fuel consumption in the whole life cycle as the comprehensive evaluation index, an optimization design method is proposed to match the capacity and the SOH of the battery pack. The simulation results show that when batteries do not need to be replaced, the best economical results will be achieved if the parameters of battery pack and the control strategy parameters are both taken the minimum.



## 1. Introduction

At present, pure electric vehicles are faced with some disadvantages, such as short driving range, inconvenient charge service, long charging time, short life and high battery pack prices. To solve these disadvantages, REEBs are designed with APUs and small capacity battery packs [1]. REEBs have the advantages of both the pure electric drive model and the hybrid power drive model, and they also can extend driving ranges and reduce cost. Thus, this model is gradually becoming a development trend of electric vehicle products [2,3].

The energy management strategy is critical for a REEB to extend driving ranges and reduce engine fuel consumption [4–6]. There are two main controlling modes: blended (BL) and charge depleting-charge sustaining (CD-CS) [7]. The BL control mode, with the goal of maximizing the use of clean and cheap electricity, does not have the working condition of pure electric drive, while the CD-CS control mode, with the goal of reducing emissions and improving fuel efficiency, does have the working condition of pure electric drive. In view of these reasons, this study adopts the CD-CS mode and mainly focuses on the CS section. Energy management strategies are usually carried out on the basis of four control methods: rule control, instantaneous optimal control, global optimization control and self-adaptive control [8,9]. To determine the optimal strategy, researchers have conducted a series of studies using the optimal control algorithm of modern control theory [10] and found that the most widely used strategy is the global

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optimization control strategy using the DP algorithm. The strategy can be used to obtain optimal fuel consumption in known conditions and evaluate control effects of other energy management strategies in the actual application [11–15].

Compared to pure electric vehicles, REEBs have relatively less battery capacity. They are not advisable: the majority of the existing research focuses only on fuel efficiency because it may limit the life of the battery pack and thereby increase the cost. Thus, the health state of the battery needs to be considered. Serrao et al. propose an energy management strategy for hybrid electric vehicles (HEVs) with consideration of both fuel consumption and battery ageing, but the authors convert the cost of battery replacement to the cost of fuel consumption and use the postulated ageing model rather than an experimental validated model [16]. Moura et al. consider the battery health by using an electrochemical model to describe solid electrolyte interphase (SEI) growth when they propose an energy management strategy for plug-in hybrid electric vehicles (PHEVs) by stochastic control [17]. Ebbesen et al. impose the SOH model to represent the battery ageing model. However, the energy management strategy proposed by the authors does not fully explore the tradeoff between the cost of the battery and the cost of fuel consumption [18]. To determine the tradeoff, it is necessary to establish a properly ageing model.

Battery ageing models are mainly divided into three types [19]: electrochemical ageing models, Ah-throughput-ageing models and ageing event-based models. Compared to the other two models, the electrochemical ageing model has the most complex effect factors and the highest accuracy and reliability. Unfortunately, the calculation of the simulation is rather large, and the electrochemical parameters are difficult to obtain accurately. Ning et al. have developed a 1-D ageing model of battery internal resistance and capacity, and their experimental results prove that the model is of high prediction accuracy [20]. Matthew B.S. of the University of Waterloo in Canada simplified Ning's model, and applied it to analyse battery ageing in a vehicle simulation environment [21]. Both modes of the Ah-throughput-ageing model and ageing event-based model take capacity losses as the results are caused by different conditions. However, the parameters and limitations of the two models are different. HRL Lab of USA and Wang et al. from GM Corporation have conducted many life experiments on lithium-ion phosphate batteries [22], and the Ah-throughput-ageing model was ascertained by fitting the experiment data.

According to the above research, the energy management problem in REEBs is formulated as a multi-objective optimal control problem, and the control algorithm is required to find a tradeoff between two objectives: (1) minimizing fuel consumption of APU and (2) minimizing battery SOH loss. In this study, the APU fuel consumption model, the battery model and the power demand model of a DC bus are built based on the powertrain of the REEB. Then, the multi-objective performance function of the APU fuel consumption and the battery SOH is proposed and optimized by using the DP algorithm. Based on the results of single-objective and multi-objective optimizations, respectively under specific working conditions, the effect of the penalty coefficient on fuel consumption and battery SOH is analysed. Finally, from the economical perspective of energy management, a design optimization with respect to the battery pack configuration and the SOH penalty coefficient is conducted, and the results can provide an important basis for initial design parameters.

The organization of this paper is as follows: Section 2 illustrates the compositions of the Power System for REEB. Section 3 describes the multi-objective optimization of engine fuel consumption and battery SOH. Then, the optimization results and the economic analysis are presented in Section 4. The conclusions are presented in Section 5.

## 2. Compositions of the power system for REEB

### 2.1. Configuration of the power system

According to differences between mixed modes of hybrid drive, the power system of REEB has three main types of powertrain structure: series, parallel, and series-parallel. This paper adopts the series structure. Compared with the other two structure types, the series structure has some advantages. For example, the structure of the powertrain system is simple and the cost is low. The battery pack used as the main energy sources can provide all the power demanded in the CD section of CD-CS control mode, and the APU will start to work only when the SOC of the battery pack is at a relatively low level. Because there are no mechanical connections between the engine and the driving wheels, APU can theoretically work at any point on the speed torque map [23]. The structure of the power system is shown in Fig. 1, and the basic parameters are shown in Table 1. The APU system adopts a diesel engine with a maximum power of 80 kW, which is coaxial with the permanent magnet synchronous generator. The system is transformed into DC by the rectifier. The driving motor is the permanent magnet synchronous motor with a maximum power of 180 kW and a maximum torque of 850 Nm. Voltage matching can be achieved by a DC/DC converter between the battery pack and the APU systems. The parameters of the battery cell and pack are shown in Table 2.

### 2.2. System modelling

#### 2.2.1. Fuel consumption model of APU system

The combustion process of an engine is a multivariate nonlinear process, and its analysis involves knowledge of flow, combustion and dynamics. Its dynamic characteristic is not the focus of this paper. Therefore, the study of the APU fuel consumption only takes into account the torque and the speed without consideration of dynamic effects. The speed differential equation of the APU can be determined by Eq. (1).

$$T_{eng}(k) - T_g(k) = 0.1047(J_e + J_g)\frac{n_g(k+\Delta T) - n_g(k)}{\Delta T} \tag{1}$$

where $T_{eng}$ denotes the engine output torque, $T_g$ denotes the generator electromagnetic torque, $T_f(k)$ denotes the connection resistance torque for the engine and generator, $(J_e + J_g)$ denotes the rotational inertia with both engine and generator contributions, and $n_g$ denotes the speed of the engine.

Based on the above differential equations, the engine fuel consumption $m_f(k)$ can be a checked through the fuel consumption map of the engine, which leads to Eq. (2).

$$m_f(k) = f_e(n_g(k), T_{eng}(k)) \tag{2}$$

To establish the relationship between the APU and the DC bus power, a generator-rectifier model is established by the generator electromagnetic torque. This paper adopts the equivalent circuit method [24]. The equivalent circuit diagram is shown in Fig. 2

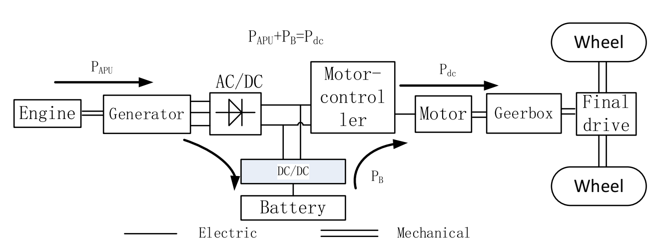


**Fig. 1.** Configuration of the REEB.