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An optimal structure selection and parameter design approach for a dual-motor-driven system used in an electric bus

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ABSTRACT

A number of driving system topologies have been developed for electric vehicles, but the topology design and optimal sizing always challenge the performance of electric vehicles. This paper attempts to address three aspects. First, two novel topologies were derived from the original dual-motor-driven system, and the efficiency models of the system components were built, including motor efficiency, planet gear system efficiency and drag loss of the wet clutch. Second, a systematic optimal sizing framework was constructed. The feasible region of the design parameters was divided into a certain number of grid points, and each grid point represented different design results. Then, a dynamic programming algorithm was applied to each grid point to locate the optimal control strategy and obtain the best grid points under different power levels. After that, a bi-level optimization method was applied at these selected grid points to find the optimal design parameters. Last, the simulation results showed that, compared with the original design, the new topology with two clutches can reduce energy loss by 12.4%, and the optimal design results for the original topology can reduce energy loss by 3.36%.

1. Introduction

Increasing air pollution and decreasing fossil fuel supply have encouraged the development of BEVs (battery electric vehicles) [1]. BEVs seems to be a promising solution to these problems as they can realize zero emissions, and electric power can be obtained from various reproducible or clean sources, such as solar energy, water energy, wind energy and nuclear energy [2]. However, the disadvantages of BEVs, such as high cost, short drive range and long charging time, have obstructed their wide application in the private vehicle market [3]. Thus, to generalize the application of BEVs in public transportation first seems to be a better choice. Considering the traffic congestion in city driving conditions, the employment of a dual-motor-driven electric bus can effectively promote the vehicle's efficiency performance [4]; when the vehicle speed and power requirement is low, the vehicle could be driven by a small motor, and when the vehicle speed and power requirement is high, the vehicle can be driven by two motors [5]. The proper topology design and power management strategy can effectively promote the efficiency performance of EVs [6], and significant improvement may help reduce the number of batteries [7] and promote the driving range [8].

1.1. Literature review

Researchers have conducted much valuable work in developing different types of electric or hybrid electric driving systems to promote their performance [9]. The architectures of EVs (electric vehicles) can be classified into four types [10]: series hybrid electric drive trains [11], parallel hybrid electric drive trains [12], series/parallel hybrid electric drive trains and complex hybrid electric drive trains. In the series hybrid electric drive trains, the APU (assistant power unit) does not have mechanical connection with the wheels [13], which makes it possible to always keep the APU (engine-generator) working in its optimal operation points or working according to the optimal fuel rate line [14]. In the parallel hybrid electric drive trains, the engine has the mechanical connection with the wheels, and the working condition of the engine will sometimes change according to the driving conditions [15]. Based on the relationship between the engine and motors, a parallel hybrid system can be classified as a torque coupling system [16], speed

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coupling system [17] or torque-speed coupling system [18]. In terms of BEVs, the topologies can be classified into two categories according to their distribution methods: distributed driving (D-D) and centralized driving (C-D). In the D-D topologies, the driving motors are installed near wheels or integrated with the wheels [19]. This type of topology is space-saving and of high efficiency due to its compact structure and short transmission chain [20]. Compared with D-D topologies, C-D topologies take over more from conventional vehicles. The C-D vehicles can be seen as a conventional vehicle whose engine is replaced by a motor [21].

Once the driving system topology of an EV is determined, a reasonable parameter sizing and a power management design method are necessary to ensure the excellent performance of the vehicle [22]. Many optimal theories have been applied in power management, such as the PMP (Pontryagin maximum principle) [23], DP algorithm (dynamic programming) [24], and SDP (stochastic dynamics programming) [25]. Given a driving cycle, the DP algorithm can effectively locate the global optimal control strategy [26]. Though the DP algorithm cannot be applied in the online condition because this method needs future road grade and vehicle velocity information [27], the DP algorithm is one of the best choices in integration optimal sizing. The optimal control strategy and optimal system parameter design is a coupled problem, which means an optimal control strategy with unsuitable system parameters cannot guarantee optimal system performance. Ref. [28] summarizes four types of combined optimization strategy, including sequential, iterative, bi-level, and simultaneous methods. Ref. [29] applied a bi-level optimal design method for a hybrid vehicle, where the optimal control is obtained by discretizing the associated Hamilton–Jacobi–Bellman equations, and the optimal design parameters are obtained by solving a non-convex non-smooth optimization problem with a bundle method. Ref. [30] proposed an optimal sizing frame work based on NLPQL (nonlinear programming by a quadratic Lagrangian) algorithm and DP algorithm for a heavy hybrid electric truck. Refs. [31] and [32] applied particle swarm optimization and genetic algorithms, respectively, to design the parameters for HEVs. Most of the previous work is to design the parameters for HEVs, but for BEVs, the optimization targets are quite different. For a BEV, fuel consumption and exhaust emissions no longer need to be considered. The most needs to be considered are three aspects: system efficiency performance, motivation performance and system costs.

Ref. [33] proposed a parameter design method for a DMDS (dual-motor-driven system) based on engineering experience. In this design process, the rated power for two motors is determined by vehicle motivation requirement, and the design target is to minimize the system power level, but the system efficiency performance is not considered. Alternately, the output power of the motor connected with the ring gear will exceed its rated power when the vehicle speed is at 80 km/h due to structural constraints. Ref. [34] applied the PMP (Pontryagin's Minimum Principle) algorithm to optimize the control strategy for the topology presented in Ref. [33]. The PMP results show that, in the optimal condition, the system prefers to use an auxiliary motor while maintaining the main motor in the low-power condition, which indicates that if the main motor is connected with the braking clutch, the system performance may be improved.

1.2. Motivation and innovation

To improve the performance of DMDS, this paper derived two new DMDS topologies to investigate which types of topology are the best for the target electric bus. At the same time, a design framework was constructed to optimize the parameters for the three topologies. The power level and efficiency performance of the system were considered in the parameter design process. A bi-level optimal design method was iteratively applied under different power levels to locate the optimal parameters for each topology. The components' efficiency models were built, including motor efficiency, gear system efficiency and wet clutch losses. The influence of the design parameter was analyzed.

1.3. Organization of the paper

This paper is organized as follows: in Section 2, the DMDS configurations and original design are introduced; the DMDS modeling and optimization framework is displayed in Section 3; the simulation results and discussion are given in Section 4; and finally, conclusions are presented in Section 5.

2. DMDS configurations and original design

2.1. DMDS configurations

The target vehicle in this paper is a pure electric bus, and the target system is a DMDS developed by Beijing Institute of Technology, as displayed in Fig. 1(b) [33]. The power sources of the system are two motors: Motor-S and Motor-R. The Motor-S is connected with the sun gear, and the Motor-R is connected with the ring gear. The output power of the driving motors goes through the planet mechanism, reduction gear and wheels. The DMDS is a speed coupling system, which means that the output speed of the system is the linear superposition of the rotation speed of two driving motors. There is a wet clutch connected with the ring gear, and the wet clutch is used for working mode switching. This structure has two working modes: dual-motor working mode (when the wet clutch is disengaged) and Motor-S working mode (when the wet clutch is engaged). The topologies in Fig. 1(a) and (c) show two new structures derived from the original structure in Fig. 1(b). It is worth noting that the topologies displayed in Fig. 1(a), (b) and (c) are abbreviated as the Two-clutch topology, R-clutch topology and S-clutch topology, respectively, and the clutch connected with the sun gear shaft and ring gear shaft will be abbreviated as clutch 2 and clutch 1, respectively. Compared with the R-clutch topology, the Two-clutch topology adds another clutch to the shaft of the sun gear, which enables the system to work in three working modes: dual-motor working mode (when two clutches are disengaged), Motor-S working mode (when clutch 1 is engaged and clutch 2 is disengaged) and Motor-R working mode (when clutch 2 is engaged and clutch 1 is disengaged). The S-clutch topology has the same clutch number as the R-clutch topology, but the clutch is placed in the sun gear shaft, not the ring gear. The S-clutch topology has two working modes: dual-motor working mode (when the wet clutch is disengaged) and Motor-R working mode (when the wet clutch is engaged).

2.2. Original design and operation principle for DMDS

The clutch behavior in the R-clutch topology mainly depends on vehicle speed. In low speed conditions, when the vehicle is accelerating or climbing, the clutch is engaged and DMDS can output a large torque by enlarging the output torque of the Motor-S through the planet mechanism. When the vehicle speed is high, the clutch is disengaged, and the Motor-R begins to work together with the Motor-S. The motivation requirement of the electric bus is displayed below:

(1) Highest vehicle speed reaches or exceeds 80 km/h;
(2) Maximum grade ability is 20% (with initial speed of 10 km/h);