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System design and energetic characterization of a four-wheel-driven series–parallel hybrid electric powertrain for heavy-duty applications

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ABSTRACT

Powertrain topology design is vital for system performance of a hybrid electric vehicle. In this paper, a novel four-wheel-driven series–parallel hybrid electric powertrain is proposed. A motor is connected to the differential of the rear axle. An auxiliary power unit is linked to the differential of the front axle via a clutch. First, a mathematical model was established to evaluate the fuel-saving potential. A rule-based energy management algorithm was subsequently designed, and its working parameters were optimized. The hybrid powertrain system was applied to a transit bus, and the system characteristics were analyzed. Compared to an existing coaxial power-split hybrid powertrain, the fuel economy of the four-wheel-driven series–parallel hybrid powertrain can be at the same level under normal road conditions. However, the proposed four-wheel-driven series–parallel hybrid powertrain can recover braking energy more efficiently under road conditions with a low adhesive coefficient and can alleviate the torsional oscillation occurring at the existing coaxial power-split hybrid powertrain. Therefore, the four-wheel-driven series–parallel hybrid powertrain is a good solution for transit buses toward more robust performance.

1. Introduction

Vehicle electrification is gaining popularity in the global vehicle market and has the potential to reduce lifecycle energy consumption and greenhouse gas emissions [1]. Currently, the mileage and lifetime of a pure electric vehicle are still less than those of a conventional vehicle. Therefore, using HEVs to save energy and improve the environment is a feasible and necessary approach. The fusion of electric machines into powertrains greatly diversifies powertrain architectures and enriches the means of saving energy.

Essentially, series, parallel, power-split, and series–parallel hybrid powertrains are currently in used [2]. The main architectures of the hybrid powertrains for heavy-duty applications are shown in Fig. 1. A basic series hybrid topology is shown in Fig. 1a. A motor is connected to the driving axle to propel the vehicle or recover braking energy. An engine and a generator are combined as an auxiliary power unit (APU), which can provide electric energy to the power line. Two parallel hybrid topologies are shown in Fig. 1b and c, respectively. An engine is linked to the powertrain via a clutch. If the clutch is disengaged, the entire system operates in the pure electric mode; otherwise, the engine and the electric propelling system output energy together to drive the vehicle. A dual-mode hybrid powertrain developed by Allision and GM that operates based on the power-split principle is shown in Fig. 1d [3]. A series–parallel hybrid powertrain for heavy-duty transit bus applications was studied by Ouyang et al., and the topology is given in Fig. 1e. When the clutch is disengaged, the system works in the series control mode. Once the clutch is engaged, the system switches to the parallel control mode [4].

The performance of a plug-in series hybrid electric powertrain developed for urban buses was evaluated through experimental tests, and impressive energy savings are achieved [5]. Damiani et al. studied a mild parallel hybrid powertrain adopting an intelligent transmission control and start/stop control and found that the fuel consumption can be reduced by 23% [6]. Bishop et al. also indicated that a parallel hybrid powertrain could obviously reduce fuel consumption [7]. Finesso et al. investigated the energy efficiency of a four-wheel-driven parallel hybrid powertrain [8]. Asaei presented the design, simulation, and manufacturing of a through-the-road parallel hybrid electric motorcycle with a brushless direct current motor in the front wheel [9]. A full hybrid electric motorcycle with power split e-CVT was studied by Chung and Hung, and a maximum fuel economy improvement of 32% was obtained

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Nomenclature

A	vehicle frontal area (m^2)
C	capacitance (F)
C_D	aerodynamic drag coefficient
F	tractive force (N)
f	rolling resistance coefficient
g	standard gravitational acceleration (9.8067 m/s^2)
h_g	height of center of gravity of the vehicle
i	speed ratio, current (A)
J	inertia (kg m^2)
L	wheelbase
L_a	distance between front axle and center of gravity of the vehicle
L_b	distance between rear axle and center of gravity of the vehicle
m	vehicle mass (kg)
P	power (W)
q	instantaneous fuel consumption (kg/s)
Q	equivalent fuel consumption (L/100 km)
R	resistance (Ω)
r_d	wheel radius (m)
s	slip of a tire
T	torque (N m)
t	time (s)
U	voltage (V)
v	vehicle velocity (m/s)
W	normal load acting on the axle

Greek letters

α	road angle (°)
β	ratio of front axle braking force to total braking force
δ	mass factor
η	efficiency (%)
μ	tractive force coefficient of a tire
ρ	air density (kg/m^3)
ω	angular speed of a tire

Subscripts

bf	braking force of the front axle
br	braking force of the rear axle
clt	clutch
df	driving force of the front axle
dr	driving force of the rear axle
eng	engine
f	front, fuel
fd	front differential
gen	generator
mot	motor
r	rear
rd	rear differential
sc	supercapacitor

Acronyms

APU	auxiliary power unit
CNG	compressed natural gas
CTBCDC	Chinese transit bus city driving cycle
DC/AC	direct current/alternating current inverter
ESS	energy storage system
e-CVT	electronic continuous variable transmission
FWD	four-wheel-driven
HEV	hybrid electric vehicle
ICE	internal combustion engine
OOL	optimal operation line
PMSG	permanent magnetic synchronous generator
PMSM	permanent magnetic synchronous motor
RWD	rear-wheel-driven
SOC	state of charge

[10]. All of these studies were concentrated on series, parallel, or power-split hybrid powertrains. Few of them focused on the four-wheel-driven hybrid architecture. To the best of our knowledge, no series–parallel hybrid topology was investigated. In fact, Hutchinson et al. analyzed 44 hybrid cars available in the US and found that most of the hybrid architectures are mild parallel and power-split hybrid powertrains at present [11].

Supercapacitors are the most direct method to store electricity, offering fast response with lifecycles of tens of thousands and very high efficiency, which make them very suitable for transit buses to smooth the short-term high-frequency fluctuations [12]. Supercapacitors are not only used for HEVs but also for other energy storage applications such as wind energy systems [13]. An equivalent circuit model is preferred to calculate the general performance of a supercapacitor instead of a detailed high-order model such as that proposed by Drummond et al. [14]. Sedlakova et al. designed a second-order two-branch equivalent circuit, and the results of NessCap supercapacitors show that the relative error is less than 5% [15].

Generally, rule-based strategies can be successfully used in the energy management of independent microgrids [16]. Similarly, this type of strategy can also be used for an HEV. Shabbir and Evangelou used a control map for the optimal power share between the engine and batteries [17]. Zhang et al. presented a sliding mode controller for a series hybrid powertrain [18]. An intelligent management system was designed using a fuzzy logic controller by Khayyama and Bab-Hadiashar [19]. On the other hand, a rule-based control can be combined with an optimal approach to form a suboptimal strategy for real-time applications. Torres et al. developed a rule-based optimal controller for a plug-in hybrid electric vehicle [20]. The optimal problem was calculated offline in advance. Hemi et al. employed Pontryagin's minimum principle and the Markov chain approach for the optimal energy management of a fuel cell/supercapacitor electric vehicle [21]. These rule-based control strategies can be implemented within a very short time. However, they must be optimized by a wide range of tests before being actually used. Recently, more advanced optimal algorithms such as nonlinear programming [22], gravitational search [23], and artificial bee colony [24] were applied to the energy management systems for islanded microgrids. However, the effectiveness of these approaches for an HEV is still not estimated.

In our previous investigation, the performance of a coaxial series–parallel hybrid powertrain was analyzed [4]. The coaxial series–parallel hybrid powertrain is a very high-efficiency topology for a transit bus under normal road driving conditions. However, if running on an icy road with a low adhesive coefficient, the acceleration time will be extended, and the recovered braking energy will obviously decrease. On the other hand, the engine, generator, clutch, and motor are connected by a long axle, which may cause serious vibration. Torsional oscillation is a common problem for HEVs owing to quick transient processes in which some of the components must alter their output torques swiftly [25], especially if a clutch is adopted [26].

To reduce the torsional oscillation of the coaxial series–parallel hybrid powertrain and improve the energy efficiency and driving