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A combined optimal sizing and energy management approach for hybrid in-wheel motors of EVs

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HIGHLIGHTS

- An innovative combined sizing/control concept for hybrid in-wheel motors of EVs.
- Two novel indexes: power ratio and *T–N* ratio for baseline motor modification.
- Global search method (GSM) utilized with nested-structure for-loop programs.
- 15+% energy improvement of combined sizing/control optimization for EVs under two driving scenarios.
- Real light-duty EV implementation in the future.

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ABSTRACT

In-wheel motors (IWMs) substantially influence the output performance of electric vehicles (EVs). Size design and control issues are two critical factors to be explored. This paper proposes the use of hybridization for integrating dual motors to enhance EV system dynamics. A combined optimal sizing/control approach was developed using the global search method (GSM). The optimal control (torque ratio) of dual motors was first proposed using the nested-structure for-loop program to minimize the consumed power according to various power ratios. The next combined sizing/control developed using the GSM facilitated the search for the optimal control, power ratios, and *T–N* (Torque–Speed) ratios to minimize the accumulated energy consumed during ECE40 and UDDS driving cycles. The results from simulations of these two cycles indicated that the energy consumption during optimal control improved by 1.23% and 1.40%, 8.34% and 7.16% after optimal sizing, and the combined optimization improved total consumed energy by 15.31% and 15.16%, respectively. These results suggest that employing the novel hybrid IWM powertrains while using the combined sizing/control method can facilitate energy conservation. A real testing platform will be developed in the future.

1. Introduction

Because of increasing environmental concerns and stringent legislation, fuel-efficient vehicles such as electric vehicles (EVs), fuel cell EVs, hybrid EVs, and plug-in hybrid EVs have been commercialized or developed by research organizations [1–3]. To increase the overall efficiency and reduce the occupied volume of the powertrain, several types of in-wheel motors (IWMs) have been developed and equipped with advanced features. For example, in [4], two permanent-magnetic-brushless-dc motors are connected directly in serial for the purpose of cutting down the differential algorithm in vehicle velocity control. In [5], it evaluated a series hybrid vehicle with four wheel motors experimentally. Types of IWMs motors include DC motors, inductance motors, permanent magnetic synchronous motors, and switched reluctance motors. Key factors that should be considered during motor selection are efficiency, cost, reliability, technological maturity, and power density [6,7]. Therefore, choosing an IWM with adequate traction to fulfill the requirements of vehicle performance is a crucial topic.

Recently, the hybridization concept has been applied widely to develop environmentally friendly vehicles and particularly to determine system configurations and control strategies. The design philosophy of hybridization is to strengthen advantages and compensate for the inherent drawbacks of the power (or energy) sources [8]. Hybrid power sources that have been developed include the engine/motor and engine/motor/generator hybrid

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Nomenclature

A	area, m^2
C_d	air drag coefficient
E	energy, J
F	force, N
GR	gear ratio
J	cost function
OP	operation point
P	power, W
R	ratio
r	radius, m
T	torque, $N-m$
TR	torque ratio
ω	rotational speed, rpm
η	efficiency, %
ρ	density, kg/m^3

Subscripts

acc	acceleration force
axis	axis of the *T–N* map
base	baseline motor
bat	battery
d	demand
fin	final
Inc.	increment
M	motor
*M*1	motor 1 (high-torque low-speed motor)
*M*2	motor 2 (low-torque high-speed motor)
max	maximum
min	minimum
new	scaled axis
p	power
roll	rolling resistance
TN	torque-speed
t	time
veh	vehicle
w	wheel
wind	wind force

powertrains [9–11], in which the engine is responsible for extending the traveling mileage and the motor/generator compensates the rest power; this enables energy recovery and properly distributes energy [12]. Types of battery/supercapacitors [13], fuel cell/supercapacitors [14], fuel cell/batteries [15], and fuel cell/battery/supercapacitors [16] used as hybrid energy sources in (hybrid) EVs have been studied. Fuel cells are generally used to improve cruising mileage; the battery is used to enhance cruising mileage, high-power output, or energy recovery; and the supercapacitor is used for high-power output or energy recovery. In this study, a novel two-motor hybrid powertrain was evaluated by using the hybridization concept.

Numerous algorithms have been proposed to enable the effective management of the energy or power sources. Rule-based control (i.e., fuzzy rules, if-else rules) is the most practical and intuitive engineering method that can be directly implemented in the vehicle control units (VCUs) [17,18]. However, optimization energy management, particularly in complex systems, is unfeasible. To analyze systems quantitatively, the equivalent consumption minimizing strategy (ECMS) has been used to globally seek the optimal control of dual power or energy sources [19]. To achieve absolute optimization, dynamic programming (DP) has been used widely because it facilitates exhaustive searching according to predetermined test scenarios [20]. The limitation of this method, however, is that the rule extraction from DP for a real VCUs. Other theoretical methods such as stochastic dynamics programming (SDP) [21] and the genetic algorithm [22] have been incorporated in hybrid systems. In this study, considering the accommodation of implementing and optimizing VCUs, we integrated the rule-based control with global search method (similar to ECMS) to manage energy in hybrid IWMs (HIWMs).

In addition to optimal energy management, motor size (specification) is a key factor that decreases consumed energy, indicating that a system/control co-design is necessary to derive the system design and the control strategy simultaneously. In [23], four types (iterative, sequential, bi-level, and simultaneous) of coupling between plant and control optimizations were proposed. After a thorough review of relevant publications, only a few addressed the co-design process for advanced vehicles. In [24], an integrated system/control optimization method was proposed for application in battery/supercapacitor EVs using the global search method. More than 5+% of the energy was determined to be capable of being saved compared with that expended by the baseline vehicle. In [25], optimized subsystem sizing and control laws for fabricating a fuel cell hybrid electric bus were studied; the use of a multi-objective genetic algorithm, low energy consumption and minimal powertrain cost were achieved. In [26], the power management/system design was optimized for application in fuel cell/battery hybrid vehicles. Subsystem-scaling models were created to simulate component size, and the controller design process involved SDP. In [27], a sequential-type codesign for a fuel cell/battery/supercapacitor hybrid EV was developed, and component size was designed to comply with vehicle performance constraints. The resulting EV had nearly optimal operating points when the output power was effectively managed. In [28], the integrated optimization of the energy management control and the key component sizing of plug-in HEVs have been studied. Results show that with component downsizing, cost reductions within the order of 2–9% can be realizable.

In the literature, numerous studies have explored the hybrid configuration and optimal energy management to create environmentally friendly vehicles; however, few studies have discussed integrated system/control optimization, or the hybridization of IWMs. In this study, an innovative method of integrated system/control optimization for IWMs is proposed. Section 2 describes the structure of the dual motor powertrains as well as the operation modes and relationships of torques and speeds. Section 3 discusses the steps of global search method for integrated sizing/control optimization of dual motors. Section 4 demonstrates the simulation results to prove that using this optimization approach could be used to conduct appropriate sizing and energy management by minimizing the overall consumed energy and accommodating preset output performance requirements.

2. Hybrid in-wheel motor system

The assumptions used to develop the hybrid motors in this study are listed as follows: (i) the motor type is the same; (ii) the motor power flow is parallel; and (iii) the motor control unit (MCU) commands two motors simultaneously; (iv) the motors only provide traction power without regenerative brakes. Fig. 1 illustrates the configuration of a HIWM system for use in an EV. The novel design proposed in this study is based on the philosophy of hybridization, and involves one motor with high-torque and