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A pseudospectral method for solving optimal control problem of a hybrid tracked vehicle

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HIGHLIGHTS

- A serial hybrid propulsion system with two motors for tracked vehicle is modeled.
- A DC-DC converter is equipped to enabling a more flexible power distribution.
- The Radau pseudospectral method is used to solve optimal energy control problem.
- The Radau pseudospectral method and dynamic programming are compared.
- RPM offers the higher computation efficiency and better fuel economy than DP.

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ABSTRACT

This study explored the feasibility of using the Radau pseudospectral method (RPM) to optimize the energy management strategy for a hybrid tracked vehicle. The engine–generator set and the battery pack of the serial hybrid tracked vehicle were modeled and validated through the bench test. A DC-DC converter was equipped between the battery pack and the DC bus in this hybrid powertrain, which increased the flexibility of energy distribution between the engine–generator set and the battery. It was simplified as a voltage regulator in the hybrid powertrain model. The power demand during the vehicle operation was calculated according to the vehicle dynamics and driving schedules. The optimal control problem was formulated to minimize the fuel consumption through regulating the power distribution properly between the engine–generator set and battery pack during a typical driving schedule. The RPM was applied to transform the optimal control problem to a finite-dimensional constrained nonlinear programming problem. A comparison of the solutions from RPM and dynamic programming showed that the former offers the higher computation efficiency and better fuel economy.

1. Introduction

To cope with the global energy shortage and satisfy the growing performance requirement, the powertrains in the machinery and military tracked vehicles have been increasingly hybridized. The hybrid electric drive configuration has potential to improve the fuel economy and the maneuverability, and bring more reliable onboard electricity supply; also, the additional stealth operation mode can be fulfilled when the internal combustion engine switches off. The typical powertrain configurations for mature hybrid tracked vehicles on the market include the electric drive–hydraulic steering system of the Caterpillar D7E bulldozer, the multimode hybrid electric-mechanical transmission from General Motors, and the E-X-Drive system from BAE Systems, etc. [1–5]. In this study, a serial dual-motor drive configuration is used in a hybrid tracked vehicle to realize a relative flexible package under the constraints of the component power density and installation space inside the vehicle, as shown in Fig. 1. In this configuration, the two electric motors drive the two sprockets separately. A diesel engine–generator set (EGS) and a traction battery pack supply power to the two motors. A DC-DC converter between the DC bus and the lithium-ion battery pack regulates the voltage of the DC bus, enabling the output power of the battery pack controllable. Therefore, through optimizing the power distribution between the engine-generator set and the battery pack, the engine can be controlled to operate with greater efficiency in order to improve the

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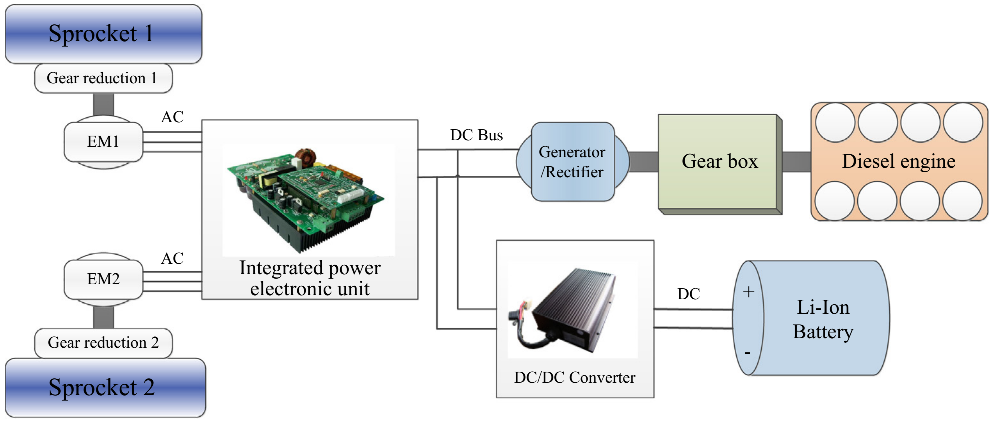

Fig. 1. Dual-motor drive configuration of a hybrid tracked vehicle.

fuel economy. In addition, the DC-DC converter can prevent overdischarging and overcharging of the battery to improve the system reliability. An integrated power electronic unit works as the inverter, and it is responsible for regulating the speed and torque of the two motors. Differing from the previous studies [6,7], the DC-DC converter in this study makes the energy utilization more flexible, however it increases the complexity of energy distribution control.

The design of a controller with an optimal energy management strategy to regulate the power distribution efficiently is challenging. Numerous articles focusing on this topic mainly use two typical methods: dynamic programming (DP) and Pontryagin's minimum principle (PMP). Based on Bellman's principle of optimality [8], the DP method yields a global optimal solution generally used as a benchmark to evaluate the controller design or to be reproduced and extracted to generate a set of rules for real-time control [9–11]. However, this method involves high computational load, especially when there is a relatively high number of state and control variables, and/or these variables are discretized on a fine grid [8]. When the probabilistic statistics of the power request over a period of time is considered, the stochastic dynamic programming (SDP) algorithm can be applied to find the optimal control map to minimize the cost expectation [12]. The PMP method is used to formulate the analytical necessary condition equation, which defines the mathematical relationship among the state variables, the Hamiltonian, and co-states. The extremal solution is obtained by computing and minimizing the Hamiltonian function at each instant. It is reasonable to consider the variation of the co-state with respect to time negligible, due to the fact that the battery efficiency is almost constant in this application, which makes the necessary conditions of optimality provided by PMP also sufficient [13–15].

The nonlinear programming (NLP) method, which theoretically differs from the DP and PMP methods, has been used to solve the optimal energy management problem for hybrid electric vehicles [16]. When the state and control variables are discretized into the finite grid in a time span, the differential equations and constraints are reduced to a set of the algebraic equations, and the optimal solution is directly extracted by solving a large-scale NLP problem with the help of sophisticated software packages, such as GPOPS-II or PSOPT [17]. The convex optimization method is a special NLP method. In the method, the optimal control problem is reformulated as a convex optimization problem, and the developed solver, such as CVX [18], is applied to find the solution. Because of the convex property, the computation efficiency is substantially improved. However, the necessary convex property for the reformulated optimal control problem often leads to relaxation of the constraints or model changes and affects the solution accuracy [19,20]. A few studies have explored the possibility of applying NLP to the optimization of the energy management strategy for hybrid electric vehicles [16,21]; however, such investigations are barely sufficient or comprehensive, partly because of the lack of general methodologies and tools to achieve direct transcription of the optimal control problem to an NLP problem. As typical direct methods categorized as NLP methods, pseudospectral methods have been increasingly used in the numerical solution to optimal control problems for various dynamic systems [22–24]. The pseudospectral methods are a class of direct collocation methods in which the optimal control problem is transcribed to an NLP problem by parameterizing the state and control variables through global interpolation polynomials, and collocating the differential-algebraic equations at the nodes obtained from a Gaussian quadrature. They are potentially computationally more efficient than DP methods because they exploit well developed NLP codes, and the problem can be reformulated more flexibly compared with the use of optimality conditions or the convex method. In practice, three types of collocation schemes, namely Legendre–Gauss, Legendre–Gauss–Radau, and Legendre–Gauss–Lobatto schemes, are often used, and the Radau pseudospectral method (RPM) outperforms other methods in terms of computation convergence and accuracy in some cases [25].

Compared with the energy management investigations based on the principle of optimality for the hybrid wheeled vehicle, pseudospectral method–based energy management studies on the hybrid tracked vehicle are scarce. DP and stochastic DP methods have been applied to find the optimal control strategy for the serial hybrid electric tracked vehicle without a DC-DC converter between the battery and the DC bus [6,7]. The existence of the DC-DC converter provides a more flexible power distribution but also leads to greater complexity and challenge because the excessive state variables lead to the "curse of dimensionality" in DP and PMP, considerably increasing the computation time. In this study, the RPM is applied to solve the optimal energy management problem for the hybrid tracked vehicle. The optimality and effectiveness of the RPM were validated through the comparison with the DP method and the rapid convergence and high computation efficiency is observed. The remaining of the paper is organized as follows. The modeling of the power demand and the hybrid powertrain is discussed in Section 2, including the power balancing, the diesel engine–generator rectifier, and the lithium-ion battery with a DC-DC converter. This section also formulates the two-state and two-control optimal energy management problem to meet the power request history calculated from a field driving schedule. Section 3 describes the RPM-based transcription from the optimal