Postprint of Performance and Economy Validation for a Fuel Cell Vehicle Based on Global Optimization Strategy

Authors: Xin Weiwei, Wei Shangjun, Zheng Weiguang, Zhang Ping, Zheng Weiguang

Date: 2022-09-26T00:00:00+00:00

Abstract

To validate the rationality of the powertrain configuration for a certain fuel cell commercial vehicle, a model encompassing a hybrid energy source (including fuel cell and battery pack), motor system (including drive motor and motor controller), and vehicle transmission system (including final drive and wheels) was constructed on the Matlab simulation platform based on the key parameters of this vehicle' s powertrain. A globally optimized energy management strategy based on dynamic programming algorithm was employed, with three loading modes—no-load, half-load, and full-load—established, and the European typical driving cycle EUDC_{LOW} was adopted as the simulation condition to analyze the vehicle' s power performance and fuel economy under different loading modes. Simulation results demonstrate that under all three loading modes, the hybrid energy source configuration can satisfy the vehicle' s power demand under the specified driving cycle; however, as the vehicle load increases, the terminal SOC of the battery pack gradually deviates from its initial value. Considering that commercial vehicles need to operate under heavy-load conditions for extended periods, a lower SOC is detrimental to maintaining optimal vehicle power performance. The validation results for this vehicle model indicate that in subsequent research and real vehicle validation, the configuration of a higher-power onboard fuel cell should be considered.

Full Text

Verification of Power and Economy of a Fuel Cell Vehicle Based on Global Optimization Strategy

Xin Weiwei[1], **Wei Shangjun**[2], **Zheng Weiguang**[1], **Zhang Shangjun**[2]
[1]School of Mechanical and Electrical Engineering, Guilin University of Elec-

tronic Technology, Guangxi
[2]Commercial Vehicle Technology Center, Dongfeng Liuzhou Automobile Co., Ltd., Guangxi

Abstract

To verify the rationality of power system selection for a fuel cell commercial vehicle, a simulation model was constructed based on key parameters of the vehicle' s power system. The model includes a hybrid energy source (comprising fuel cell and battery pack), drive motor and motor controller, and vehicle driveline (including final drive). A global optimization energy management strategy based on dynamic programming algorithm was employed under three load modes, using a typical European driving cycle as the simulation condition.

1. Introduction

As environmental pollution and energy security issues caused by traditional fossil fuel combustion attract increasing attention, countries worldwide have introduced new measures to alleviate these problems. The transportation industry, a major energy consumer, is at a crossroads of industrial upgrading. Among the main new energy vehicle configurations, hydrogen fuel cell vehicles have become one of the most competitive candidates due to their zero pollution, renewable fuel, high system efficiency, and long driving range characteristics [1-4]. However, due to the soft discharge characteristics and slow dynamic response of fuel cells, a single fuel cell energy source cannot meet the complex and variable driving environment requirements [5-7]. Therefore, fuel cell vehicles are generally equipped with an auxiliary energy source to work together with the fuel cell. Typically, this auxiliary energy source consists of a single battery pack or a single supercapacitor [8], though some scholars [9-10] have studied composite auxiliary energy sources comprising both power batteries and supercapacitors.

In hydrogen fuel cell vehicles, power splitting among energy sources primarily depends on the vehicle' s energy management system. Common energy management strategies include rule-based control strategies (including deterministic rule-based strategies [11-12] and fuzzy logic rule-based strategies [13]) and optimization-based strategies (including instantaneous optimization strategies [14-15] and global optimization strategies [16-17]). Global optimization strategies based on dynamic programming (DP) or Pontryagin' s Minimum Principle (PMP) can obtain globally optimal control rules when future driving cycle information is known, thereby achieving optimal hydrogen consumption for the current trip.

2. Vehicle Model Construction

2.1 Vehicle Longitudinal Dynamics Modeling When a vehicle travels on a flat road, longitudinal forces play a decisive role in fuel economy. Therefore, the model primarily considers the vehicle's longitudinal dynamics while ignoring the effect of lateral dynamics on stability. During normal driving, the vehicle's driving resistance includes tire rolling resistance F_r, air resistance F_a, grade resistance F_g, and acceleration resistance F_i. The vehicle driving force satisfies:

$$F_t = F_r + F_a + F_g + F_i$$

The motor demand torque T_{req}, demand speed ω_{req}, and required power P_{req} are functions based on given vehicle parameters:

$$T_{req} = f(F_t, \eta_{fd}, r_w)$$
$$\omega_{req} = f(v, r_w)$$
$$P_{req} = T_{req} \cdot \omega_{req}$$

where r_w is wheel rolling radius, η_{fd} is final drive efficiency, and v is vehicle speed. Vehicle parameters are shown in .

2.2 Fuel Cell Modeling Common fuel cell simulation models include mechanism models, neural network models, and efficiency models. Considering simulation time constraints, the simplest efficiency model was selected. The fuel cell efficiency curve can be obtained experimentally, as shown in [Figure 1: see original paper]. The fuel cell hydrogen consumption rate is calculated as:

$$\dot{m}_{H_2} = \frac{P_{FC}}{\eta_{FC} \cdot LHV_{H_2}}$$

where P_{FC} is fuel cell power, η_{FC} is fuel cell efficiency, and LHV_{H_2} is the lower heating value of hydrogen.

2.3 Battery Modeling The battery pack model adopts the widely used equivalent circuit model shown in [Figure 2: see original paper]. In this model, the battery is equivalent to an ideal voltage source V_{oc} in series with an internal resistance R_i. The battery pack output power P_{bat} is:

$$P_{bat} = V_{oc} \cdot I_{bat} - R_i \cdot I_{bat}^2$$

The battery pack State of Charge (SOC) change rate satisfies:

$$\frac{dSOC}{dt} = -\frac{I_{bat}}{Q_{nom}}$$

where I_{bat} is battery current and Q_{nom} is nominal capacity.

2.4 Motor Modeling In fuel cell vehicles, the permanent magnet synchronous motor serves as the sole device for converting electrical energy to mechanical energy. When driving, the motor acts as a motor, converting electrical energy from the fuel cell and battery pack into mechanical energy. During braking, the motor acts as a generator, converting braking mechanical energy into electrical energy to recharge the battery pack. Motor efficiency can be described as a function (MAP) of torque and speed, as shown in [Figure 3: see original paper].

3. Energy Management Strategy Based on Dynamic Programming

3.1 Dynamic Programming Algorithm The energy management optimization for fuel cell vehicles can be regarded as a multi-stage decision problem. Dynamic programming, as a mathematical method for solving multi-stage decision process optimization, can assist in completing vehicle energy management global optimization [19-21].

Assuming a multi-stage decision problem exists, when the state variable at a certain stage is determined, the system evolves from the initial state to the next stage based on different decision variables, forming several policy sets. The indicator function is defined as the fuel consumption of the entire driving cycle. The optimal value function represents the minimum total cost from the current stage k to the terminal stage n.

3.2 State and Decision Variables In the fuel cell vehicle energy management strategy, the battery SOC is selected as the system state variable, and the fuel cell output power P_{FC} is the decision variable. The state transition equation is:

$$SOC_{k+1} = SOC_k + f_k(SOC_k, P_{FC,k})$$

The constraints on powertrain components are:

$$\begin{gathered} P_{FC,min} \leq P_{FC,k} \leq P_{FC,max} \\ P_{bat,min} \leq P_{bat,k} \leq P_{bat,max} \\ SOC_{min} \leq SOC_k \leq SOC_{max} \end{gathered}$$

The indicator function is defined as the hydrogen consumption over the entire cycle:

$$J = \sum_{k=0}^{N-1} \dot{m}_{H_2}(P_{FC,k}) \cdot \Delta t$$

where Δt is the time length of each stage.

4. Simulation Results Analysis

The European standard driving cycle EUDC_{LOW} was used for simulation, with the velocity profile shown in [Figure 4: see original paper]. Simulations were conducted under three load modes: no-load, half-load, and full-load.

4.1 Power Performance Under Different Loads Simulation results show that the hybrid energy source can meet the vehicle' s power requirements under the specified driving cycle in all three load modes. However, as vehicle load increases (half-load and full-load), the battery pack terminal SOC gradually deviates from its initial value. For this vehicle verification, a larger on-board fuel cell should be considered, as the current configuration is not conducive to maintaining optimal dynamic performance.

The relationship between motor demand power and time under the three load modes is shown in [Figure 5: see original paper]. The relationship between battery pack output power and time is shown in [Figure 6: see original paper].

4.2 Economic Performance Under Different Loads The vehicle economic performance simulation results under the three load modes are shown in . The equivalent hydrogen consumption gradually increases with vehicle mass. The battery pack' s SOC deviation from initial to terminal values is converted to equivalent hydrogen consumption. As load mass increases, the battery pack output power changes over a larger range, while the fuel cell output power variation range is smaller.

In a single load case, the fuel cell operates at high power output for extended periods, which is also the region of higher fuel cell efficiency. Part of the battery pack output power is used to meet motor demand, while another portion is used for [Figure 7: see original paper]. Since motor demand power varies significantly with load ([FIGURE:8(a), (b)]), the battery pack output power range also changes accordingly.

5. Conclusion

Taking a fuel cell commercial vehicle from Dongfeng Liuzhou Automobile Co., Ltd. as the prototype, this study employs a global optimal energy management method based on dynamic programming to verify the vehicle' s power and economy performance. Simulation results indicate that:

1. The hybrid energy source can meet the power requirements for normal driving under the given cycle in no-load, half-load, and full-load modes.
2. As vehicle load increases, the battery pack SOC deviation from its initial value increases, leading to higher equivalent hydrogen consumption.
3. Considering that heavy commercial vehicles operate under large loads for extended periods, which is detrimental to maintaining optimal dynamic performance and may even cause the vehicle to fail to operate normally,

future research and vehicle development should adapt fuel cells with larger peak power to improve vehicle power and economy performance.

Acknowledgments

This work was supported by the Guangxi Innovation Driven Project (AA18242033) and Liuzhou Science and Technology Plan Project (2020GAAA0403; 2019AD10203).

References

[1] ZHANG Ridong, TAO Jili. GA-Based Fuzzy Energy Management for FC/SC-Powered Hybrid Electric Vehicles Considering Consumption Variation[J]. IEEE Transactions on Fuzzy Systems, 2018, 26(4): 1833-1843.

[2] WANG Yujie, SUN Zhendong, CHEN Zonghai. Rule-Based Energy Management Strategy for Lithium-Ion Capacitor System[J]. Energy Procedia, 2019, 158: 2555-2560.

[3] 中国科学院院刊．氢能与燃料电池发展现状及展望, 2019, 34(4): 469-477.

[4] HEMI H, GHOUILI J, CHERITI A. Real-Time Energy Management Strategy for Hybrid Electric Vehicle[C]//IEEE Conference on Vehicular Technology. Piscataway, NJ: IEEE Press, 2014.

[5] SAMI K, RABIH J, RIAD C. Optimal Energy Management Based on Battery, Super Capacitor, and Fuel Cell Hybrid Source Vehicle[J]. SAE Technical Paper, 2015, 1: 1359.

[6] GUZZELLA L, SCIARRETTA A. Vehicle Propulsion Systems: Introduction to Modeling and Optimization[M]. Berlin Heidelberg: Springer, 2013.

[7] THOUNTHONG P, RAËL S, DAVAT B. Energy Management of Fuel Cell/Battery/Super-Capacitor Hybrid Power Source for Vehicle Applications[J]. Journal of Power Sources, 2009, 193(1): 376-385.

[8] AMIN B, BAMBANG R, ROHMAN A S, et al. Energy Management of Hybrid Power Sources Using Model Predictive Control[J]. IEEE Transactions on Industrial Informatics, 2014, 10(4): 1992-2002.

[9] ZHOU Wei, YANG Lin, CAI Yishan, et al. Dynamic Programming Based Energy Management Strategy for Fuel Cell Hybrid Vehicles Considering Their Tri-City Driving Modes[J]. Journal of Power Sources, 2018, 406: 45-55.

[10] SUN Xiaosong, HU Xiao, MOURA S, et al. Velocity Predictive Energy Management for Electric Vehicles[J]. IEEE Transactions on Control Systems Technology, 2015, 23(3): 1197-1204.

[11] BUNTIN R, BROOKER A, MARKEL T, et al. ADVISOR: A Systems Analysis Tool for Advanced Vehicle Modeling[J]. Journal of Power Sources, 2002, 110(2): 255-266.

[12] FARES N, CHERITI H, GHOUILI J. Power Management Strategy for Hybrid Electric Vehicles Based on Dynamic Programming Technique[J]. International Journal of Hydrogen Energy, 2015, 40(24): 7777-7790.

[13] HEMI H, GHOUILI J, CHERITI A. Energy Management Strategy for Hybrid Fuel Cell Vehicles Based on Adaptive Fuzzy Logic[C]//IEEE Vehicular Technology Conference. Piscataway, NJ: IEEE Press, 2017: 6-9.

[14] PAGANELLI G, DELPRA S, GUERRA T M, et al. Equivalent Consumption Minimization Strategy for Parallel Hybrid Powertrains[J]. IEEE Transactions on Vehicular Technology, 2002, 51(1): 2076-2081.

[15] ZHANG Ridong, TAO Jili. Fuzzy Energy Management Strategy for Fuel Cell Hybrid Electric Vehicles[J]. IEEE Transactions on Vehicular Technology, 2018, 67(1): 302-311.

[16] ZHOU Wei, YANG Lin. Dynamic Programming for Energy Management of Fuel Cell Hybrid Vehicles[J]. Journal of Power Sources, 2019, 412: 186-196.

[17] 中国电机工程学报. 基于运行模式和动态混合度的燃料电池混合动力有轨电车等效氢耗最小化能量管理策略, 2019, 39(13): 3867-3878.

[18] MARKEL T, BROOKER A, HENDRICKS T, et al. ADVISOR: A Systems Analysis Tool for Advanced Vehicle Modeling[J]. Journal of Power Sources, 2002, 110(2): 255-266.

[19] GAO Y, CHEN J, EHSANI M. Investigation of the Effectiveness of Regenerative Braking for EV and HEV[J]. SAE Technical Paper, 1999, 1: 2910.

[20] SCHOUTEN N J, SALMAN M A, KHEIR N A. Energy Management Strategies for Parallel Hybrid Vehicles Using Fuzzy Logic[J]. Control Engineering Practice, 2003, 11(2): 171-177.

[21] KOOT M, KESSELS J, DE JAGER B, et al. Energy Management Strategies for Vehicular Electric Power Systems[J]. IEEE Transactions on Vehicular Technology, 2005, 54(3): 771-782.

Note: Figure translations are in progress. See original paper for figures.