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Investigating on Different Methods of Energy Management System in Hybrid Electric Vehicles and Presenting Proposed Solutions for its Optimization

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Abstract: Air pollution, saving fuel and spreading greenhouse gases are the most issues that have led to increase utilizing hybrid-electric vehicles. Energy management performances and its effectiveness is considered in these vehicles in terms of accuracy and efficiency. The aim of this paper is to investigate the suggested optimization designs for energy management system and proposed solutions are presented regarding to improving the effectiveness of these designs.

Keywords: Hybrid-electric vehicles, energy management system, energy consumption optimization

1. Introduction

Limitation of the world's oil reserves, and the significant role of the cars with fossil fuels as one of the largest sources of pollution in big cities are the primary reasons for optimal use of these fuels. Automotive design, since the beginning, has been based on the availability, low price and abundance of fossil fuels. That is the reason for less efforts over the last hundred years to reduce the pollutants or to use other energy resources and car manufacturers have been mostly trying to improve efficiency, comfort and performance of their products. However, the high amount of pollutants in the crowded cities and the realization that reserves of fossil fuels are near depletion, have attracted the attention of the scientific community and consequently the car manufacturers to use other energy resources. One of the methods proposed to approach the above mentioned problems is using electric cars. Although these cars do not generate pollution, they have some problems and limitations including limited range and maximum speed which makes them incomparable with fuel burning cars regarding their characteristics and operation. In order to overcome the limitations of using electric and fuel burning cars, the use of automobiles with hybrid energy sources (electrical and fossil) has been proposed as a suitable option across the world.

2) Methods of energy management system in hybrid electric vehicles:

2-1) Intelligent Energy-Management Strategy for Plug-in Hybrid Electric Vehicles

In [1], a smart strategy is proposed for energy management in PHEV[1]. In a travel, the proposed strategy works based on the compared information related to the position of a vehicle, characteristics of road path and traffic conditions as online from intelligent transportation systems and computes general speed pattern for travel period. General pattern of velocity is used in the next stage for determining controlling pattern of battery charging and de-charging which is as a linear real-complex programming problem and its goal is to minimize fuel consumption during the way. This strategy can be extended in order to optimize vehicle fuel consumption in long travels based on the predicted travel pattern and also the information related to the stations of battery recharge.

2-2) Dynamic Traffic Feedback Data Enabled Energy Management in Plug-in Hybrid Electric Vehicles

In [2], a framework of predictive energy management with data empowerment is made for power-sharing in plugin hybrid electric vehicle (PHEV) compared to classic model of predictive control (MPC)[2], additional supervision state from state of charge (SoC)[3] based on real time data of traffic. A PHEV model was created

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[1] Plug-in Hybrid Electric Vehicle (PHEV)

[2] Model Predictive Control (MPC)

[3] State of Charge (SOC)

based on power balance for this higher level for fast production of SoC path lines of battery which was created for final state limitations in MPC level. This framework of PHEV energy management is evaluated under three scenarios:

1) Without traffic flow data
2) With static data of traffic flow
3) With dynamic data of traffic flow

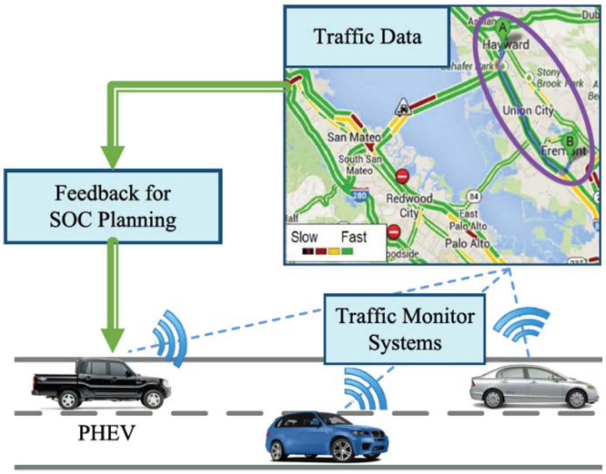

Fig. 2. Traffic data feedback framework and the traffic flow velocity provided by Google Maps

The numerical results using real world dynamic data show that the proposed strategy successfully combines traffic flow dynamic data in the PHEV energy management algorithm in order to achieve the increased economy of fuel. Programming level of supervised SoC, rapidly creates a SoC line from traffic data for SoC terminal limitation in MPC level. A PHEV model of power balance is developed for this higher level of data development. With this model, DP[4] computes SoC optimized route in real time- with appropriate rate to updating rates of traffic data (300s). The results of simulation show that the predicted strategy of energy management together with traffic dynamic data can reach to 94-96% of appropriate fuel value from DP deterministic criterion in the driving scenario in highway.

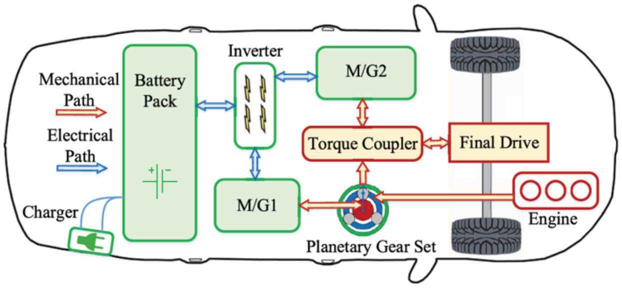

Fig.3. Structure of the power-split PHEV configuration

2-3) Dynamic Programming Sub problem in Hybrid Vehicle Energy Management

In [3], Dynamic programming algorithm (DP) with complex calculation is usually used in academic research for solving the problem of energy management in hybrid electric vehicles. In this reference, we concentrate particularly on the method of decreasing the computational need in this method. The main idea is that in each point (node) o time and state network, local estimation of expected cost function in each node and extracting an analytical solution for determining optimized sharing moment. There is no need to use measurement formula of sharing moment and identification of optimized decision using expected cost extrapolation. In this paper, two different approximations of expected cost function have been considered:

1) Local linear approximation
2) Approximation using second order transmission point line

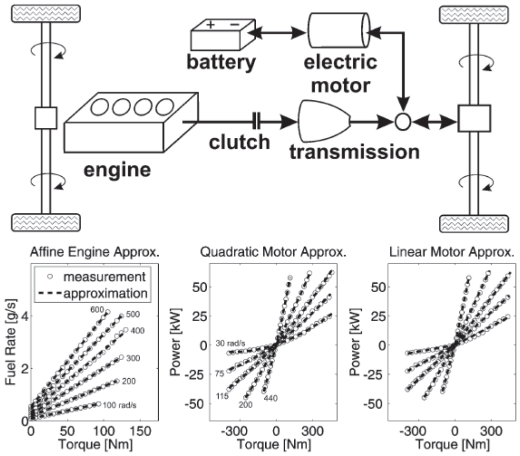

Fig. 4. PHEV configuration considered and the linear least squares approximations of the engine and the motor. Each line represents different engine/motor speeds

2-4) A Novel Optimality and Stability Framework

In [4], the problem of finding an optimized solution of energy management problem for hybrid electric vehicles considers charge saving and proposes stability framework and its optimization. The problem of energy management is reformulated as a non-second-order non-linear infinite time optimization problem which leads to a set of rules for feedback control and provides optimization towards an infinite time horizon performance goal and guarantees asymptotic stability. Stability problem in HEVs of charge saving is formulated in a way that provides designing analytical

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[4] Dynamic Programming (DP)

ways using Lyapunov. The suggested control rule is implemented in pre-transmission parallel hybrid operation vehicle and the operation of closed ring system is investigated in simulation. Adaptive PMP[5] is compared by solving the provided criterion from minimum principle (PMP) and real-time adaptive controller.

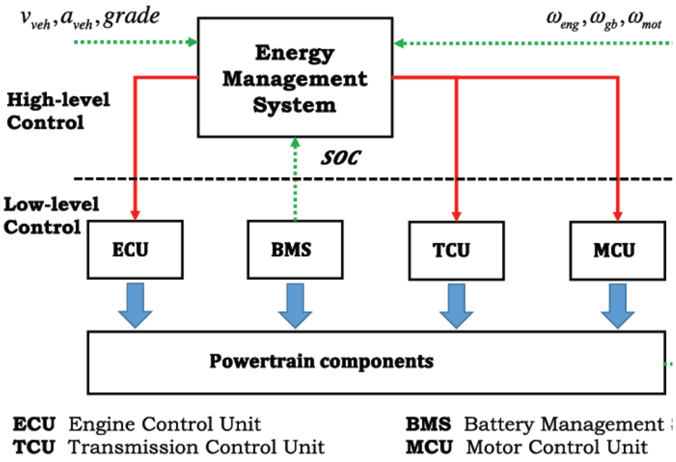

Fig. 5. Two-level control scheme in a hybrid vehicle

2-5) Real-Time Optimization for Power Management Systems of a Battery/Super capacitor Hybrid Energy Storage System in Electric Vehicles

In [5], the installed batteries on Electric vehicles are often damaged because of the power with high-peak and rapid cycles of charge-discharge – which are happening because of frequent increase/decrease of vehicle velocity especially in urban spaces. Hybrid energy saving system (HESS)[6] of battery/capacitor cloud (SC)[7] is considered as a solution for decreasing battery damage, because SC can operate as a buffer against large volumes of power and also its oscillations. While the main aim of using HESS in EVs is to minimize magnitude/variation of battery power or power waste, the previous approaches that are suggested to control HESS have disadvantages and problems; they neither consider these goals simultaneously nor reflect real time load dynamic for calculating SC source voltage. In this paper, we present a framework for power control which is constituted from two stages: one for computing SC source voltage and the other for optimizing power current in HESS. In the presented framework, we addressed a method for computing SC source voltage by considering real time load dynamic and without supposed future operation characteristic. Moreover, we formulate the problem of controlling HESS power as a convex optimization problem which minimizes magnitude/oscillation of battery power and power waste simultaneously. Optimization problem is formulated in a way that it can be solved frequently by general solvers in polynomial time.

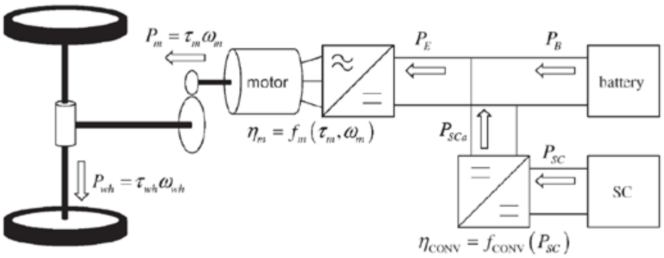

Fig. 6. Schematic of the system architecture

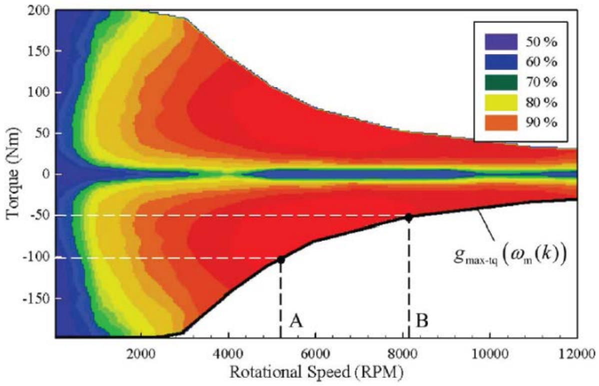

Fig. 7. Motor efficiency map

2-6) Reinforcement Learning of Adaptive Energy Management with Transition Probability for a Hybrid Electric Tracked Vehicle

In [6], a reinforcement learning-based adaptive energy management (RLAEM) is suggested for hybrid electric tracked vehicles (HETV)[8]. First, a control-oriented model is created from HETV in which state of charge of battery and generator speed are state variables and engine torque is control variable. As the result, transition matrix is trained by specified driving scheduling of HETV. The suggested RLAEM determines the appropriate power between battery and engine-generator set (EGS) for minimizing fuel consumption towards different driving schedules.

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[5] Pontryagin's Minimum Principle (PMP)

[6] Hybrid Energy Storage System (HESS)

[7] Super capacitor (SC)

[8] Hybrid Electric Tracked Vehicle (HETV)

Utilizing RLAEM ensures the need of power for driver and improves the fuel economy. Finally, RLAEM is compared with energy management based on stochastic dynamic programming (SDP)[9] for different driving scheduling. RL method is used for the result of optimized energy management strategy of HETV. Different driving schedules are applied with RL-based optimized control policy learning ability and optimality validation.

2-7) Optimal Calibration of Map-Based Energy Management for Plug-in Parallel Hybrid Configurations: A Hybrid Optimal Control Approach

In [7], optimization framework of regulating energy management for plug-in hybrid electric vehicle (PHEV) is suggested. This framework is based on modeling of hybrid vehicles as hybrid systems in mathematical expression i.e. as a system consisting discrete and continuous variables as input. This solution provides flexibility capability in discrete decision-makings such as driving states and gear selection. Then the problems of optimized control are formulated which are optimized with regard to continuous and discrete system inputs and some methods are explained for solvation with appropriate efficiency. This framework provides the allowance of considering losses which are occurred because of the change in discrete variable. Then the results can be used for automatic calculation of reference tables for optimal gear transmission, sharing optimal torque among engine (generator), internal combustion engine and determining driving mode (electric or hybrid state). It was shown that when switching cost is not considered, the main challenge is still finding the first gear. Practical strategies for determining online gear number including rule-based method, optimal Co2 method and predictive energy management are explained.

Efficient algorithms for solving HOCPs along with valuable set of LUTs can be calculated which can be used in combination with predicted case as online for complete definition of energy management strategies for continuous and discrete decision makings.

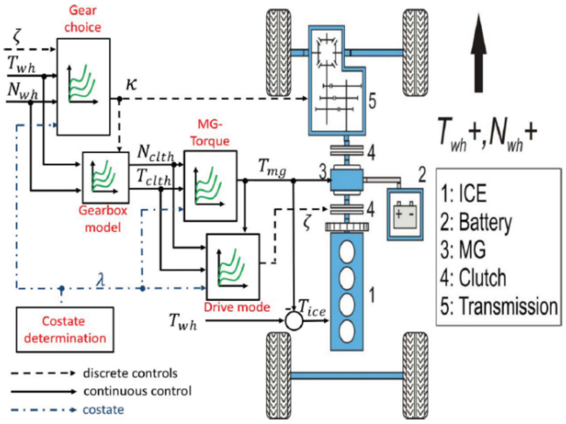

Fig. 8. Configuration of the parallel hybrid powertrain and structure of the supervisory control. (Without low-level control schemes)

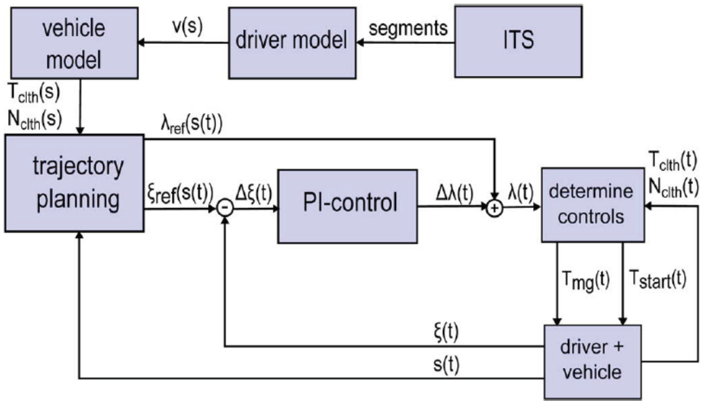

Fig. 9. Control structure of predictive energy management

2-8) Development of a Thermal Management System for Energy Sources of an Electric Vehicle

In [8], Modern Hybrid thermal management system with high efficiency (HTMS)[10] is considered for green energy sources of electric vehicles. This system includes two routs of cooling flow, air-cooling thermal generator, proportional valve and cooling pump for managing optimal temperatures of dual thermal sources. Pilot sample is created for evaluation of this system. Mechanical elements (elements of cooling system) and electric elements (generators, sensors and data logger) are properly combined together. A systematic microchip algorithm and an algorithm are designed and are included in HTMS. Specific heat dissipation performance indicator is created to provide creating quantitative evaluation of HTMS. The results of steady and momentary responses showed that optimal temperatures of heat sources can be obtained via controlling and designing appropriate system of HTMS. The HTMS showed its ability for industrial and

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[9] Stochastic Dynamic Programming (SDP)

[10] Hybrid Thermal Management System (HTMS)

academic participations and also application in future EVs. The conclusion of the study and also academic and industrial participations can be summarized as following:
Applications: With regard to academic participation, this study developed a HTMS using SHD efficiency indicator and also new conception of HFR and a variety of integrated arrangements; moreover, HTMS performance is evaluated quantitatively. With regard to industrial participation, the results of test showed high commercial potential of HTMS for EV application because of high efficiency advantages and low energy consumption during longer distance by EV and the need to smaller space. An electric vehicle with hybrid energy source, even a HEV with hybrid energy source can have the mentioned benefits with having HTMS for improving output performance.

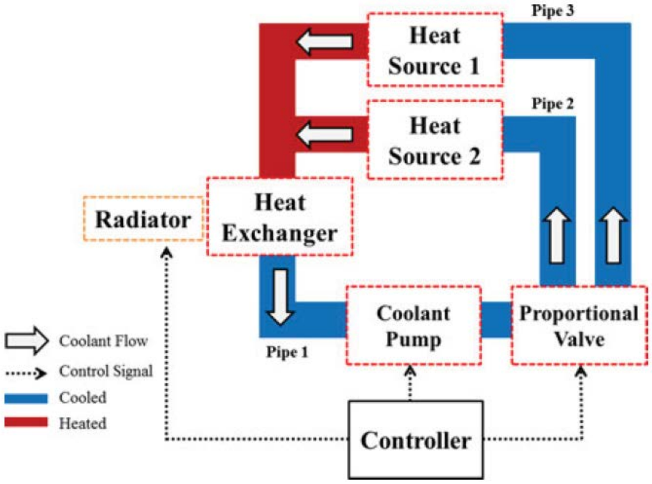

Fig. 10. Schematic of a new-type thermal management system

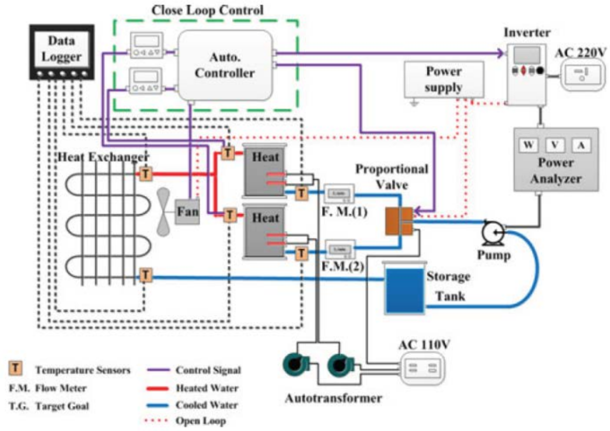

Fig. 11. Configuration of the experimental platform for steady-state and transient response

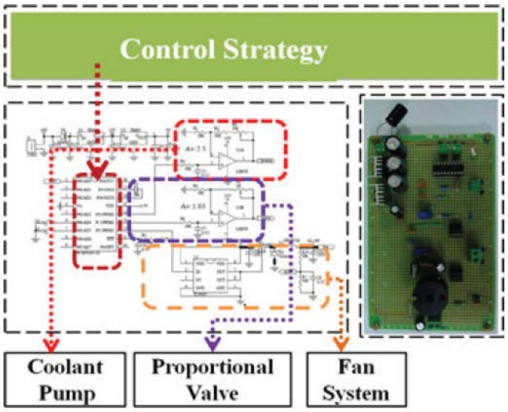

Fig.12. Configuration of the microchip controller and the real implementation

2-9) Intelligent Hybrid Electric Vehicle ACC with Coordinated Control of Tracking Ability, Fuel Economy, and Ride Comfort

In [9], order to amplify energy efficiency and integrity of controlling system, new ACC[11] system is investigated in this study for intelligent HEVs (i-HEV[12] ACC). This controller is suggested in non-linear model predictive control framework and position-based non-linear longitudinal in-car dynamic model is developed. An optimal coordinated control problem is formulated for the safety of pursuit and fuel consumption than the binds on stable pursuit. Multi-stage off-line dynamic programming optimization and an online reference table are used for implementing real time control algorithm. There are other experiments performed which show the suggested i-HEV ACC achieves improved harmony and performance in the safety of traffic, fuel efficiency and ease of driving.

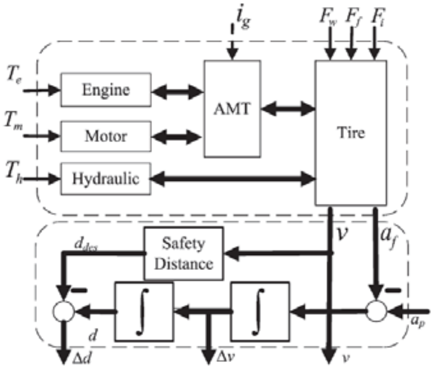

Fig.13. Global longitudinal dynamics model for an i-HEV

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[11] Adaptive Cruise Control (ACC)

[12] Intelligent Hybrid Electric Vehicles (i-HEVs)

Practical research and operational analysis are performed using a real vehicle and the obtained results are summarized as following:

1) New position-based NMPC[13] i-HEV ACC system which supplies safety of routing, fuel consumption and ease of driving based on stability binds in routing is presented and is solved using predictive horizon control.

2) The practical analyses and experiments performed on vehicle represent that utilizing i-HEV ACC system provides an appropriate operation for safety of traffic, fuel efficiency and ease of driving while provides better controlling harmony between fuel efficiency, traffic safety compared common and previous ACC algorithms.

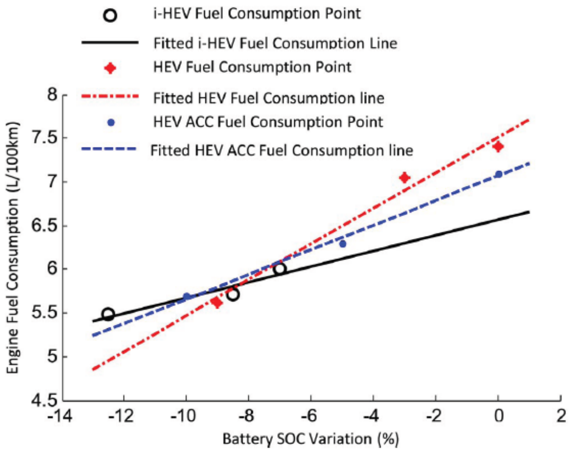
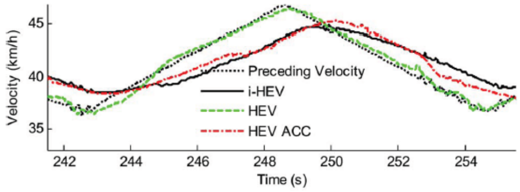
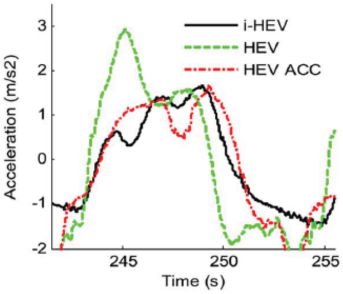


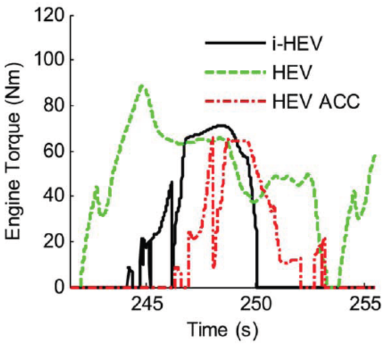
Fig.14. Fuel consumption versus the variation in the SOC for the iHEV ACC, the HEV, and the HEV ACC



(a)



(b)



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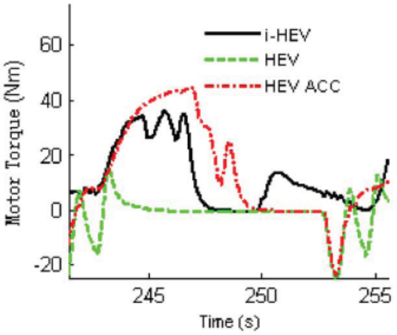

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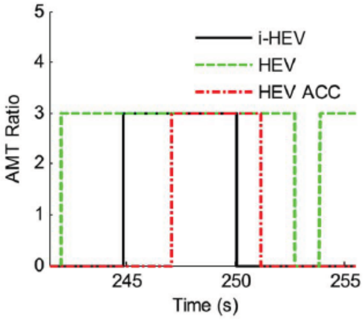

(e)

Fig. 15. Representative test results for the i-HEV ACC, the HEV, and the HEV ACC.
(a) Comparing results of velocity.
(b) Comparing results of acceleration.
(c) Comparing results of engine torque.
(d) Comparing results of motor torque.
(e) Comparing results of AMT ratio.

2-10) Engine ON/OFF Control for the Energy Management of a Serial Hybrid Electric Bus via Convex Optimization

In [10], on/off conditions of optimal global engine is analytically considered. This shows that on/off strategy of optimal engine is for switching to turned on state only and if only the intended power is specified above non-constant limit. By repetitive calculations and sharing power using convex optimization, the optimal solution for the problem of energy management is found. The first research case deals with high energy

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[13] Nonlinear Model Predictive Control (NMPC)

batteries, while the second research case is about super-capacitors that have very lower energy capacity. In both cases, the suggested algorithm reaches to optimal results very faster than dynamic programming algorithm [11].

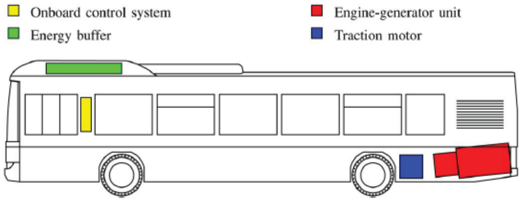

Fig.16. Serial hybrid electric city bus

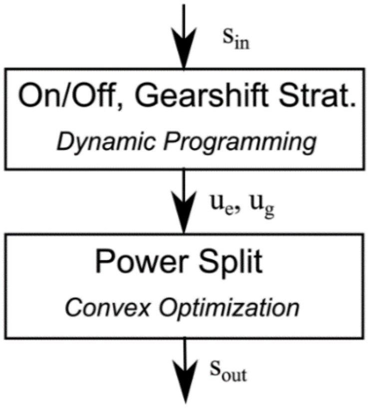

Fig. 17. Sequential optimization of the engine ON/OFF strategy and the power split

2-11) A Parallel Hybrid Electric Vehicle Energy Management Strategy Using Stochastic Model Predictive Control with Road Grade Preview

In [12], HEV energy efficiency is a function of load position and road slope as random variable using discrete and unlimited-time Markov chain by considering unknown the road ahead has reached battery SoC preservation and proportional control ring energy consumption efficiency.

2-11-1) MARKOV-CHAIN-Based Road Grade and Vehicle Speed Profile Model

The road grade can be described by a finite-state Markov chain model after dividing the road into a series of segments and discretizing the grades [13]. A Markov chain model reserves more information than a simple random variable with a probability distribution. It is both simple and informative. As the road grade will be considered as a state in the MPC problem, it is convenient to model it as a Markov chain and then solve the problem using SDP. In this section, the Markov-chain-based road grade model for a determined route is introduced first, and the model is extended to the stochastic route situation where the historical traffic data, if available, may help improve the model accuracy. In addition to the road grade, the vehicle speed also has a great influence on the energy consumption and battery SoC. However, in general, it is even more difficult to predict the vehicle speed than the road grade in the long term. However, in the hilly regions with light or no traffic, as the road grade will dominate the energy consumption and there will not be frequent accelerations or brakes, the details of the future speed, e.g., the details of an acceleration process or a braking process will not be of significant importance. Only the vehicle cruising speed and whether the vehicle makes a stop–start or a deceleration–acceleration in the road segment are important. In the proposed method, the vehicle speed profile will be described by the road speed limit and a variable indicating whether it makes a stop or a low-speed turn. The vehicle speed profile will also be modeled using Markov chains with a similar method to the road grade model.

- Road Grade Model for a Determined Route.
- Road Grade Model for Stochastic Routes.
- Speed Profile Model.

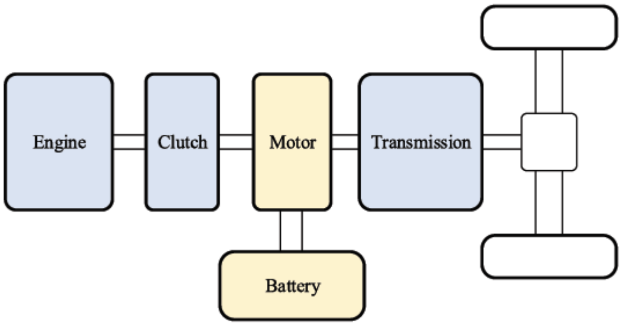

Fig. 18. HEV configuration

2-12) Trip-Oriented Energy Management Control Strategy for Plug-In Hybrid Electric Vehicles

In [14], The suggested strategy provides system optimization and controlling methods for improving fuel economy (FE)[14] by optimizing the distribution of the request of fuel power and battery electricity and sharing power delivery between electric and mechanic routs in the architecture of PHEV power sharing. System's model with two freedom degree is created for describing operating dynamic and properties of transmission power delivery. PHEV energy management control is obtained by three main help*:*

[14] Fuel Economy (FE)

1) The problem of optimal control is solved by considering both non-linearity of battery efficiency and complexity of power-sharing architecture;
2) A new pre-programming method of travel energy consumption is suggested using driving-pattern dynamic programing approach;
3) A feedback control system is designed for understanding energy optimal consumption process in real applications.
Finally, energy-goaled management is obtained with minimum loss from system operation.

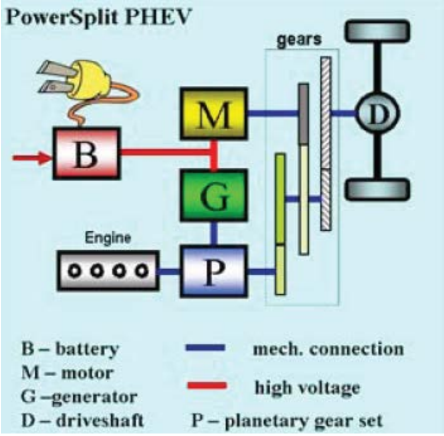

Fig. 19. Power Split PHEV system configuration

2-13) A Supervisory Energy Management Control Strategy in a Battery/ Ultra capacitor Hybrid Energy Storage System

In [15], the problem of multi-goal optimization is formulated for optimizing power sharing in order to elongate battery lifetime and decreasing HESS power losses. In this HESS energy management problem, joint dc-dc converter model is considered for including both wastes of conduction and wastes of switching. Using Dynamic programming (DP), optimization problem is solved numerically for several informational sets of propulsion cycle. Using the results from DP, intelligent and efficient online implementation, neural-network-based (NN)[15] optimal power sharing is recognized. The suggested online intelligent energy management controller is used for medium size EV[16]. Rule-based control strategy is also implemented for comparison with suggested energy management strategy. Suggested online energy management controller distributes load demand effectively and gives extraordinary results from energy efficiency. The results show that battery lifetime had considerable increase compared to single saving system while this value is very lower in rule-based strategy.

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[15] Neural Network (NN)
[16] Electric Vehicle (EV)

Review on Energy Management System Techniques

Constraint and Technique	Goal function
Route characteristics. Real-complex linear programing.	Optimization of fuel consuption in long distances.
Traffic indices. Dynamic programming algorithm (DP).	Reaching increased-economy of fuel consumption.
Dynamic programming algorithm (DP). Linear approximaiton using quadratic pass-point line.	Decreasing required computational time in order to determine optimal decision .
Re-formulation quadratic non-linear and unlimited optimization. Lyapunov law.	Finding a solution for optimizing charge saving.
Convex optimization algorithm. Battery/super-capacitor storage system.	Minimizing volume/oscillation of battery power and power waste.
Learning and reinforcement based adaptive energy RLAEM. Algorithm Q.	Determining appropriate power between battery and engine-generator set for minimizing fuel consumption than different driving timing.
Modeling of hybrid cars as hybrid systems in mathematical expression.	Providing flexibility capability in discrete decision-making like the situations of driving and the selection of gear.
Putting systematic mircochip controller in HTMS and its Designed algorithm .	Optimizing optimal temperatures of thermal resources along with high effciency and low energy consumption during long distance.
Amplifying energy efficiency and integrity of controlling system and new ACC system based on routing safety, Fuel consupmtion and ease of driving.	Routing safety, decreasing fuel consumption and ease of driving, better controlling harmony between fuel efficiency and traffic safety.
Repetitive calculations and power partitioning by convex optimization algorithm.	Optimal energy management in engine on/off conditions.
Unlimited and discontinuous time Markov chain considering ambiguity of the road ahead.	In order to obtain battery SoC saving and proportional control loop. Energy consumption efficiency.
Optimization of distributing fuel and electricity power demand and sharing power delivery between electric and mechanic paths in the architecture of power sharing PHEV.	Improving fuel economy.
Dynamic programming algorithm (DP). Neural networks.	Optimizing power sharing in order to elongate battery lifetime and decreasing power losses HESS.

CONCLUSION

There has been an increased interest in green transportation systems over the course of last few years. The advent of technological advances such as smart networks, hybrid and electric automobiles have paved the way for reaching green transportation systems management. In this paper we have dealt with various energy management systems in electric and hybrid automobiles. In so doing, we have had a review of modern methods proposed in the field of energy management. An analysis has been made of challenges and obstacles that have to obviate in the future in order for a practical and efficient green transportation system to exist. Finally, an integral and comprehensive framework that holds the fundamental components and factors in energy management systems of electric and hybrid automobiles is proposed.

Acknowledgements

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