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Optimal Cost Minimization Strategy for Fuel Cell Hybrid Electric Vehicles Based on Decision Making

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ABSTRACT: The low economy of fuel cell hybrid electric vehicles is a big challenge to their wide usage. A road, health, and price-conscious optimal cost minimization strategy based on decision making framework was developed to decrease their overall cost. First, an online applicable cost minimization strategy was developed to minimize the overall operating costs of vehicles including the hydrogen cost and degradation costs of fuel cell and battery. Second, a decision making framework composed of the driving pattern recognition-enabled, prognostics-enabled, and price prediction-enabled decision makings, for the first time, was built to recognize the driving pattern, estimate health states of power sources and project future prices of hydrogen and power sources. Based on these estimations, optimal equivalent cost factors were updated to reach optimal results on the overall cost and charge sustaining of battery. The effects of driving cycles, degradation states, and pricing scenarios were analyzed.

KEYWORDS: ECMS; fuel cell; hybrid system; EMS; degradation

I. INTRODUCTION

The design of an energy management strategy is critical to improving the fuel efficiency of a vehicle system with an alternative powertrain system, such as hybrid electric vehicles or fuel cell electric vehicles. In particular, in fuel cell electric vehicles, the energy management strategy should consider system degradation and fuel savings because the hardware cost of the fuel cell system is much higher than that of a conventional powertrain system. In this paper, an easily implantable near-optimal energy management controller is proposed. The proposed controller distributes power generation between the fuel cell and the battery to simultaneously minimize system degradation and fuel usage. The controller is designed to consider the degradation cost and fuel cost in the framework of the equivalent consumption minimization strategy concept. The proposed controller was validated with a fuel cell electric vehicle model in MATLAB/Simulink (MathWorks, Natick, MA, USA). The proposed control strategy showed significant overall cost reduction compared to a thermostat control strategy and a conventional Equivalent Consumption Minimization Strategy (ECMS) strategy.

An energy management strategy (EMS) efficiently splits the power among different sources in a hybrid fuel cell vehicle (HFCV). Most of the existing EMSs are based on static maps while a proton exchange membrane fuel cell (PEMFC) has time-varying characteristics, which can cause mismanagement in the operation of a HFCV. This paper proposes a framework for the online parameters identification of a PMEFC model while the vehicle is under operation. This identification process can be conveniently integrated into an EMS loop, regardless of the EMS type. To do so, Kalman filter (KF) is utilized to extract the parameters of a PEMFC model online. Unlike the other similar papers, special attention is given to the initialization of KF in this work. In this regard, an optimization algorithm, shuffled frog-leaping algorithm (SFLA), is employed for the initialization of the KF. The SFLA is first used offline to find the right initial values for the PEMFC model parameters using the available polarization curve. Subsequently, it tunes the covariance matrices of the KF by utilizing the initial values obtained from the first step. Finally, the tuned KF is employed online to update the parameters. The ultimate results show good accuracy and convergence improvement in the PEMFC characteristics estimation

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II. LITERATURE REVIEW

Studies on EMSs can be divided into the rule-based strategy (RBS) and optimization-based strategy (OBS) [3]. The heuristic rules are the core of the RBS. These rules can be expressed as the deterministic rules in deterministic rule-based strategies or fuzzy rules in fuzzy rule-based strategies. Based on these rules, the on/off of fuel cell, operating models of ESSs, and corresponding power of power sources are determined to make sure the normal operation of the vehicle. Load following strategy, operating mode control strategy and fuzzy logic control are typical RBSs. The RBSs can be easily designed by engineers based on their experience. The real-time implication of these RBSs is also simple and their resilience on different driving patterns is strong. But optimal results for the designed objectives of EMSs are hardly reached. In order to overcome the deficiency of the RBS, OBS is designed to optimize the operation of vehicles and achieve the optimal objectives. The general configuration of OBS includes one or more optimal objectives and certain constraints such as limiting the state of charge (SOC) of ESSs and power ranges of power sources. Based on the optimization horizons, OBS can be divided into the global OBS taking the whole driving cycle as optimization horizons and local OBS on the instantaneous sampling time. Dynamical programming (DP), genetic algorithm (GA) and particle swarm optimization are widely used algorithms to solve global optimization problems to achieve optimal objectives [4, 5]. Equivalent consumption minimization strategy, Pontryagin's minimum principle (PMP) and model predictive control (MPC) are typical local OBSs [6, 7]. Many studies on EMSs for FCHEVs only focus on the minimization of hydrogen consumption or equivalent hydrogen consumption from ESSs without sufficiently considering the degradation of fuel cell and battery. A small number of studies try to make a tradeoff between battery degradation and hydrogen consumption. For example, in [8] and [9] discrete dynamic programming and convex optimization are respectively used to optimize the costs of battery degradation and hydrogen consumption. But the fuel cell degradation is not considered into the optimal objectives of these studies. In [9], minimizing the hydrogen and fuel cell lifetime costs as the objective function is solved through stochastic dynamic programming (SDP). Three representative EMSs: DP, PMP, and MPC in [09] are developed to minimize hydrogen consumption and fuel cell durability. In [5] and [6], the fuel cell models are identified online to find the variation of fuel cell.system performances and to operate the fuel cell in the best efficiency and power operating points through PMP. Battery degradation is not considered in the above researches. The deficiency for the above researches on the minimizing oval cost of FCHEVs can be concluded as not considering all power sources degradation. Fuzzy logic control optimized by GA in [5], MPC based sequential quadratic programming in [9] and DP in [6, 7] consider all hydrogen cost and degradation costs of fuel cell and battery. But empirical degradation models of fuel cell and battery used to calculate their degradation costs are not precise, which cannot describe the dynamical degradation rates of power sources under the dynamical conditions of vehicles like the changeable external environment condition, temperature, and operating conditions. The lifetime costs calculated based on the unprecise degradation rates bring a big challenge to the reliability of their developed EMSs. The deficiency for these researches can be defined as not reliable and precise lifetime cost estimation, which also occurs in the researches with the first deficiency. Furthermore, a common serious drawback in present researches is that the variable driving situations, state of health (SOH) of power sources and prices of hydrogen and power sources, which affect the optimal cost results and charge sustaining of battery, even more seriously, the normal operation of the vehicle, are totally not considered. The EMS control parameters optimized for specified driving cycles cannot meet all kinds of road situations. The degradation of power sources leads to the decrease of their performances and corresponding degradation rates will change along with SOHs [8]. Prices of hydrogen and power sources will also change along with their technology development on production, usage, investment, and operation. In a word, the constant parameters in the EMSs aiming to improve the economy of FCHEVs cannot meet the dynamical and variable operating conditions of FCHEVs, no matter in the external environment like variable driving conditions and prices or in the internal conditions like degradation and failures. Well known as an efficient and eco-friendly power source, fuel cell, unfortunately, offers slow dynamics. When attached as primary energy source in a vehicle, fuel cell would not be able to respond to abrupt load variations. Supplementing battery and/or supercapacitor to the system will provide a solution to this shortcoming. On the other hand, a current regulation that is vital for lengthening time span of the energy storage system is needed. This can be accomplished by keeping fuel cell's and batteries' current slope in reference to certain values, as well as attaining a stable dc output voltage. For that purpose, a feedback control system for regulating the hybrid of fuel cell, batteries, and super capacitor was constructed for this study. Output voltage of the studied hybrid power sources (HPS) was administered by assembling three dc-dc converters comprising two bidirectional converters and one boost converter. Current/voltage output of fuel cell was regulated by boost converter, whereas the bidirectional converters regulated battery and super capacitor. Reference current for each converter was produced using Model Predictive Control (MPC) and subsequently tracked using hysteresis control. These functions were done on a controller board of a dSPACE DS1104. Subsequently, on a test bench made up from 6 V, 4.5 Ah battery and 7.5 V, 120 F super capacitor together with a fuel cell of 50 W, 10 A, experiment was conducted. Results show that constructing a

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control system to restrict fuel cell's and batteries' current slope and maintaining dc bus voltage in accordance with the reference values using MPC was feasible and effectively done.

An energy management strategy (EMS) is responsible for distributing the power between the electrochemical power sources of a fuel cell hybrid electric vehicle (FCHEV) with a view to minimizing the hydrogen consumption and maximizing the lifetime of the system. However, the energetic characteristics of the electrochemical devices (fuel cell, battery, and supercapacitor) are time-varying due to the influence of ageing, and different ambient and operating conditions. Any drift in the characteristics of the power sources can lead to the mismanagement of an EMS. According to the literature, ignorance of health adaptation can increase the hydrogen consumption from almost 6.5%–24% depending on the EMS. Therefore, it is necessary to develop a strategy which is aware of the actual state of the components while conducting the power split. Health monitoring techniques are potential candidates to deal with the uncertainties arising from the mentioned factors. In this respect, this paper first puts forward a concise review of the general modeling techniques which are essential for developing precise health monitoring techniques and in turn EMSs. Subsequently, the utilized methods for prognosis, diagnosis, and health state tracking of each of the mentioned power sources in a FCHEV are introduced. Then, a new taxonomy for the classification of the EMSs based on their health-awareness is proposed based on which three categories of prognostic-based, diagnostic-based, and systemic EMSs are formed. Each category is thoroughly explained, and a state-of-the-art review of these health-aware EMSs is presented. Finally, future perspectives of this new line of research and development are discussed before drawing a conclusion. [2]

III. PROPOSED ARCHITECTURE

To the best knowledge of the authors, no efforts have been made to develop a cost minimization strategy (CMS) to minimize the hydrogen cost and lifetime costs of power sources under variable internal and external conditions on power sources and road situations with adaptive control parameters. In order to bridge this research gap and overcome shortcomings of present researches on improving FCHEVs economy, an OCMS for FCHEVs based on decision making framework considering the dynamical road information, power sources degradation, price evolution of materials is developed. Three main original contributions can be concluded to distinguish our research from other exiting studies. First, a CMS is built to improve the fuel economy and decrease the lifetime costs of fuel cell and battery based on their degradation models. Second, a decision making framework, for the first time, is built composed of the driving pattern recognition-enabled decision making (DPRDM), prognostics-enabled decision making (PDM), and price prediction-enabled decision making (PPDM). Based on the DPRDM, real-time driving patterns can

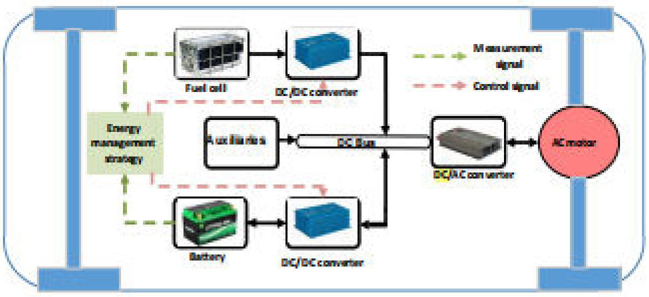

Fig. 1.Power train architecture.

be recognized through the support vector machine (SVM). Based on the PDM, the health states of fuel cell and battery are online estimated based on the unscented Kalman filter (UKF) and are further able to precisely calculate the lifetime costs of power sources cooperating with their empirical degradation models. Through the PPDM, the price evolutions of hydrogen and power sources until the end of the lifetime of the vehicle are projected based on the experience rate approach. Under the innovative decision making framework, the internal and external conditions of the vehicle can be determined. Third, the pre-optimal equivalent cost factors (ECFs) through the GA are calculated. Based on the recognized diving cycle, estimation of SOHs and price prediction, optimal ECFs and corresponding suitable control policies are adjusted to extend the lifetimes of fuel cell and battery, keep the charge sustaining of battery and achieve the minimization objective of the overall cost.

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IV. CONCLUSIONS

This paper developed a cost optimal, decision making energy management strategy considering the fuel cell and battery lifetimes and the uncertainness on the driving pattern, degradation states of power sources, and prices of fuel and drivetrain components. The overall cost including the hydrogen cost, fuel cell and battery degradation cost was minimized. The decision making framework was built to supply optimal equivalent cost factors at all kinds of situations on the driving pattern, health state and price. Simulation results proved that the optimal cost and charger sustaining of battery were achieved through the cooperation between CMS and decision making framework composing the OCMS..

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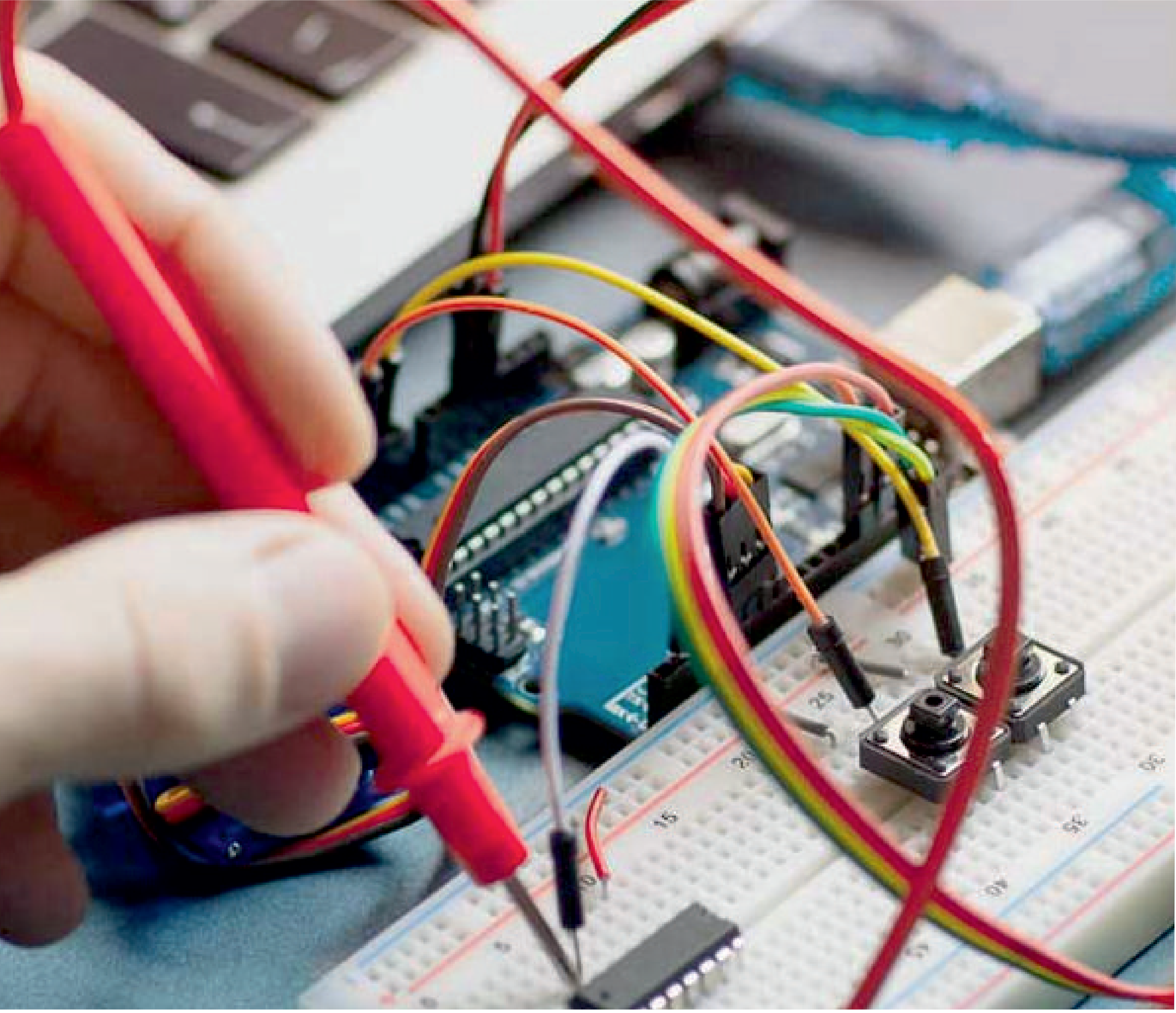

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