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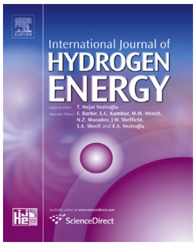

Design of an adaptive EMS for fuel cell vehicles

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ABSTRACT

This paper addresses the energy management strategy (EMS) for a fuel cell hybrid electric vehicle (FC-HEV). In this work, model parameters are identified online by using the square root unscented Kalman filter (SR-UKF) method to seek a variation in the fuel cell performances. Then, an optimization algorithm is used on the updated model to find the best efficiency and power operating points. This process is used into two strategies: (i) A hysteresis energy management strategy (EMS) and (ii) an optimal EMS based on Pontryagin's minimum principle, for a FC-HEV. The effectiveness of the proposed EMSs is demonstrated by conducting studies on a FC-HEV model.

Introduction

An interesting solution to produce near zero local emission electricity in an embedded system (as hybrid vehicle) is the fuel cell system (FCS). The most practical FCS for fuel cell hybrid electric vehicles (FC-HEV) is the proton exchange membrane fuel cell (PEM-FC) thanks to its low operating temperature and pressure, tolerance to carbon dioxide and solid membrane [1]. Furthermore, hydrogen with high purity can be produced with renewable energies, such as electrolysis and biomass processes (e.g., photosynthetic or fermentative organisms) to produce near zero global emission electricity [2,3]. A good durability is ensured for the PEM-FC when slow load dynamics are applied in practice [4]. Consequently, an energetic buffer such as battery, supercapacitor, flywheel should be used with the PEM-FC to satisfy the fast dynamic load for the traction power on a vehicle DC bus [5]. Additionally, hybridization of sources makes it possible to approach the performance of a conventional vehicle in terms of autonomy [6]. As the energy is distributed between two sources, energy management strategy (EMS) is required.

In the literature, two classes define the EMS of the FC-HEV: the rule-based and the optimization-based controls [7]. The rule-based controls are based on efficiency map such as Feroldi et al. [8] and Ettihir et al. [9]. The second approach is based on optimization of a cost function, which frequently defines the criterion regarding the fuel consumption, system efficiency, or system power [10]. For example, Bernard et al. [11] design an EMS based on Pontryagin's minimum (PMP) to reduce the hydrogen consumption and perform experimental validation. Fares et al. [12] develops an optimal power splitting strategy based on a weighted dynamic programming technique. The optimal management shows a

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List of symbols

Acronyms

APMP	Adaptive Pontryagin's Minimum Principle
EMS	Energy Management Strategy
ESP	Extremum Seeking Process
FC–HEV	Fuel Cell Hybrid Electric Vehicle
FCS	Fuel Cell System
PEM–FC	Proton Exchange Membrane Fuel Cell
HRI	Hydrogen Research Institute
IM	The Induction Motor
LSV	Low Speed Vehicle
MEPT	Maximal Efficiency Point Tracking
ME	Maximal Efficiency
MPPT	Maximal Power Point Tracking
MP	Maximal Power
PMP	Pontryagin's Minimum Principle
SOC	State of Charge of the battery
SR–UKF	Square Root Unscented Kalman Filter

Greek symbols

α	The fitting parameter of the fuel cell Squadrito model, –
α_{rc}	The empirical parameter of the lead acid battery temperature when charging, –
α_{rd}	The empirical parameter of the lead acid battery temperature when discharging, –
$\beta_{1\ldots4}$	The empirical parameter of the activation overpotential, –
γ	The scaling parameter
λ	The forgetting factor
ν_k	The process noise, –
ξ	The inverse of the limiting current i_L, A^{-1}
σ	The fitting parameter of the fuel cell Squadrito model, –
ϕ_{dr}	The direct magnetic flux of the induction motor rotor, Wb
ϕ_{qr}	The quadratic magnetic flux of the induction motor rotor, Wb
ω	The shaft speed of the induction motor rotor, rad/s

Roman symbols

b	The Tafel slope, V
C_{10}	The charge and discharge current rate of the lead acid battery, Ah
C_n	The amount of useful charge available of the lead acid battery, Ah
d_k	The parameter corresponds to a nonlinear observation on w_k, –
e_k	The error of the system identification, –
E_{nernst}	The Nernst potential of the fuel cell voltage, V
F	The Faraday constant, C mol^{-1}
$f_{1,2}d$	The empirical parameter of the hydrogen molar flow
Fh_2	The hydrogen molar flow, mol/s
G(.)	The nonlinear mapping function parametrized by the vector w_k, –
HHV	The high heating value, Ω
i_0	The exchange current, A
i_{ds}	The direct current of the induction motor rotor, A
i_{fc}	The fuel cell current, A
i_{lim}	The limiting current density of the fuel cell, A
i_{qs}	The quadratic current of the induction motor rotor, A
J	The inertia of the induction machine, kg m^2
k	The time step, –
K_k	The Kalman gain, –
K_{boc}	The empirical parameter of the V_{boc} variation with the state of charge (electrolyte concentration), –
K_{bod}	The empirical parameter of the V_{bod} variation with the state of charge (electrolyte concentration), –
L_s	The stator inductance of the induction motor rotor, H
M	The mutual inductance of the induction motor rotor, H
N_{cell}	The cell number of the fuel cell, –
p	The pole number of the induction motor, –
$P_{1\ldots4}c$	The empirical parameter of the internal resistance variation of the V_c, –
$P_{1\ldots4}d$	The empirical parameter of the internal resistance variation of the V_d, –
Pw_k	The covariance matrix, –
R	The gas constant, J mol^{-1} K^{-1}
r	The ohmic resistance of the fuel cell, Ω
R^e	The measurement noise covariance, –
$R_{electronic}$	The resistance to electron flow through electrode, Ω
$R_{protonic}$	The resistance to proton flow in the membrane, Ω
SOC_0	The initial state of charge of the battery, %
Sw_k	The time step, –
T_{em}	The electromagnetic torque of the induction motor, Nm
T_{fc}	The fuel cell temperature, K
T_r	The resistive torque, Nm
Vo	The open circuit voltage of the fuel cell, V
V_{act}	The activation overvoltage the fuel cell voltage, V
V_{boc}	The discharge open circuit voltage parameter of the lead acid battery, V
V_{bod}	The charge open circuit voltage of the lead acid battery, V
V_c	The charging voltage of the lead acid battery, V
V_{cell}	The cell potential of the fuel cell, V
V_{conc}	The concentration overvoltage the fuel cell voltage, V
V_d	The discharging voltage of the lead acid battery, V
V_{ohmic}	The ohmic overvoltage the fuel cell voltage, V
W_i	The variable weighting parameters, –
w_k	The parameters correspond to a stationary process with identity state transition matrix, –

Superscripts

$\hat{.}$	The sign denote the estimation of a variable

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