Optimal Energy Management for Hybrid Electric Off-Road Vehicles

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Part 1: Optimal Energy Management for Hybrid Electric Agricultural Tractors

1. Introduction

➢ The energy management system is the supervisory control layer in hybrid electric vehicles that manage the power flows between different energy sources and loads of the vehicles, such as internal combustion engine, battery, traction motor(s), etc.

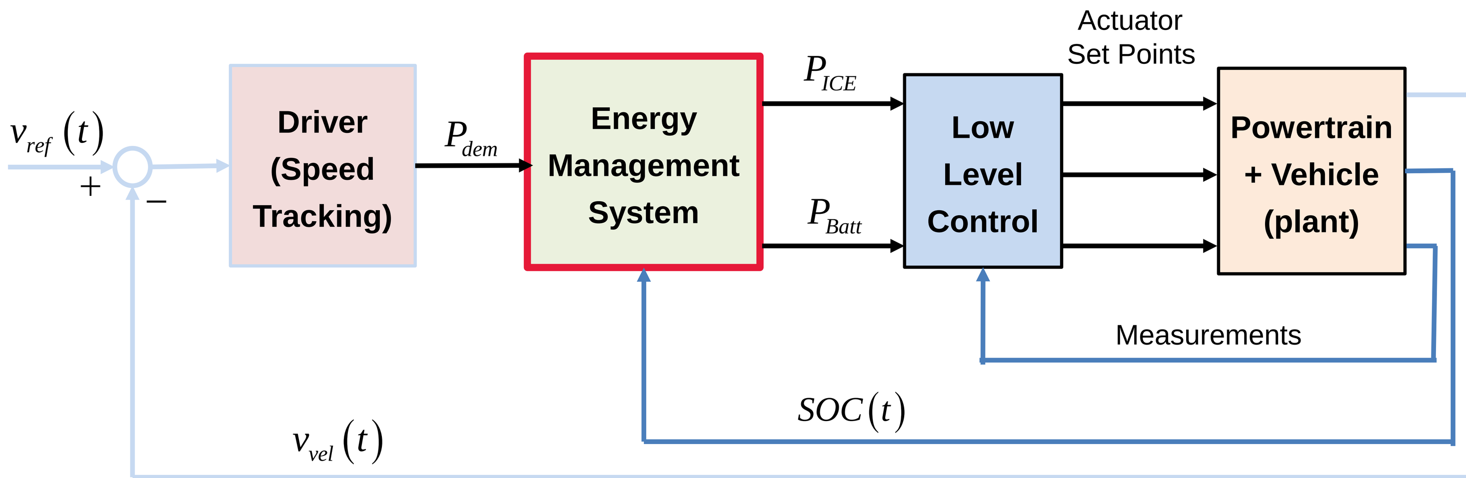


Fig. 1 The role of the energy management system in hybrid electric vehicles.

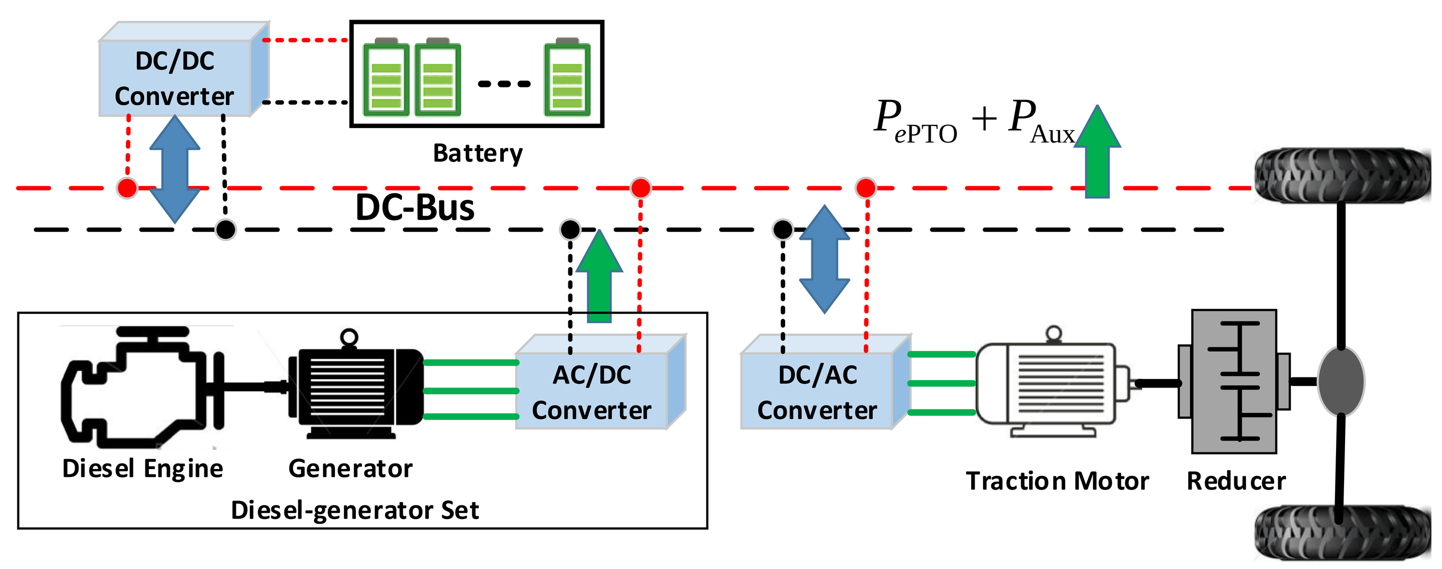


Fig. 2 The powertrain architecture of a typical series hybrid electric agricultural tractor (HEAT).

➢ **Problem description**

Develop optimal energy management strategies (EMSs) to minimize fuel consumptions in typical working cycles.

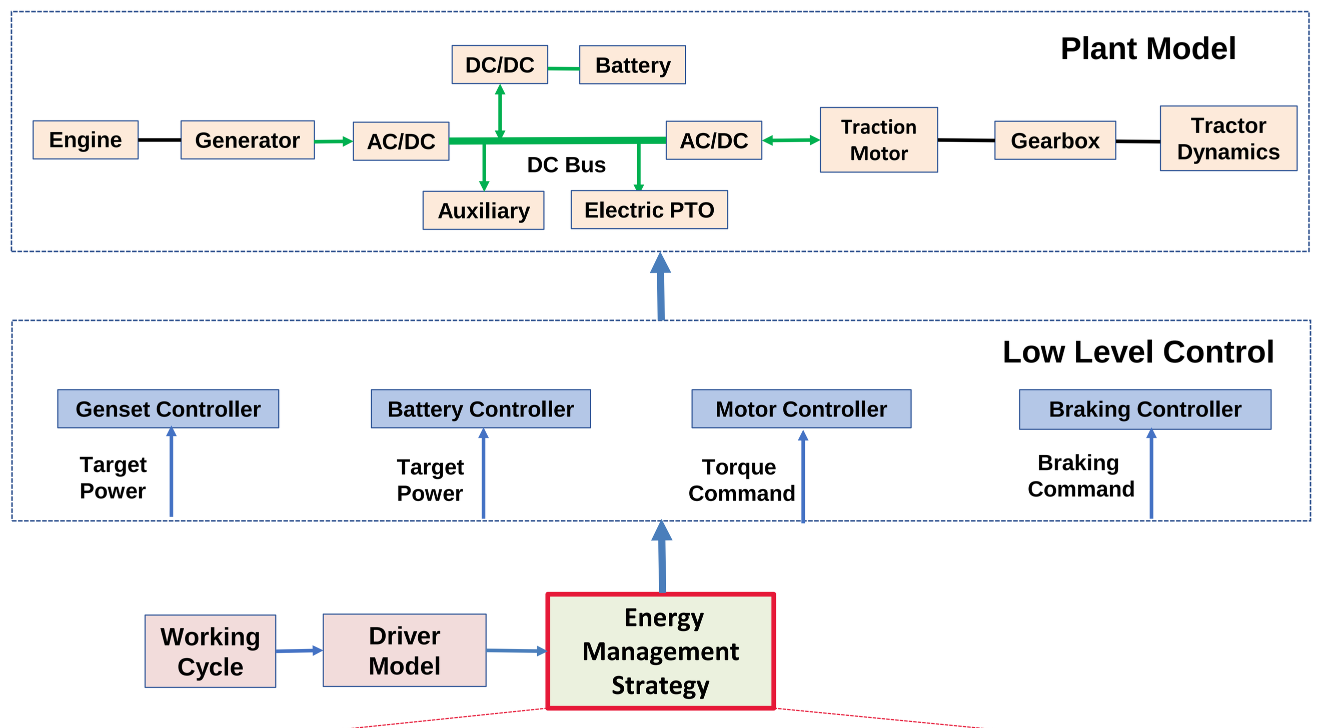
➢ **Contributions**

1) In contrast to the rule-based EMSs in the literatures, this work proposed optimization-based EMSs for HEATs.

2) The energy management problem was further formulated as a nonlinear constrained optimal control problem (OCP) to minimize the fuel consumptions.

3) Three different numerical methods were adopted to solve the OCP. Compared with typical rule-based EMSs, the optimization-based EMSs can improve 3%-5% fuel economy.

2. Modeling and Problem Formulation



Control-oriented model for EMS

1) Genset model

$$\dot{m}_f(P_g) = \sum_{0}^{3} a_i P_g^{3-i}$$

2) Battery model

$$\dot{x}(t) = -\frac{V_{oc}(x(t)) - \sqrt{V_{oc}^2(x(t)) - 4R_b(x(t))P_b(t)}}{2Q_b R_b(x(t))} = f(x(t), P_t(t))$$

3) Power demand model

$$F_t = \frac{1}{2}\rho_a C_d A_F v^2 + C_r mg\cos\theta + mg\sin\theta + \delta ma + F_{dr}$$

Optimal energy management problem

Minimize $J = \int_{t_0}^{t_f} \dot{m}_f(u(t))dt$

Subject to the following constraints:

State equation:

$$\dot{x}(t) = f(x(t), u(t))$$

Boundary conditions:

$$x(t_0) = x_0,\ x(t_f) = x_f$$

State constraints:

$$x_{min} \le x(t) \le x_{max}$$

Control constraints:

$$P_{b.min}(t) \le u(t) \le P_{b.max},$$

$$P_{dem}(t) - P_{g.max} \le u(t) \le P_{dem}(t) - P_{g.min}$$

3. Numerical Methods

➢ The optimal energy management problem is a nonlinear constrained OCP. Three different numerical methods were applied to solve the OCP.

Algorithm 1: Dynamic Programming (DP)

1) Calculate the cost-to-go function at each node in the discretized-time state space
2) Proceed backward in time (bottom-up fashion)

Algorithm 2: Indirect Method Based on Pontryagin Minimum Principle (PMP)

1) Derive the necessary conditions for optimality according to the PMP
2) Solve the two-point boundary value problem with the shooting method

Algorithm 3: Direct Method Based on Nonlinear Programming (NLP)

1) Discretize with Legendre-Gauss-Radau (LGR) orthogonal collocation method
2) Approximate state and control variables with Lagrange interpolating polynomials
3) Transcribe into a NLP framework and optimize with a powerful solver

4. Simulation Results

1. Power Demand Profiles

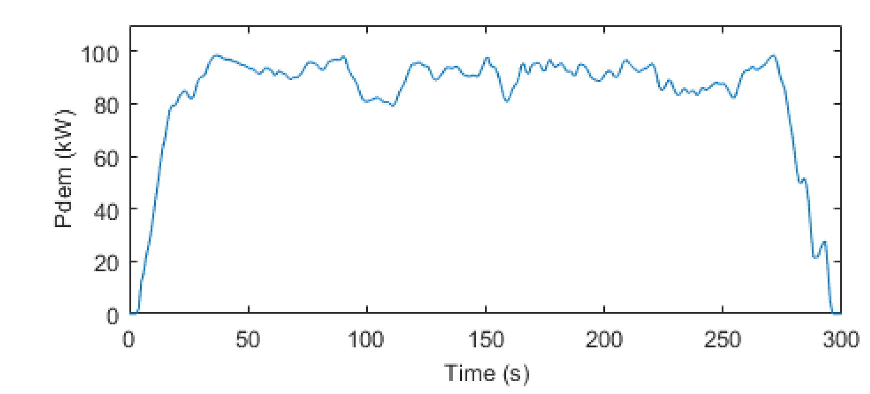


Fig. 3 Power demand of a plough cycle.

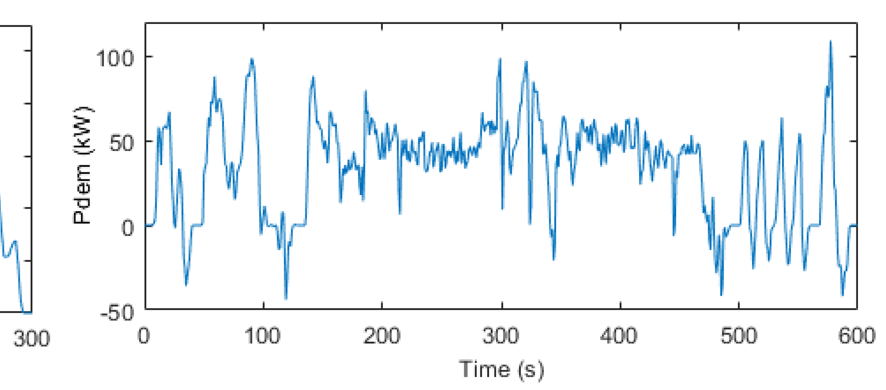


Fig. 4 Power demand of a plough cycle.

2. State of Charge (SOC) Trajectory

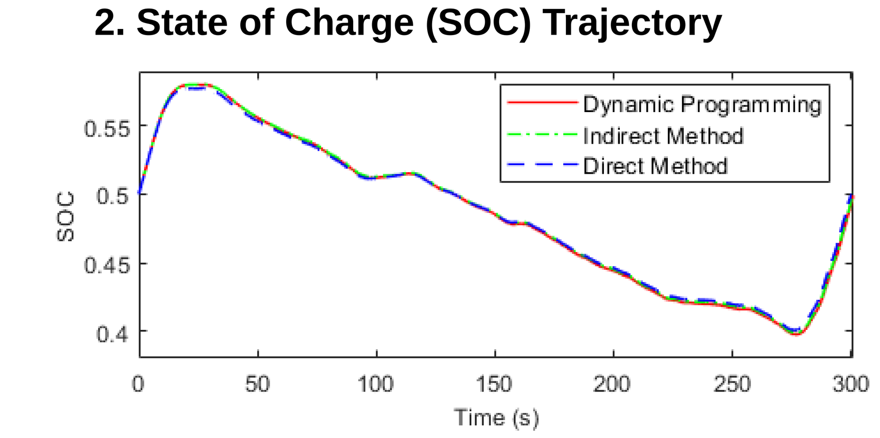


Fig. 5 Optimal SOC trajectory of a plough cycle.

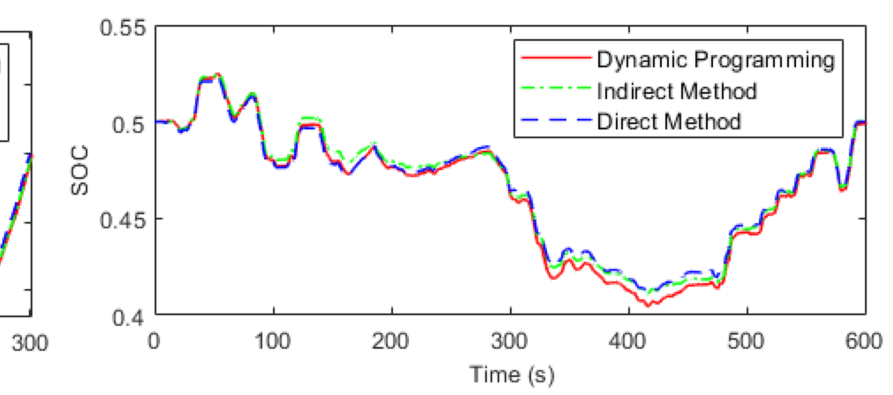


Fig. 6 Optimal SOC trajectory of a transport cycle.

3. Fuel Consumption

Working Cycle	Fuel Consumption [g]				Fuel Saving [%]
	Dynamic Programming	Indirect Method	Direct Method	Rule-based Strategy	
Plough Cycle	1717.9	1718.5	1718.5	1772.6	3.08
Transport Cycle	1359.0	1359.1	1359.7	1431.5	4.99

5. Conclusions

➢ Optimization-based energy management problem was formulated for HEATs.

➢ Three numerical methods, i.e., DP, PMP-based indirect method, and NLP-based direct method were studied to solve the energy management problem to obtain the optimal EMSs.

➢ Simulation results demonstrated that compared with the rule-based benchmark EMS (power follower strategy), the three optimal EMSs achieved up to 5% fuel economy improvement.

➢ Future work will consider battery degradation in the optimization framework to prolong the battery lifetime.

Part 2: IEEE Vehicular Technology Society Motor Vehicle Challenge 2019 – Energy Management of a Dual-mode Locomotive

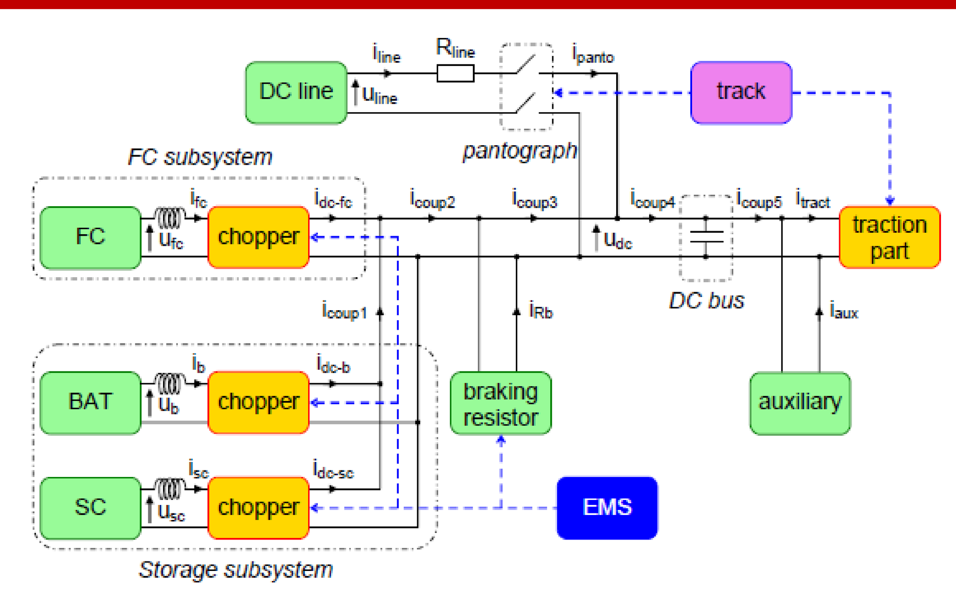


Fig. 7 Structural scheme of the studied dual-mode locomotive.

Design an EMS to minimize the trip operational costs:

- Minimize the electricity costs
- Minimize the hydrogen consumption
- Increase the lifetime of the fuel cell, battery, and supercapacitor

Operational Cost Analysis

$$€_{net}(t) = \frac{N_{cost}}{3600 * 1 * 10^6}\int_0^t p_{line}(t)dt$$

$$€_{H_2}(t) = \frac{H_{2-cost}}{1 * 10^3}\int_0^t \dot{m}_{H_2}(t)dt$$

$$€_{fc}(t) = \frac{P_{fc-rat}}{1 * 10^3} FC_{cost}\Delta_{fc}(t)$$

$$€_{fc}(t) = E_{sc-rat} SC_{cost}\Delta_{sc}(t)$$

⋮

EMS Design Considerations

- Start-stop of fuel cells is expensive. So minimize it.
- Electricity is cheap. So the battery and supercapacitor when the DC line is connected.
- After fuel cell starts, keep it work at most efficient point as much as possible.
- To minimize the battery degradation, the SOC should be maintained close to 100%.
- Constraints on DC bus voltage range, battery current, maximal variation rate of the fuel cell current, and supercapacitor voltage, should be guaranteed.
- The life cycle of supercapacitor is much longer than that of battery. So the supercapacitor can be charged and discharged frequently.

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Our Solution: Heuristic Method

- A simple control system consists of proportional controller, filtering-based controller, and state machine logic, and satisfies all the operation constraints.
- Consider three discrete states: DC line on-off, fuel cell on-off, regenerative or motoring
- Consider two continuous states: battery SOC and supercapacitor SOC.
- Pros: easy implementation, real-time strategy, and insensitive to different driving cycles.

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Result of Our Solution

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Cost results of the simulation with a Cycle Contest SNCF

1. The fuel cell cost is 7.09 €
2. The H2 cost is 0.32 €
3. The battery cost is 6.77 €
4. The supercapacitors cost is 3.90 €
5. The electricity network cost is 6.15 €
6. The penalty cost of the charge sustaining mode is -18.17 €
7. The total cost of the trip is 6.06 €

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Competition award

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- We are the second-place winner among 45 academic and professional teams from 15 countries. The winners will be officially announced and the awards will be presented at the 2019 IEEE Vehicle Power and Propulsion Conference (VPPC).
- We are invited to write a paper to report our challenge results, which will be presented in a special session dedicated to the challenge at the IEEE VPPC 2019.

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