



Optimal energy management of a hybrid electric powertrain system using improved particle swarm optimization



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HIGHLIGHTS

- Online sub-optimal energy management using IPSO.
- A second-order HEV model with 5 major segments was built.
- IPSO with equivalent-fuel fitness function using 5 particles.
- Engine, rule-based control, PSO, IPSO and ECMS are compared.
- Max. 31+% fuel economy and 56+% energy consumption improved.

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ABSTRACT

This study developed an online suboptimal energy management system by using improved particle swarm optimization (IPSO) for engine/motor hybrid electric vehicles. The vehicle was modeled on the basis of second-order dynamics, and featured five major segments: a battery, a spark ignition engine, a lithium battery, transmission and vehicle dynamics, and a driver model. To manage the power distribution of dual power sources, the IPSO was equipped with three inputs (rotational speed, battery state-of-charge, and demanded torque) and one output (power split ratio). Five steps were developed for IPSO: (1) initialization; (2) determination of the fitness function; (3) selection and memorization; (4) modification of position and velocity; and (5) a stopping rule. Equivalent fuel consumption by the engine and motor was used as the fitness function with five particles, and the IPSO-based vehicle control unit was completed and integrated with the vehicle simulator. To quantify the energy improvement of IPSO, a four-mode rule-based control (system ready, motor only, engine only, and hybrid modes) was designed according to the engine efficiency and rotational speed. A three-loop Equivalent Consumption Minimization Strategy (ECMS) was coded as the best case. The simulation results revealed that IPSO searches the optimal solution more efficiently than conventional PSO does. In two standard driving cycles, ECE and FTP, the improvements in the equivalent fuel consumption and energy consumption compared to baseline were (24.25%, 45.27%) and (31.85%, 56.41%), respectively, for the IPSO. The CO₂ emission for all five cases (pure engine, rule-based, PSO, IPSO, ECMS) was compared. These results verify that IPSO performs outstandingly when applied to manage hybrid energy. Hardware-in-the-loop (HIL) implementation and a real vehicle test will be conducted in the near future.

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1. Introduction

To reduce the increasing number of environmental concerns, green transportation has become increasingly used because of favorable characteristics such as high well-to-wheel efficiency,

low (zero) pollutant emission, high output performance, and outstanding fuel economy [1,2]. The concept of hybridization has been widely applied in designs for hybrid electric vehicles (HEVs), plug-in HEVs (PHEVs), multi-energy source (fuel cell/battery/supercapacitor) electric vehicles, and in-wheel motors [3,4]. Hybridization maximizes the advantages of power (energy) sources and minimizes the inherent drawbacks. For instance, the powertrain in an HEV drives the vehicle with the motor to avoid the low-efficiency, high-pollutant operation of the engine, and

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Nomenclature

A_f	area, m ²	$\eta_{\max}$	upper bound of particle position or velocity
C_d	air drag coefficient	ρ	air density, kg/m ³
c_1, c_2, c_3	acceleration factor	σ	learning factor
E	energy, J	ζ	inertia weight
F	force, N		
G	global solution for IPSO	Subscripts	
i	i th particle	a	actual
FIT	fitness function	$BEST$	best solution
k	k th iteration for IPSO	b	battery
m	mass, g	brk	brake
$\dot{m}$	mass flow rate, g/s	CO_2	CO ₂ emission
N	rotational speed, rpm	d	demand or dimension of the particle
P	power, W or population size	e	engine
RR	reduction ratio	m	motor
r	radius, m	oc	open circuit
r_1, r_2, r_3	uniform random number	$roll$	rolling resistance
T	torque, N m	t	transmission
t	time, s	tot	total
V	vehicle speed, kph or voltage, V	tq	torque
v	particle velocity	v	vehicle
x	particle position	w	wheel
α	power split ratio	$wind$	wind force
η	efficiency, %		
$\eta_{\min}$	lower bound of particle position or velocity		

powers the engine at a medium speed with favorable fuel economy to extend the mileage. The engine/motor hybrid mode optimizes the output performance (such as acceleration and gradeability) for heavy load or high-power requirements.

In addition to the hybrid configurations, the control strategies of the vehicle control unit (VCU) are the keys for appropriately managing the power allocation and increasing the efficiency of dual power/energy sources. According to relevant literature, rule-based control, theoretical control, and rule/theoretical integration control are three main types of control strategies. Rule-based control is characterized by rapid rule design and easy implementation in VCUs. “If–Else” rules are based on the engineering intuition that the operation modes can be determined quickly [5]. In [6], fuzzy rules from the expert system were used to construct multidimensional tables for power management. However, these rules cannot be applied to manage complicated systems with various designed variables. By contrast, for theoretical energy management, dynamic programming (DP) is an absolute optimization method for determining the energy distribution during determined driving cycles [7]. The Pontryagin Minimum Principle (PMP), as another theoretical analysis tool for optimal energy management of HEVs, was compared to DP in [8] and was found that the solution was very close to that of DP. A genetic algorithm (GA) is another method for cooperating with the hybrid powertrain [9]. These methods can be used to calculate the optimal power management offline. However, when the results are implemented in VCUs, rule extraction is difficult. The third type, rule/theoretical integration control, is characterized by easy VCU implementation and provides suboptimal power (energy) management. Methods of this type typically include stochastic dynamic programming (SDP) and the equivalent consumption minimization strategy (ECMS). In SDP, the advantages of offline DP optimization are incorporated with the concept of probability distribution for online energy management [10]. In ECMS, the consumed electricity is regarded as the equivalent engine fuel, and the appropriate allocation of the hybrid power distribution is globally searched according to the minimized equivalent fuel [11]. Meanwhile, a proposed Approximate Pontryagin Minimization Principle was used to deal with the

sub-optimal energy management for plug-in PHEVs in [12]. On the basis of the aforementioned studies, this study employed another effective optimization method for the online control of hybrid powertrain, called improved particle swarm optimization (IPSO), which incorporates both online VCU strategies and theoretical calculation for power management optimization.

PSO, a population-based optimization method, has attracted increasing attention because it is highly efficient and can search for global optimal solutions in scientific and engineering domains [13,14]. The PSO method is based on simulating the social behaviors and self-adaptive characteristics of animals.

Compared with the GA, which no longer considers previous knowledge after each evolution, PSO can remember satisfactory solutions by using all particles [15]. Moreover, the evolution of the GA is based on reproduction, crossover, and mutation. Therefore, a high computation load is required. By contrast, because the unique information diffusion and interaction mechanisms of PSO are comparably simple, a low computational burden is required, and the PSO is suitable for use in various applications such as control [16,17], system identification [18], network optimization [19], and electric power systems [20]. The aforementioned studies have revealed that PSO is a rapid and reliable tool for designing an optimal strategy and can outperform other evolutionary algorithms.

Many variants of PSO have been proposed to further enhance the particle learning and reasoning ability over the past decade [20–23]. An adaptive elite-based particle swarm optimization (EPSO) applied to VAR optimization in electric power systems was proposed in [20]. Mean value appending and particle pruning/cloning are two elite strategies used in EPSO, which facilitates the iterative process to coordinate between global and local searches. In [21], a self-adaptive learning-based PSO with inherent four velocity updating strategies was proposed to improve the universality and robustness of PSO. Moreover, a cellular automata mechanism was integrated in a cellular PSO to prevent the particle from being trapped in the local optimum [22]. Furthermore, the worst experience component is included in improved PSO (IPSO) to provide additional exploration capability.

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