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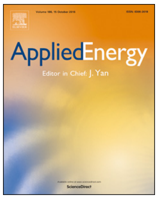

Implementation and evaluation of real-time model predictive control for load fluctuations mitigation in all-electric ship propulsion systems

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HIGHLIGHTS

- Real-time MPC has been implemented and evaluated in the physical testbed.
- Three special efforts are made to enable real-time implementation of MPC.
- Load fluctuations on the shipboard are addressed using real-time MPC.
- A filter-based algorithm is used to validate the effectiveness of MPC.
- The bus voltage variation and HESS loss can be reduced by up to 38% and 65%.

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ABSTRACT

Electrification is a clear trend for both commercial and military ship development. Shipboard load fluctuations, such as propulsion-load fluctuations and pulse power loads, can significantly affect power system reliability. In order to address this issue, this paper explores a real-time model predictive control based energy management strategy for load fluctuation mitigation in all-electric ships. A battery combined with ultra-capacitor hybrid energy storage system (HESS) is used as a buffer to compensate load fluctuations from the shipboard network. In order to implement the proposed real-time MPC-based energy management strategy on a physical testbed, three special efforts have been made to enable real-time implementation: a specially tailored problem formulation, an efficient optimization algorithm and a multi-core hardware implementation. Given the multi-frequency characteristics of load fluctuations, a filter-based power split strategy is developed as a baseline control to evaluate the proposed MPC. Compared to the filter-based strategy, the experimental results show that the proposed real-time MPC achieves superior performance in terms of enhanced system reliability, improved HESS efficiency, long self-sustained time, and extended battery life. The bus voltage variation and hybrid energy storage losses can be reduced by up to 38% and 65%, respectively.

1. Introduction

The global warming is an international issue, which requires a decrease of fuel consumption and green house gas emission in all types of ships [1]. To achieve this goal, the propulsion system efficiency is required to be improved [2]. Electric propulsion could optimize the operation of onboard generators and facilitate the use of renewable energy sources and fuel cells [3]. Electric propulsion in marine applications is not a new concept, dating back over 100 years [4]. Marine electrification became increasingly popular after the development of high power variable speed drives (VSDs) in the 1970's–1980's [5]. With the use of VSDs to electric propulsion motors, a common set of generators could power both the ship service and propulsion systems [6]. This concept is referred to as an integrated power system (IPS), which is the characterizing element of an all-electric ship (AES) [7].

IPS provides electrical power for both the propulsion system and service loads. Because of the integration of the shipboard network, load fluctuations from the propulsion system, as well as pulse-power loads from high-power missions, can significantly affect power quality and system reliability. In order to guarantee power quality and achieve

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Nomenclature

A_e/A_o	expanded blade-area ratio
C_{UC}	capacitance of ultra-capacitor
D_P	propeller diameter
$D_{1,2,\ldots,4}$	duty cycle comments of DC/DC converters
I_B, I_{UC}	current of battery and ultra-capacitor
J_A, K_Q	advance and torque coefficients
N	predictive horizon
n, $Pitch/D_P$	propeller rotational speed and pitch ratio
P_B, P_{UC}	output power of battery and ultra-capacitor
P_{FL}	shipboard load power fluctuations
Q_B	capacity of battery
R_n	propeller Reynolds number
R_B, R_{UC}	internal resistance of battery and ultra-capacitor
S	sliding surface
SOC_B, SOC_{UC}	SOC of battery and ultra-capacitor
T_{load}	propeller torque
T_s	sampling time
V_{max}	maximum voltage of ultra-capacitor
V_{OC}	battery open circuit voltage
w	wake field
Z	number of propeller blades
β	loss factor
ρ	water density
AES	all-electric ship
AMPC	adaptive model predictive control
EMS	energy management strategy
ESS	energy storage system
HESS	hybrid energy storage system
IPA-SQP	integrated perturbation analysis and sequential quadratic programming
IPS	integrated power system
MPC	model predictive control
MPEL	Michigan Power and Energy Lab
PA	perturbation analysis
SQP	sequential quadratic programming
UC	ultra-capacitor
VSD	variable speed drive

superior reliability, effects of load fluctuations must be mitigated. Given the diverse characteristics of shipboard load fluctuations, such as those due to propulsion-load fluctuations [8] and on-and-off of pulse-power loads, energy storage systems (ESSs) and advanced control algorithms are required [9]. Using single type of ESS can result in increased size, weight, and cost for electric ship operations [10]. Different combinations of ESSs are also investigated in different applications [11–15]. In [11], the engine-generator, battery and ultracapacitor (UC) are explored for a plug-in hybrid electric vehicle (PHEV). The literature [12] uses battery with UC to improve the efficiency and durability of a PHEV. In [13], different control strategies of battery combined with UC for an electric city bus have been studied. The benefits of using UC to improve the battery life cycle in a low temperature are further explored in [14]. The ZEBRA batteries with UC in a commercial vehicle have been studied in [15], and the experimental results demonstrate the benefits of this combination of ESSs. In this paper, hybrid energy storage systems (HESSs), where batteries and ultra-capacitors are used as a buffer to mitigate shipboard load fluctuations [16], are investigated. The lithium-ion batteries are chosen due to their higher power and energy densities [17].

IPS with HESS are expected to manage multiple objectives, including improving fuel efficiency, enhancing response speed, and strengthening reliability [18]. Advanced optimization-based energy management strategies are essential to achieve desired trade-off among these competing objectives [19]. Model predictive control (MPC) is an effective optimization-based approach [20]. Compared to LQG, MPC does not require unique performance criteria, and it is able to deal with constraints and process nonlinearities [21]. MPC has been successfully implemented in process industries. Recently, MPC becomes one of the promising control strategy in many applications, such as micro-grids [22], (hybrid) electric ships [23], and (hybrid) electric vehicles [24]. The sampling periods in most of those applications are from seconds to hours. However, the sampling period in this study is on the order of milliseconds, which makes the MPC implementation more difficult. In order to implement real-time MPC, the explicit MPC is one solution, which uses offline computations to reduce the computational time [25]. Online linearization is another popular approach to enable real-time feasibility [26]. Typically, the quadratic programming (QP) formulation is preferred to solve the optimization problem efficiently [27]. However, the problem studied in this paper is nonlinear and nonconvex, which requires advanced optimization solver.

In marine applications, MPC can exploit the optimal solution with a receding horizon to address constraints, such as physical dynamics and operation boundaries of IPS and HESS [28]. MPC is therefore used in this paper as an optimization-based energy management strategy (EMS). In [29], a nonlinear MPC is developed to compensate the pulse power load and follow the desired references, including the desired bus voltage, reference power for generator sets and reference speed for the motor. A sensitivity-function-based approach is proposed in [30] in order to achieve real-time trajectory tracking. In [31], the stochastic MPC is developed to smooth out low-frequency power fluctuations. Scenario-based MPC is developed for dynamic safety constraints in [32]. Multi-level MPC is used in [33] to address the disturbances from the environment. However, most of those state-of-the-art MPC-based EMSs only present software or hardware-in-the-loop simulation results. The main challenge to implement the MPC-based approaches is to solve the optimization problem in real-time within a relatively short sampling period, as the system dynamics in this paper is fast and the sampling period is on the order of milliseconds.

The objective of this paper is to address shipboard load fluctuations, including not only propulsion-load fluctuations but also pulse-power loads, and validate the effectiveness of MPC on a physical testbed. A filter-based power split EMS is used as a baseline strategy to illustrate the benefits of the proposed MPC-based EMS. For the filter-based EMS, the battery compensates low-frequency load fluctuations, while the UC handles high-frequency fluctuations. Note that the filter-based EMS requires much less computational time, which makes it easy to implement in real time. On the other hand, the main challenge for MPC based EMS is to handle the computational tasks. In order to achieve real-time feasibility of the proposed MPC-based EMS, three special efforts have been made:

- A novel MPC formulation with state of charge (SOC) reference being incorporated is used to achieve the desired performance with a relatively short predictive horizon [16].
- An integrated perturbation analysis and sequential quadratic programming (IPA-SQP) algorithm [34] is used to solve the optimization problem with high computational efficiency.
- A multi-core hardware implementation is used for the real-time system controller to guarantee system signal synchronization and separate system-level and component-level controls, thereby increasing real-time capabilities.

Load fluctuation compensation and HESS loss minimization are two main control objectives for the load fluctuation mitigation problem. In order to implement MPC in real-time, a short predictive horizon is