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Ship energy management for hybrid propulsion and power supply with shore charging

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ABSTRACT

Hybrid technology in marine vehicles can significantly reduce fuel consumption and local CO_2 emissions. It has been applied successfully to several ship-types, mostly with conventional, rule-based, strategies. To further improve performance, intelligent control strategies are necessary. This work, inspired by automotive research in Energy Management Strategies, applies the Equivalent Consumption Minimisation Strategy (ECMS) to a ship powered by a hybrid propulsion plant with hybrid power supply that can be recharged with renewable shore power. This hybrid configuration has the additional challenge to determine the optimal power-split between three or more different power sources, in real-time, and to optimally deplete the battery packs over the mission profile. To this end, a Mixed-Integer Non-Linear optimisation Problem is formulated and solved by combining Branch & Bound and Convex optimisation. Dynamic Programming (DP) is used to benchmark the real-time strategies, which are also compared to the current rule-based (RB) controller. Simulation results of a case study tugboat with validated models show that, with unknown load demand, 6% additional fuel savings can be achieved with ECMS.

1. Introduction

The shipping sector is responsible for 90% of global freight transportation, which has been increasing by 2.3% *annually* since 2000 (Shaheen & Lipman, 2007; Stopford, 2008). Currently, the industry's annual carbon emissions account for more than 3% of the global anthropogenic CO_2 emissions, which could rise up to 8% by 2050 if no CO_2 reduction measures are taken (International Maritime Organization, 2014). Given these trends, a drastic reduction of fossil fuel usage is practically mandatory. While stationary power consumers can progressively switch to renewable energy sources such as wind energy (Kumar et al., 2016), tidal energy and solar energy (Jamel, Rahman, & Shamsuddin, 2013), mobile power consumers often cannot be connected to the electric grid for renewable energy. Moreover, renewable fuels and fuel cells are not available for maritime application in the short term (Taljegard, Brynolf, Grahn, Andersson, & Johnson, 2014; Van Biert, Godjevac, Visser, & Aravind, 2016). Therefore, the transportation field has to reside to stored energy for its renewable power supply, recharging the energy storage when connected to the main grid. However, only ship types that can connect to the grid regularly, such as ferries, can rely purely on energy storage. Other ship types can use energy storage to reduce fuel consumption, recharging the energy storage with renewable energy from the grid when moored alongside.

For vessels that experience significant power demand peaks followed by long periods of very low loading, hybrid technology could significantly reduce fuel consumption and emissions. Hybrid technology refers to all plants that consist of (1) hybrid propulsion: a combination of mechanical and electrical propulsion, and (2) hybrid power supply: a combination of combustion power supply and energy storage, found mostly in combination with electric propulsion (Geertsma, Negenborn, Visser, & Hopman, 2017a). These hybrid propulsion and power supply architectures are capable of reducing fuel consumption and emissions by 10% to 35% according to Geertsma et al. (2017a). However, advanced control strategies are required to regulate power production of all energy sources onboard in order to achieve these savings (Geertsma et al., 2017a; Grimmelius, de Vos, Krijgsman, & van Deursen, 2011; Herdzik, 2013; Sciberras, Bashar, David, et al., 2015; Shiraishi, Minami, Kobayashi, et al., 2013; Vu, 2015; Vu et al., 2014; Yuan, Tjahjowidodo, Lee, et al., 2016; Zhan, Gao, Chen, & Lin, 2015) and Energy Management strategies are required to make optimum use of

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Nomenclature

Greek Symbols

β	hydrodynamic pitch angle in rad
η	efficiency
λ	air excess ratio
λ	air excess ratio
ω	rotational speed in rad/s
ψ	flux linkage in Wb
ρ	density in kg/m^3
θ	angle in rad

Roman Symbols

c	capacitance in F
c_f	friction factor (fraction of nominal power)
C_Q	propeller torque coefficient
C_T	propeller thrust coefficient
c_{sfo}	specific fuel oil consumption in g/kWh
D	diameter in m
f	frequency in Hz
f_p	power factor
f_w	wake factor
I	Moment of inertia in kg m^2
i	current in A
i_{gb}	gearbox reduction ratio
k_{p}	number of propellers
L_1	per phase winding inductance in H
M	torque in Nm
m	mass in kg
$\dot{m}_{\mathrm{f}}$	fuel consumption in kg/s
m_1	trapped mass at the start of compression in kg
m_{f}	fuel injection per cylinder per cycle in kg
n	rotational speed in Hz
P	power in W
p_1	charge air pressure in Pa
p_6	average pressure in the cylinder during exhaust opening in Pa
$p_{\max}$	maximum pressure during combustion in the Seiliger cycle in Pa
p_{p}	pole pairs
p_d	pressure in the exhaust receiver in Pa
Q	heat in J
Q_{bat}	battery capacity in Ah
Q_{lhv}	lower heating value of fuel at ISO conditions in kJ/kg
q_{23}	specific heat release at constant volume in kJ/kg
q_{34}	specific heat release at constant pressure in kJ/kg
q_{45}	specific heat release at constant temperature in kJ/kg
R	ship resistance in N
r	resistance in Ohm
s	equivalence factor
s_l	slip
S_{OC}	state of charge
T	thrust in N
t	time in sec
T_6	average temperature in the cylinder during exhaust opening in K
t_p	thrust reduction factor
u	voltage in V
u_{c}	control variables for the control problem
v_a	advance velocity in m/s
v_s	ship speed in m/s
w_{i}	specific indicated work during the Seiliger cycle in kNm/kg
w_{e}	exogenous inputs for the control problem
X_{tow}	tow force in N

Superscripts

*	normalised values

Subscripts

aux	demand for auxiliary loads
b	base
bat	battery
chg	charge
d	direct axis in dq reference frame
dg	diesel generator
dis	discharge
el	electric
eqv	equivalent
fc	frequency converter
g	synchronous generator
gb	gearbox
i	core branch
im	induction machine
line	network line
loss	losses
m	mutual
me	main engine
mmf	stator magnetic field
nom	nominal
oc	open cell
p	propeller
pd	demand for propulsion
q	quadrature axis in dq reference frame
r	rotor
rec	rectifier
rr	relative rotative
s	stator
set	setpoint
sh	shaft
sl	slip
sync	synchronous
t	terminal
th	thruster
tot	total

batteries over time and thus reduce fuel consumption and emissions (Sciarretta, Back, & Guzzella, 2004; Vu, 2015; Vu et al., 2014).

1.1. Literature review

Hybrid propulsion is typically applied to naval vessels (Castles, Reed, Bendre, & Pitsch, 2009; Geertsma, Negenborn, Visser, & Hopman, 2016; Sulligoi et al., 2012), towing vessels (Wijsmuller M., 2007), offshore vessels (Barcellos, 2013; Herdzik, 2013), research vessels (Capasso et al., 2016) and yachts (van Loon & van Zon, 2016). These applications all feature an operating profile with a significant period of time at high speed and power and a significant period of time at low speed and propulsion power. The mechanical propulsion plant provides very efficient high speed operation and the electrical propulsion plant provides efficient and potentially very silent low speed operation due to the power station concept (Geertsma et al., 2017a; Veneri, Migliardini, Capasso, & Corbo, 2012).

Hybrid power supply has recently become a realistic option for many maritime applications due to the development of power dense lithium-ion battery technologies, developed for the automotive industry. As argued in Capasso and Veneri (2014), lithium-ion batteries provide power and energy dense energy storage with good life cycle performance