IEEE VTS Motor Vehicle Challenge 2025 – Energy Management and Control of a Marine Electric Propulsion System

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***Abstract*—The topic proposed for the IEEE VTS Motor Vehicle Challenge 2025 (MVC 2025) consists of developing an energy management strategy for a marine Electric Propulsion System (EPS). The key component of the proposed EPS is a Dual Three-Phase Permanent Magnet Synchronous Machine (DTP-PMSM), whose windings are supplied by a Battery Pack (BP) and a Supercapacitor Module (SM) through appropriate DC/DC and DC/AC converters. The DTP-PMSM shaft is connected to a marine propeller, which is devoted to develop the thrust force needed to move the vessel. The MVC 2025 participants should propose an energy management strategy that splits the DTP-PMSM power demand among its two windings, each of which is supplied by a different energy storage unit, by minimizing a given cost function.**

***Keywords*—Batteries, Electric propulsion systems, Energy management, Permanent magnet synchronous machines, Supercapacitors**

I. Introduction

Vessel operations in ports are managed by tugboats, due to their high manoeuvrability and extremely high bollard pull. Their job is to tow heavy vessels to the harbour, where the waters are too shallow to move safely by themselves. These small boats (15-30 m length) have minimal energy requirements, but they must have enough power to aid larger vessels when required. Thus, full power, which is typically greater than 1 MW, is required only for short time periods, while tugboats are almost idle for most of the time. Expensive and heavy combustion engines have typically been installed to provide surges in power, but these are rarely used [1]. This segment of navigation still largely relies on diesel engines operating at low efficiency (typically around 10%), causing high carbon fuel consumption and high emissions [2]. Consequently, since the International Maritime Organization (IMO) and national authorities aim at limiting emissions of waterborne transports, especially in port areas, tugboat electrification represents a viable solution to address this environmental issue [3].

Full Electric Propulsion Systems (EPSs) for tugboats require a careful design and management of both the electric motor and energy source onboard [4]. Particularly, different energy storage typologies (e.g. batteries, supercapacitors, and fuel cells) can be adopted on tugboats, but the Energy Management System (EMS) should rely on several and different energy conversion systems to manage the energy flow appropriately. In this regard, an attractive solution is represented by the employment of multiphase electric motors, which are often employed in marine applications due to their enhanced performance and redundancy compared to conventional three-phase solutions [5].

Among multiphase electric machines, the Dual Three-Phase Permanent Magnet Synchronous Machine (DTP-PMSM) offers a good compromise between redundancy and complexity [6]. Each of the two DTP-PMSM three-phase winding can be fed by a different energy source, thus obtaining a full electric tugboat equipped with a hybrid energy storage system. This requires managing and controlling each DTP-PMSM winding differently, in accordance with the power and energy features of the corresponding energy storage unit. In other words, it is necessary to achieve an unbalanced torque and current distribution between the two windings [7], thus spreading the motor power differently between them. As a result, each energy storage unit can be charged and discharged as needed without affecting the overall DTP-PMSM performance [8].

In this scenario, the IEEE VTS Motor Vehicle Challenge 2025 (MVC 2025) consists of developing the EMS for the novel EPS architecture described previously. The MVC is an annual competition for researchers from all over the world who have to develop appropriate EMSs to improve electric vehicle performance. Previous editions have dealt with a number of case studies, such as hybrid locomotives [9], three-source electric vehicles [10], and multi-motors EPSs [11], [12]. This year, MVC focuses on marine electrification for the first time, i.e. an EPS for electric vessels. This consists of a DTP-PMSM supplied by a hybrid energy storage system, namely a Battery Pack (BP) and a Supercapacitor Module (SM), each of which supplies one of the two DTP-PMSM windings through appropriate DC/DC and DC/AC converters. The EPS is driven by a control system, which regulates vessel speed, DTP-PMSM speed and current sequentially to achieved the desired dynamic and steady-state performance. The participants are asked to define the most suitable torque sharing between the two DTP-PMSM windings to minimise a given cost function, which accounts for BP usage, energy consumption, DTP-PMSM loading and exploitation.

The paper is structured as follows: a general system overview is given first (Section II), followed by detailed models of the main EPS components (Section III). Some details on the

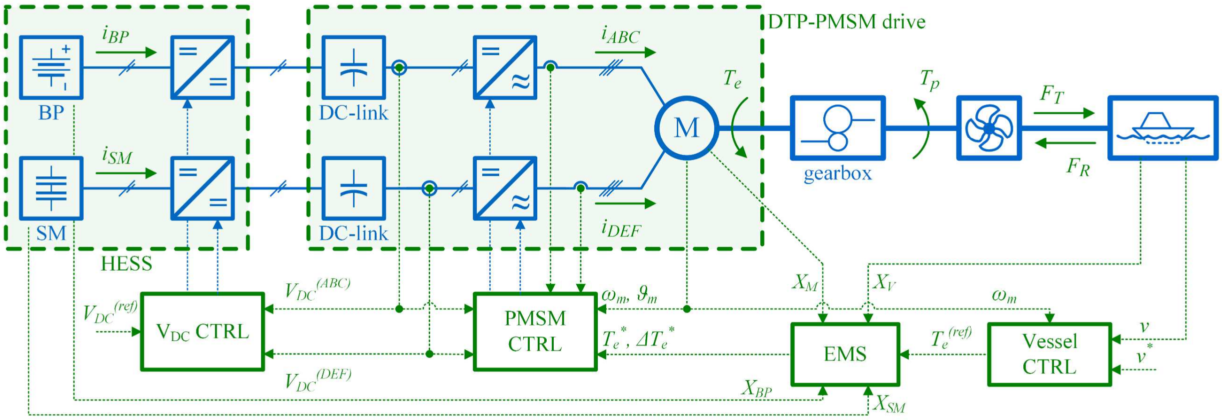

Fig. 1. Overview of the EPS architecture proposed for the MVC 2025, in which (X_{BP}, X_{SM}, X_M, X_V) denote all the signals available for developing the EMS.

vessel and DTP-PMSM control systems are then given (Section IV), together with those related to the cost function to minimise (Section V). Some information on simulations and scoring are then provided (Section VI), while final remarks (Section VII) and references conclude the manuscript.

II. System Overview

The proposed EPS structure is depicted in Fig. 1. The key-component of the proposed architecture consists of a DTP-PMSM (denoted by M in Fig. 1), whose electromagnetic torque (T_e) is applied to a fixed-pitch marine propeller through a gearbox. The propeller, in turn, develops a propulsion torque (T_p) proportional to its rotating speed (ω_p), which results in a corresponding thrust force (F_T) to move the vessel in accordance with the resistance force (F_R).

Regarding the DTP-PMSM power supply, a hybrid energy storage system made up of BP and SM has been considered. This is because the vessel under study, i.e. a tugboat, is characterized by very different load operating conditions, thus justifying the need for both high-energy and high-power energy storage units. A novel power supply architecture is thus proposed, in which BP and SM supply a DTP-PMSM three-phase winding each through a multi-stage DC/AC converter. Particularly, a DC/DC converter is introduced to decouple voltage and current of the energy storage units, i.e. (V_{BP}, i_{BP}) and (V_{SM}, i_{SM}), from the corresponding DC-link counterparts. Energy management can be achieved by properly differentiating the phase currents of the two DTP-PMSM windings (i_{ABC} and i_{DEF}) and, thus, their contribution to the overall torque/power demand. The energy exchange between BP and SM is also possible in case the windings produce opposite torques at the DTP-PMSM shaft, thus employing the DTP-PMSM as an isolated transformer.

III. Modelling of EPS components

A. Battery pack and supercapacitor module

The BP equivalent electrical circuit considered in this paper is shown Fig. 2 [13]. This consists of a voltage source (V_{OC}), which represent the BP open circuit voltage that depends on the State-of-Charge (*SoC*), a series resistance (r_{BP}), and an RC branch to account for BP dynamic response.

The electrical model of SM is instead shown in Fig. 3 [14], [15], which is made up of three RC branches and a self-discharge

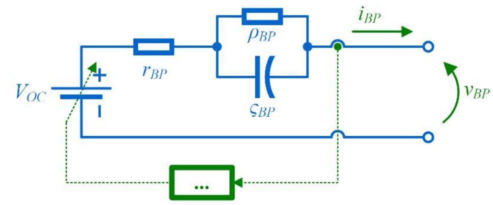

Fig. 2. BP equivalent circuit.

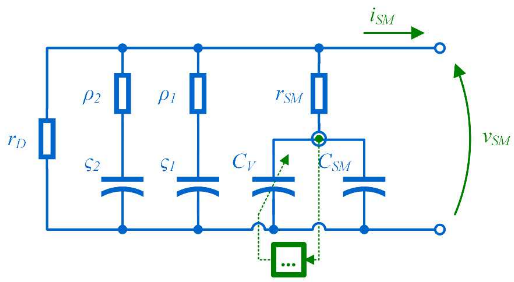

Fig. 3. SM equivalent circuit.

resistance (r_D). Particularly, the right-side branch consists of a series resistance (r_{SM}) and a voltage-dependent capacitance (C_{SM} + C_V), while the other two RC branches account for charge redistribution over the medium-long term.

B. Dual Three-Phase PMSM

The DTP-PMSM voltage space vector equations can be usefully expressed as [8]

$$\begin{aligned} v_{dq+} &= \left(r + j\omega L_s\right) i_{dq+} + L_s \frac{di_{dq+}}{dt} + 2\, j\omega\Lambda \\ v_{dq-} &= \left(r - j\omega L_0\right) i_{dq-} + L_0 \frac{di_{dq-}}{dt}, \quad v_{0z} = r\, i_{0z} + L_0 \frac{di_{0z}}{dt} \end{aligned} \tag{1}$$

in which dq+ and dq– denote the synchronous rotating and counter-rotating reference frames, while 0z represent the zero-sequence components of the two DTP-PMSM windings. Particularly, dq+ and dq– are achieved from the stationary αβ and xy reference frame by applying the Park and inverse-Park transformation, respectively. Still referring to (1), *v* and *i* denote the voltage and current space vectors, *r* is the phase resistance,

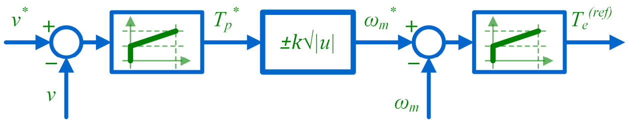

Fig. 4. Exploded view of the Vessel CTRL block shown in Fig. 1.

L_s and L_0 are the synchronous and zero-sequence inductances, ω is the electrical rotor speed, and Λ is the equivalent magnetic flux linkage due to PMs.

Given (1), and denoting by p the number of pole pairs, electromagnetic torque T_e and torque unbalance ΔT_e can be achieved as:

$$T_e = \frac{3}{2} p \Lambda i_{q+} \,, \quad \Delta T_e = \frac{3}{2} p \Lambda i_{q-} \,. \tag{2}$$

Particularly, T_e represents the overall torque applied by the DTP-PMSM, while ΔT_e quantifies the difference between the electromagnetic torque provided by the winding DEF compared to ABC (positive values). As a result, constant q+ and q– current components can be imposed in accordance with DTP-PMSM overall torque and torque sharing requirements.

In conclusion, the torque equation at the DTP-PMSM shaft can be expressed as:

$$T_e = J \frac{d\omega_m}{dt} + D\omega_m + T_L \tag{3}$$

in which J and D represent the inertia and damping coefficient, respectively, ω_m is the rotor speed, while T_L is the load torque due to the propeller.

C. Marine propeller and vessel

A fixed-pitch propeller has been considered in this study, whose torque T_p and thrust force F_p can be expressed as [16]

$$T_p = \sigma_\omega k_T \rho D_p^5 \left(\frac{\omega_p}{2\pi}\right)^2 , \; F_P = k_F \rho D_p^4 \left(\frac{\omega_p}{2\pi}\right)^2 = \frac{k_F}{k_T}\frac{T_p}{D_P} \tag{4}$$

where σ_ω is the sign of the propeller speed (ω_p), k_T and k_F are the torque and the thrust coefficient, respectively, ρ is the water mass density, and D_p is the propeller diameter. Propeller torque and speed depend on DTP-PMSM speed and load torque through the gear ratio τ as

$$T_L = \frac{T_p}{\tau} \,, \quad \omega_p = \frac{\omega_m}{\tau} \,. \tag{5}$$

Given (4), the propeller efficiency can be computed as

$$\eta_p = \frac{F_P v}{T_p \omega_p} = \frac{k_F}{k_T} \frac{v}{\omega_p D_P} \tag{6}$$

in which v denotes the vessel speed. The latter varies in accordance with the following force equation:

$$F_p = M \frac{dv}{dt} + F_r \,, \quad F_r = \sigma_v f \frac{1}{2} \rho S_v v^2 \tag{7}$$

in which M is the vessel mass, while F_r is the resistance force. Particularly, assuming no sea current speed, F_r depends on ρ, f, which is a dimensional-less coefficient depending on the Froude's number, and the vessel wetted area (S_v) [16].

IV. EPS Control System

The EPS is controlled in accordance with the equivalent block control scheme shown in Fig. 1 [8]. Particularly, Vessel CTRL consists of an outer vessel speed and an inner rotor speed PI-based control loops, as shown in Fig. 4. The outer loop is designed in accordance with (4) and (7) so that a reference propeller torque profile can be achieved. However, given the non-linear relationship between v and F_r highlighted by (7), a linear approximation is introduced to ease the design of the regulator gains. Given (4) and (5), the T_p reference profile can be converted successfully into a corresponding reference rotor speed profile; this can be tracked by the inner PI-based control loop, whose gains can be defined by introducing a linear approximation of the T_p-ω_m relationship. As a result, a reference electromagnetic torque profile can be achieved.

Regarding DTP-PMSM control system (i.e. the PMSM CTRL block shown in Fig. 1), the reference electromagnetic torque profile already achieved by Vessel CTRL is combined with the reference torque unbalance, which is synthesized by the EMS in accordance with the chosen strategy. Therefore, based on (2), reference q current components are achieved. Assuming that no zero-sequence and d-current components occur (no flux-weakening is concerned), the reference currents are all defined, which can be tracked by a conventional PI-based control system in accordance with (1), by introducing proper feed-forward compensations as needed. The reference dq+, dq– and 0z voltages thus determined can be converted into their corresponding reference phase voltages and, then, into suitable DC/AC converter command signals through PWM modulation.

Regarding the energy sources onboard, both BP and SM are connected to their corresponding DC-link through DC/DC converters, whose control system has the task of keeping the DC-link voltage constant at the desired reference value. This is accomplished by the block V_{DC} CTRL shown in Fig. 1, by assuming that the two DC-links share the same reference voltage value.

In conclusion, it is worth noting that the EPS control system takes into account all operating constraints, such as current limitation and voltage saturation. This means that all EPS variables cannot overcome their operating thresholds whatever the EMS is. Consequently, the EMS must guarantee the compliance with BP and SM energy constraints only.

V. Energy Management

The aim of the MVC 2025 is to develop an EMS of the marine EPS described in the previous sections that minimises the following cost function over a given mission profile:

$$\Phi = k_{BP}\phi_{BP} + k_E\phi_E + k_{SPM}\phi_{SPM} + k_w\phi_w \,. \tag{1}$$

Particularly, $\{k_{BP},\ k_E\ ,\ k_{SPM}\ ,\ k_w\}$ are appropriate positive weighting coefficients to make all the terms of Φ consistent to each other, while each cost function term is described in detail in the following subsections.

A. BP usage

The first right-side term of the overall cost function aims at penalizing BP current fluctuations, especially when they occur at high time rates. The root-mean-square value of BP current time derivative has been thus selected as the most suitable index to this purpose, leading to:

$$\phi_{BP}^{2} = \frac{1}{T}\int_{T}\left(\frac{di_{BP}}{dt}\right)^{2} dt \tag{8}$$

where T represents the time window of the mission profile.

B. Energy consumption

The overall cost function also accounts for energy usage through the following equation:

$$\phi_{E} = \left(E_{BP} + E_{SM}\right)\Big|_{T}^{0} \tag{9}$$

where E_{BP} and E_{SM} denote the energy content of BP and SM, respectively, whose initial and final values are thus compared to each other and weighted by k_E.

C. DTP-PMSM loading

The third right-side term of the overall cost function depends on the torque/power sharing between the two DTP-PMSM windings, which are supplied by BP and SM alternatively. In this regard, it is assumed that each winding is able to handle up to a certain percentage (γ) of the DTP-PMSM rated power ($P_{m,nom}$) safely. Consequently, when this power threshold is overcome, a penalty is applied through the following cost function:

$$\phi_{SPM} = \frac{1}{T}\int_{T}\sum_{h}\left(P_{m,h}^{2} - \left(\gamma P_{m,nom}\right)^{2}\right)\Big\rangle_{0}^{+\infty} dt \tag{10}$$

where h denotes ABC and DEF alternatively, while:

$$x\rangle_{0}^{+\infty} = max\{x, 0\} \tag{11}$$

D. DTP-PMSM winding exploitation

The last term of the overall cost function aims at penalizing a weak exploitation of the DTP-PMSM windings. In other words, the DTP-PMSM torque/power should not be provided by just one winding, even if this complies with (8)-(10), because this means that the other winding is superfluous. Consequently, the following cost function has been defined:

$$\phi_{w} = \frac{1}{T}\int_{T}\left(1\Big|_{\|i_{ABC}\|=0} + 1\Big|_{\|i_{DEF}\|=0}\right)\tau_{e}^{*} dt\ , \quad \tau_{e}^{*} = \frac{\left|T_{e}^{*}\right|}{T_{e,nom}} \tag{12}$$

where $\|i_{ABC}\|$ and $\|i_{DEF}\|$ denote the magnitude of the two three-phase current sets, T_e^* and $T_{e,nom}$ are the reference and rated torque, while the operator | means

$$1\Big|_{x=0} = \begin{cases} 1 & if \quad x = 0 \\ 0 & otherwise\ . \end{cases} \tag{13}$$

As a result, when no reference torque is required, the cost expressed by (12) is nullified to prevent inappropriate penalization when the EPS is idle.

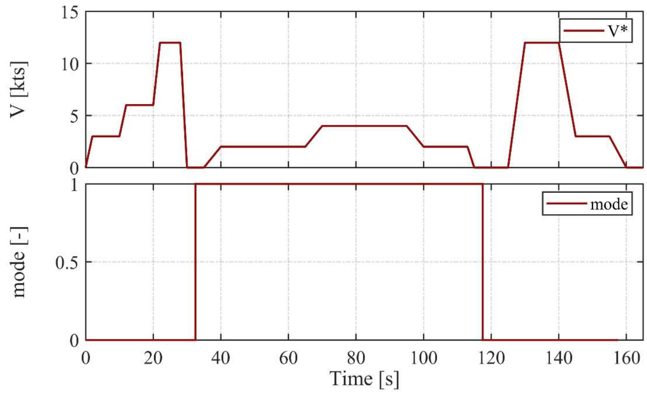

Fig. 5. Reference speed (up) and mode (bottom) evolutions.

VI. Simulation and Scoring

The MVC 2025 participants will be provided with the EPS model shown in Fig. 1, implemented in MATLAB-Simulink by employing the Simscape library. The vessel speed profiles shown in Fig. 5 will be given as well: it comes along with the operating mode profile (m), which determines if the tugboat is towing any vessel ($m = 1$) or not ($m = 0$). In this regard, it is worth noting that a suitable time scaling factor has been introduced so that a one-second simulation corresponds to a minute in a realistic scenario. As a result, several hours can be simulated rapidly and effectively.

The main simulation parameters are resumed in Table I and Table II. In particular, simulation parameters were defined based on similar-size vessel examples [16], [17] supplemented and validated also referring to existing electric tugboats, e.g. Damen RSD Tug 2513 and Navtek Zeetug [18], [19]. A default EMS will be also provided [8] to enable the participants to run simulations without the need of designing and implementing any solution, as done in past MVC editions.

Scoring will be provided automatically at the end of the simulations, together with the most important evolutions (tugboat speed, propeller torque, etc.). Participants will be thus

TABLE I. Tugboat, assisted vessel and propeller parameters

Parameter	Unit	Value
Tug & Assisted vessel		
M_{tug}	tons	600
L_{tug}	m	27.8
$S_{v,tug}$	m^2	392
$V_{tug,nom}$ @ transit mode	m/s (kts)	7.716 (15)
$V_{tug,nom}$ @ assist mode	m/s (kts)	2.058 (4)
M_{ves}	tons	100410
L_{ves}	m	246
$S_{v,ves}$	m^2	12339
ρ	kg/m^3	1000
v_w	m/s	0
Marine Propeller (MP)		
$W_{p,nom}$	rpm	200
D_p	m	3
k_T	-	0.0347
k_F	-	0.1483
τ	-	5

TABLE II. DTP-PMSM, BP AND SM PARAMETERS

Parameter	Unit	Value
DTP-PMSM		
$P_{m,nom}$	MW	2.101
$T_{e,nom}$	kNm	20
$\omega_{m,nom}$	rpm	1000
I_{nom} (for each three-phase winding)	A	327.4
V_{nom}	kV	4.436
p	-	3
r	mΩ	20.6
L	mH	2.5
M	mH	0.8
Λ	Wb	6.788
δ	deg	30
Battery Pack (BP)		
$V_{DC,nom}$	kV	5
$P_{BP,nom}$	MW	2.2
$E_{BP,nom}$	MWh	2
$V_{BP,nom}$	V	800
r_{BP}	mΩ	10
ρ_{BP}	mΩ	1
ς_{BP}	F	0.1
Supercapacitor Module (SM)		
$P_{SM,nom}$	MW	2.2
$E_{SM,nom}$	MWh	0.07
$V_{SM,nom}$	V	800
r_D	mΩ	2
ρ_1	Ω	90
ς_1	F	1.5
ρ_2	Ω	1000
ς_2	F	4
r_{SM}	mΩ	2
C_{SM}	F	2.5
C_V/V_{SM}	F/V	1.5

able to develop their own solutions inside the EMS block shown in Fig. 1, by using all the available signals from the different EPS components (X_{BP}, X_{SM}, X_M, X_V). They can therefore check if these solutions can achieve better performance compared to the default EMS. However, it is worth highlighting that final scoring will not be based only on the vessel speed profile shown in Fig. 5, but it will result from a weighted average of the scoring achieved with that and some other tugboat speed and operating profiles. Furthermore, the EMS developed by participants must take into account only BP and SM energy constraints, i.e. BP and SM energy contents must not overcome the given thresholds. This is because the compliance with all speed, torque, power, current, and voltage constraints are ensured by the EPS control system automatically, regardless of the proposed EMS.

VII. CONCLUSION

This paper presents the topic proposed for the IEEE VTS Motor Vehicle Challenge 2025 (MVC 2025), which consists of developing an energy management strategy of an Electric Propulsion System (EPS) for tugboats. Differently from the previous MVC competitions, a marine application has been selected, with particular reference to a tugboat that experiences very different load operating conditions (when towing other vessels or not). In this scenario, a novel EPS architecture is proposed, in which the two three-phase windings of a Dual Three-Phase Permanent Magnet Synchronous Machine (DTP-PMSM) are supplied by a Battery Pack (BP) and a Supercapacitor Module (SM) alternatively. The MVC 2025 participants should thus propose an energy management strategy that splits the DTP-PMSM torque/power demand among its two windings, in accordance with the different BP and SM power and energy capability, and by minimizing a given cost function.

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