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The NEPTUNE Project: Highly-Integrated All-Electric Propulsion-Charging System on Zero-Emissions Tugboats for Next-Generation Harbours

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ABSTRACT

The project NEPTUNE, which has been funded under the call PRIN 2022, proposes an integrated propulsion-charging architecture and design methodology for electric tugboats (eTugs) to enable effective and sustainable electrification of harbours. NEPTUNE has thus investigated the integration of onboard energy storage systems and electric machines with both charging and propulsion converters, enabled by modular and highly-flexible configurations, as well as by advanced energy management, smart charging and propulsion control systems. In particular, modular multilevel converter (MMC) configurations have been considered to integrate the multi-source energy storage system onboard, thus achieving a distributed and flexible configuration during both propulsion and charging stages. High power and torque density permanent magnet synchronous machines have been considered as well, particularly multi-motor solutions consisting of a number of dual three-phase permanent magnet synchronous machines have been selected to comply with the MW-size propulsion stage, by ensuring fault-tolerance, redundancy, and easing charging system integration simultaneously. Advanced energy management and control systems have been developed, enabling suitable power exchanges among the various components of the overall propulsion-charging system. The project has also included real-time simulations and experimental activities on reduced-scale prototypes available at participants' premises.

1. INTRODUCTION

The commitment towards more shore-side electricity usage by ships introduced by the European Commission Recommendation 2006/339 is pushing the research towards a more electric ship propulsion. Ports near residential areas, a common situation for many of the 58 strategic ports identified by the Italian Ministry of Transport and Infrastructure, may suffer from poor air quality and high levels of noise nuisance [1]. From this perspective, the initial commitment of the International Maritime Organization has been to decrease the emission of greenhouses gasses produced by ships by 80 % by 2050 compared to 2008 [2].

Operations of ships 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 (15-25 m length) have minimal energy requirements, but they must have enough power to aid larger vessels when required. Thus, since full power is required only for short time periods, tugboats are almost idle for most of the time [3]. Expensive and heavy engines have typically been installed to provide surges in power, but these are rarely used. This segment of navigation still largely relies on diesel engines operating at low efficiency (typically around 10 %), causing high fossil fuel consumption and high greenhouse gas emissions. Additionally, a diesel engine takes 4-6 seconds to generate the rated torque from its idle condition and comprises several preparatory stages, such as speed control, load uptake, and warm-up period [4].

An alternative approach consists of implementing hybrid solutions [5]; induction or synchronous generators coupled to diesel engines have been used to supply one or two electric motors and propellers, whereas an additional battery system has been also included as energy buffer [6, 7]. Hybrid configurations on tugboats increase overall efficiency, but also increase costs and complexity, thus the energy management system (EMS) must ensure that engines operate close to their optimum to achieve fuel saving [8]. Although hybridization increases overall system efficiency, it does not solve the greenhouse gas emission issue as full electric solutions can do. In this regard, the development of new power electronic devices and converters have made possible to redesign the whole architecture of shipboard power generation, distribution, and utilization [9].

Tugboat electrification, which is going to be vital in the next-generation harbours, is still an open field. All-electric tugboats (eTugs), whose outside structure is actually very similar to the traditional ones, feature two main propellers moved by two full electric powertrains. So far, only few eTugs

have been known for both seaports and inland waterways, e.g. Lianyungang Port Holding Group has completed the first Chinese eTug [10]. Another example is the ZEETUG by Navtek, which is 18.7 m long and it is powered by two 925 kW motors (one propeller each) [11]. The operation of two battery packs is optimized by a smart EMS to extend the operative range (total capacity is 1.45 MWh, but it can be customized as needed). The battery full recharge is carried out in one hour by means of a 2 MW off-board charger. The RSD-E Tug 2513 by Damen is slightly longer (24.3 m), more powerful due to two 2.5 MW Permanent Magnet Synchronous Machines (PMSMs), and reaches 70 tonnes of bollard pull capability thanks to two very efficient azimuth propellers [12]. A highly redundant power system and a modular battery configuration (2.5 MWh) ensure high reliability, which is further increased by two 1 MW diesel gensets that may be used only under emergency conditions. Full charge is expected to be completed in two hours by using a 1.5 MW charger derived from automotive applications. Damen also built the first Europe's fully electric tugboat Volta1; this was launched in 2025 and operates in the Port of Antwerp-Bruges, featuring 2.8 MWh lithium-titanium-oxide battery pack [13]. The German project ELEKTRA consists of an eTug designed to operate in inland waterways and takes advantage of two energy sources, namely three 100 kW Proton-Exchange Membrane fuel cells (a 750 kg hydrogen tank is included) and a 2.5 MWh battery pack, while the two thrusters are powered by a 200 kW electric motor each [14]. As a final example, an 82-foot harbour tug has started operations in 2024 at the Port of San Diego by Crowley Engineering Services, which features 6 MWh energy storage system from ABB [15]. Despite of different design solutions and capabilities, eTugs promise to strongly reduce the operating costs of about 65-80 %, thus making the higher investment cheaper over a long-time horizon [3].

In this context, the main objective of NEPTUNE has been proposing an integrated propulsion-charging architecture and design methodology for eTugs, to enable effective and sustainable electrification of harbours, thus technically supporting the aims of 2030 Sustainable Development Goal 11 "Make cities and human settlements inclusive, safe, resilient and sustainable". Particularly, the Specific Objectives (SOs) of this project have been:

•design of a highly reliable and fault-tolerant propulsion system to guarantee the eTug minimum functionality (SO1);

•integration of a multi-source energy storage system within the MMC used for propulsion/charging, which occurs in a distributed way to preserve redundancy and fault-tolerance (SO2);

•integration of the charger into the powertrain to exploit the three-phase links already available in the port areas (e.g. for cold ironing), while retaining a DC charging capability (SO3);

•development of an integrated energy management and control system that combines motor operations, charging and balancing of the distributed energy storage system onboard synergistically (SO4);

•devising a smart recharge management based on load demand forecast, to enable lifetime improvement of batteries and of the overall energy storage system (SO5).

All these objectives were achieved throughout the project, as detailed in the following sections.

2. SYSTEM OVERVIEW

The architecture of the electric propulsion and charging system (EPCS) developed within NEPTUNE consists of several and identical modules, which can be replicated as needed according to the size of the specific eTug under investigation. Each module features five main components/devices, as shown in Figure 1 and detailed in the following.

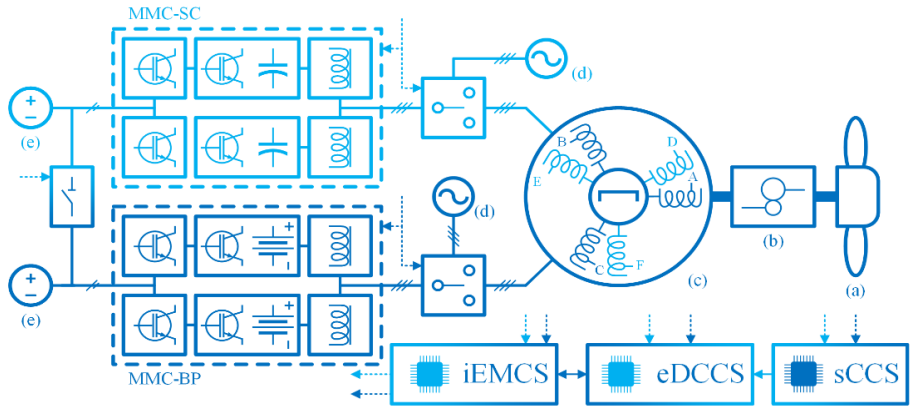


Figure 1. A schematic overview of the EPC proposed in NEPTUNE: a) propeller, b) transmission system, c) electric machines, d) harbour grid (AC and/or DC), e) MMC with distributed energy storage system, f) hydrogen tank

Note: iEMCS: integrated energy management and control system, eDCCS: electric drive and charging control system, sCCS: smart charging control system, MMC: modular multilevel converter, EPC: electric propulsion and charging.

2.1 Dual Three-Phase PMSM

The Dual Three-Phase PMSM (DTP-PMSM) represents the electric propulsion motor of the EPCS and it is widely employed in marine applications due to its enhanced performance and reliability compared to its three-phase counterpart. Additionally, NEPTUNE has investigated the possibility of supplying the two three-phase windings by different energy storage units, leading to an asymmetrical winding exploitation. More specifically, one three-phase winding can be supplied by batteries ("battery winding", W-BP) and employed during both eTug free running and towing, whereas the other winding can be supplied by supercapacitors ("supercapacitor winding", W-SC) only when needed, e.g. during dynamic operations or towing, thus providing a suitable smoothing and/or peak shaving of the battery power profile.

2.2 Modular and multilevel converters

Some modular and multilevel converter architectures have been investigated during the project to supply the DTP-PMSM, to integrate the energy storage systems onboard and to recharge them by AC and/or DC couplings. Among them, two three-phase MMCs have been considered [16-18], as shown in Figure 1. In particularly, "battery-based" MMC (MMC-BP) and "supercapacitor-based" MMC (MMC-SC) integrate different energy storage units and supply different three-phase DTP-PMSM windings. Additionally, the MMC-BP and MMC-SC can be parallel-connected to enhance the regulation of the supercapacitors state-of-energy through batteries during the propulsion stage, as well as to charge batteries and/or supercapacitors through a suitable DC recharging facility. Integrating either battery or supercapacitor cells with capacitor cells in each MMC enables several advantages; more specifically, MMC-SC enables the possibility of absorbing/delivering energy by/from each branch by keeping its overall voltage constant. Differently, cell energy imbalance can be suppressed locally in MMC-BP, i.e. without resorting to any circulating current.

Another converter configuration investigated during the project is based on Cascaded H-Bridges (CHBs); this is similar to the MMC described above, but somehow simpler, yet achieving a high number of levels. Each unit can output three voltage levels, but it lacks the loop with the upper branches, thus do not requiring the filtering inductors. This architecture has been explored for its simplicity and possibility to integrate asymmetric DC energy sources. However, differently from the MMC, this configuration lacks a common point of connection for a full DC voltage source. Both architectures have been proven to control state-of-charge, state-of-energy, and/or voltage of the integrated energy sources independently.

2.3 Integrated energy management and control systems

The main task of the integrated energy management and control systems (iEMCSs) developed within the project is splitting the overall eTug power/torque demand among the two three-phase DTP-PMSM windings as needed, by complying with the operating constraints of DTP-PMSM and energy storage units simultaneously. In particular, when the power demand increases suddenly, it is mainly provided by the W-SC through the MMC-SC first; subsequently, these are gradually replaced by W-BP and MMC-BP, respectively, thus smoothing battery current variations properly. Supercapacitors are then slowly recharged by W-BP and/or MMC-BP through the DC-link, namely batteries provide additional electromagnetic and/or DC-link power to reinstate supercapacitor state-of-energy at the desired reference value. Similar considerations apply during the charging stages, when the DTP-PMSM is replaced by one or two three-phase AC charging facilities, while DC-link charging may also occur simultaneously. Regardless of the specific operating mode (propulsion or charging), the iEMCS converts the reference torque/power profiles into reference currents, which are tracked by means of suitable current/energy loops and Pulse Width Modulation (PWM) patterns.

2.4 Electric drive and charging control system

The electric drive and charging control system (eDCCS) has the dual purpose of setting the reference DTP-PMSM speed and torque profiles during the propulsion stage, as well as active and reactive power profiles during the charging stage. Considering the propulsion stage at first, the eDCCS has the primary task of regulating the speed or the power of the eTug according to the given mission profile and operating mode (i.e. idle, free running or towing); this is achieved by setting suitable reference speed and torque profiles of the propeller, resulting in an overall DTP-PMSM reference torque profile that is managed by the iEMCS. During the charging stage, the eDCCS determines the reference active and reactive powers to exchange according to the available charging facilities, battery state-of-charge and/or supercapacitor state-of-energy, which are then managed by the iEMCS.

2.5 Smart charging control system

The smart charging control system (sCCS) is a "soft" asset to preserve the lifetime of the energy storage systems onboard and, thus, of the overall powertrain. Particularly, the sCCS optimizes the charging and use phases of the eTug, by complying with its mission profile (when and where picking up/leaving the towed vessels) while guaranteeing efficient and effective charging profiles. In other words, the sCCS optimizes charging power and towing speed to minimize the aging of the batteries and losses, especially when high-power demands occur, by leveraging graph-based optimization on a discrete formulation of the problem.

3. PROJECT ACTIVITIES

NEPTUNE has been organized into five Work Packages (WPs), initially spanning over 24 months (M01-M24) as detailed in Figure 2, but later extended to M29. Apart from WP1 (Project management) and WP5 (Dissemination), the activities of all the other three WPs are described in the following subsections.

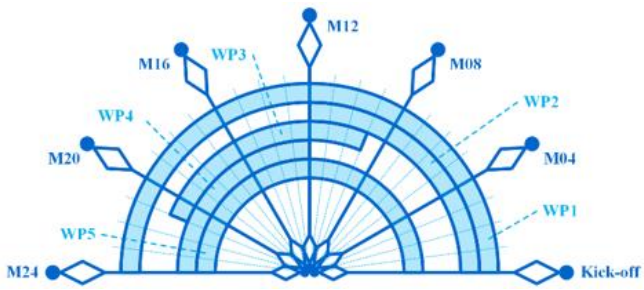


Figure 2. NEPTUNE initial Gantt chart

3.1 System design and integration (WP2)

This WP and its Tasks (Ts) regarded the design requirements and solutions for each system component, which have been defined based on the state-of-the-art and typical tugboat mission profiles.

3.1.1 Electric machine and drive/charging CTRL system (T2.1)

Based on the analysis of the state-of-the-art regarding electric motors and tugboats, a DTP-PMSM was selected as the propulsion motor of the 2-MW modular EPCS developed within the project. In particular, the eTug is assumed equipped with two 1-MW propellers, each of which is connected to three DTP-PMSM modules. As a result, DTP-PMSM power rating

has been set to 350 kW, leading to rated phase current and DC-link voltage of approximately 200-400 A and 1 kV, respectively. The DTP-PMSM control system has been developed through the well-known Space Vector Decomposition approach (SVD), which consists of mapping the phase variables (ABC and DEF) into two different reference frames (αβ0 and xyz). Subsequently, neglecting zero-sequence components (0z), the other space vectors (αβ and xy) are mapped further into a rotating and a counter-rotating reference frame (dq+ and dq-); as a result, DTP-PMSM electromagnetic torque and power can be controlled through the dq+ current components, while the corresponding imbalance can be regulated by dq- current components, enabling an asymmetrical DTP-PMSM winding supply [16].

The same control system can be usefully employed also during AC charging process, namely active and reactive powers can be controlled through dq+ current components, while the overall charging power flow can be asymmetrically split among different converters and, thus, energy storage units, by means of dq- current components. In case of DC charging, the energy flow through batteries and supercapacitors can be regulated by DC-link circulating currents, ensuring voltage and energy balancing simultaneously. Regarding the control technique, the conventional linear control approach has been employed, which represents a suitable trade-off between performance and robustness, especially due to the simplified modelling required by the complex system architecture of the EPCS under development [16].

3.1.2 Modular multilevel converter (T2.2)

Given the DTP-PMSM power, current, and DC-link voltage ratings (350 kW, 200-400 A, 1 kV), two three-phase MMCs with four cells per branch have been designed; the first one (MMC-BP) presents two cells per branches supplied by batteries instead of by conventional capacitors, and their rated voltage has been set at approximately twice that of capacitor-based cells (e.g. 350 and 150 V, respectively): this is needed to keep average capacitor voltage almost constant even during DTP-PMSM peak power demand, thus preserving the overall voltage capability of the branch. On the other hand, the MMC-SC presents two supercapacitor and two capacitor cells per branch, and their branch voltage distribution has been set as for MMC-BP (e.g. 350 V and 150 V for supercapacitor and capacitor cells, respectively); however, such an asymmetrical voltage distribution can be reversed as needed to exploit approximately 80 % of supercapacitor energy content, by keeping the overall branch voltage constant. These asymmetrical cell voltage distributions of both MMC-BP and MMC-SC are required to enable an appropriate energy and voltage regulation capability of each branch, as well as a suitable energy transfer between the two MMCs.

Both MMC-BP and MMC-SC show high flexibility and redundancy, enabling DTP-PMSM supply, AC and DC charging of batteries and/or supercapacitors, even simultaneously. Furthermore, any cell can be by-passed in case of fault so that the MMC can still operate successfully, maybe at reduced power and/or voltage capability. Additionally, the proposed MMCs are fault-tolerant also against a fault of one of the two three-phase DTP-PMSM windings: in these cases, the MMC that supplied the faulty AC winding can act as a DC-link for the other MMC, thus still enabling the employment of its energy storage units.

Another converter architecture entirely based on CHBs has been investigated. The proposed solution was to mix three battery cells and one supercapacitor cell in each phase, using equal arrangements for each phase. The battery cell voltage is the range 250-300 V, while capacitor cells cover the remaining voltage to achieve the required DC-link voltage rating (1 kV).

3.1.3 Energy storage systems (T2.3)

First, an extensive analysis of the state-of-the-art regarding the employment of energy storage systems on board vessels was carried out. It revealed that electrochemical batteries, especially Lithium-based ones, are actually the most widespread and suited energy storage technology for vessels. However, fuel cells and supercapacitors could be also employed, especially in combination with batteries, thus leading to hybrid energy storage systems. Consequently, batteries and supercapacitors have been chosen as the reference energy storage technologies for the project; batteries store an adequate energy content to make the eTug able to complete its mission profiles, while supercapacitors enable suitable smoothing and peak-shaving actions to prevent excessive battery stress and degradation.

Subsequently, batteries and supercapacitors have been sized based on the overall 2-MW EPCS and several eTug mission profiles; as a result, batteries and supercapacitors should provide 2 MW each to supply the DTP-PMSM on their own if needed. However, since batteries are the only energy supply that should be active at steady-state operation, its energy content has been set at 2.2 MWh, while much less energy is stored in supercapacitors (70 kWh) because they should act at dynamic operation mostly. Consequently, given the modular EPCS architecture described previously, 72 battery modules (30 kW, 30 kWh each) and 72 supercapacitor modules (30 kW, 1 kWh each) are concerned overall.

3.2 Energy management and control system (WP3)

This WP was devoted to developing the eDCCS, the iEMCS and the sCCS in accordance with the following tasks:

3.2.1 Electric drive and charging control system (T3.1)

The eDCCS represents the mid-level control system of the EPCS, and it has the dual purpose of setting the reference DTP-PMSM speed and torque profiles during the propulsion stage, as well as active and reactive power profiles during the charging stage. During the propulsion stage (Figure 3), the eTug speed is regulated by the propeller speed through a Proportional-Integral (PI) regulator, which takes into account either free-running or towing operating mode. In turn, propeller speed is regulated by DTP-PMSM torque through another PI regulator that feeds the iEMCS with the reference torque profiles. Alternatively, during the charging stage, the eDCCS determines the reference active and reactive powers to exchange according to the available charging facilities, battery state-of-charge and/or supercapacitor state-of-energy, which are then managed by the iEMCS.

3.2.2 Integrated Energy Management and CTRL System (T3.2)

The iEMCS is the low-level control system of the EPCS, which accounts for both energy storage management, DTP-PMSM and MMC (or CHB) control tasks synergistically [17]. During propulsion stages, the reference torque profile required by eTug operation is processed by the EMS block shown in Figure 3, which determines the most suitable torque imbalance between the two DTP-PMSM windings, as well as DC-link power exchange between MMC-BP and MMC-SC.

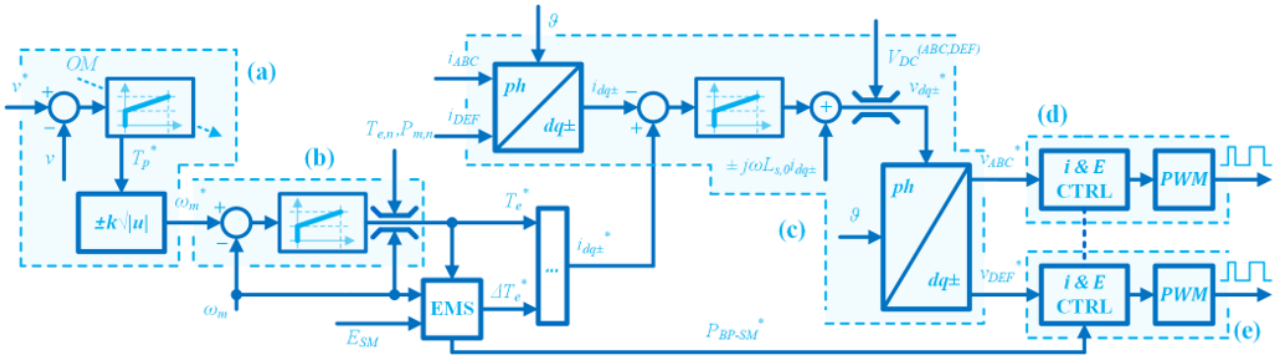


Figure 3. Overview of the proposed eDCCs (a, b) and iEMCS (c, d, e) over the propulsion stage: a) vessel speed control, b) motor speed control, c) DTP-PMSM current control, d) MMC-BP control, e) MMC-SC control system

For example, W-BP can experience smooth and reduced torque demands at dynamic operation due to W-SC supporting actions, even in terms of peak-shaving when needed [19]. When steady-state operation is reached, supercapacitors can be slowly recharged by batteries either through the DTP-PMSM shaft (by imposing resistive torques) or by the DC-link directly: this is achieved through an energy control loop, which has the task of driving the supercapacitor energy content to its reference value, which varies in accordance with DTP-PMSM operating speed and power.

Given the control approach defined in T2.1, both propulsion and charging demands can be usefully converted into dq+ and dq- reference current components, which can regulate torque, active/reactive powers and their imbalance [16]. The tracking of these reference currents has been achieved by PI regulators (Figure 3), which ensure adequate dynamic performance and robustness against model parameter variations and uncertainties at any operating mode. In particular, during propulsion stages, the torque and its imbalance can be regulated as needed, by complying with all DTP-PMSM operating constraints (current, torque and power limitation, voltage saturation). Similar considerations apply during AC charging, when reference active and reactive powers can be tracked successfully by complying with MMC current limitation and voltage saturation constraints. When DC charging occurs, it is managed by the MMC-BP and MMC-SC control subsystems directly (T2.2, Figure 3) as this goal is accomplished by means of its own circulating currents, without affecting the AC side of the converters.

Regarding the PWM patterns, they are fundamental to share the required reference branch voltage among the different cells to enable an appropriate MMC voltage and/or energy regulation; particularly, in case of MMC-SC, the PWM pattern must not interfere with the energy balancing provided by the energy and current control loops, whereas, in case of MMC-BP, the PWM pattern has the task of regulating the voltage of the capacitor cells locally, namely at branch level, so that no circulating current is required.

3.2.3 Smart charging control systems (T3.3)

The sCCS has been implemented by setting up a graph-based optimization problem, which can be solved through state-of-the-art techniques once the tugboat profile is known (time and location of vessel pick-up/release). Each node in the graph represents a physical location (pick-up/release or charging locations), while its edge represents a different eTug speed (three discrete values), each of which is associated with the corresponding energy losses and lifetime consumption of the battery. The energy losses are evaluated based on the combination of converter, motor, and energy storage efficiencies, while lifetime consumption is computed according to the aging models of the electrochemical cells effectively chosen for the system implementation. The charging power is adjustable over three different levels, as already occurs for eTug speed.

3.2.4 Control system integration (T3.4)

Once developed, the iEMCS, eDCCS and sCCS were integrated to each other, mainly, but not only, in accordance with a cascade control architecture; for example, during propulsion stages, the sCCS may influence the reference eTug speed processed by the eDCCS, which defines the DTP-PMSM reference torque demand to achieve such a target eTug speed in accordance with the specific operating mode (e.g. free-running or towing). This signal is processed further by the iEMCS to set the most suitable torque imbalance, thus enabling the tracking of both dq+ and dq- reference currents. Once the reference DTP-PMSM voltages have been achieved, the iEMCS shares them with both MMC-BP and MMC-SC control subsystems, which are integral parts of the iEMCS itself; particularly, these subsystems have the task of regulating batteries and supercapacitors usage in accordance with their actual status and eventual unavailability (e.g. low voltage levels or faults). Additionally, the iEMCS could synthesize also the reference DC-link power exchange between MMC-BP and MMC-SC. As a result, a hybrid parallel-series control architecture was achieved, which enables by-passing eventual faults of any energy storage unit and/or three-phase DTP-PMSM winding.

3.3 Simulations and experimental testing (WP4)



Figure 4. The Typhon HIL 404 device available at the University of Cagliari (UniCA)

This WP includes the real-time simulations and experimental tests conducted by each research unit on the prototyped parts, as well as the joint testing on the complete integrated propulsion and charging system. All the tests have been conducted exploiting instrumentations and test rigs already available at partners' laboratories, integrating them by the equipment and instrumentation specifically acquired for the project. In this regard, extensive simulation studies were carried out in MATLAB-Simulink and/or Typhoon-HIL environments (Figure 4) to verify the proper operation and performance of the overall EPCS and of its single components. More specifically, this WP consisted of four main Ts, which are briefly described in the following.

3.3.1 Testing of the electric machines driven by eDCCS (T4.1)

The DTP-PMSM chosen and sized for the project has been modelled and simulated to verify its performance at different operating modes and conditions; this has been done by using simplified models of both power electronic converters and energy storage systems as medium-long term time horizons are needed to simulate eTug mission profiles properly (e.g. several tens of minutes). In this regard, suitable timing factors have been employed, which scale minutes to seconds but by preserving a proper estimation of the overall EPCS and, thus, of the DTP-PMSM performance [17]. The outcomes of this activity have led to experimental tests on reduced power scale prototypes that were available at the University of Padua (UniPD) premises (Figure 5). In particular, a 3 kW DTP-PMSM with anisotropic magnetic features was adopted for evaluating the current control to test the unbalanced torque production.

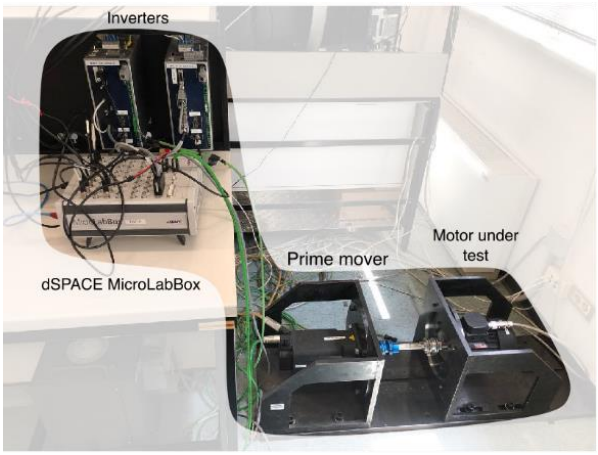


Figure 5. The electric drive test bench at UniPD

3.3.2 Testing of the modular multilevel converter (T4.2)

Both MMC-BP and MMC-SC have been tested extensively; particularly, each MMC cell has been modelled by using simplified power electronic converter and energy storage system blocks. Subsequently, each MMC has been tested separately, by connecting them to an AC grid. Once the corresponding MMC control systems and PWM patterns have been setup and verified, they have been adapted to supply a three-phase PMSM.

The same approach has been used to investigate the CHB-based architecture; a single control algorithm working for both architectures (MMC and CHB) has been developed, which takes care of implementing vector control, as well as balancing and exchanging energy among the various cells. The control system can balance different quantities, such as state-of-charge or voltage; this ensures flexibility in case other converter architectures are to be used. The same algorithm can also enable exchanging energy among converters belonging to the same phase and side (high or low, by cell switching reordering), same side of different phases (via zero sequence modulation), high and low side of the same phase (via recirculating current in case of MMC).

In parallel with simulations, the development of a hardware validation platform was started at the University of Parma (UniPR), as shown in Figure 6; in this design, the modular units operate at a limited voltage (48 V each), to guarantee operator safety during the tests, while still driving commonly available motors (e.g. 200-400 V ones). Flyback units were employed instead of using batteries, each of which is supplied by either a rectified AC voltage or a controlled DC voltage coming from laboratory power supplies.

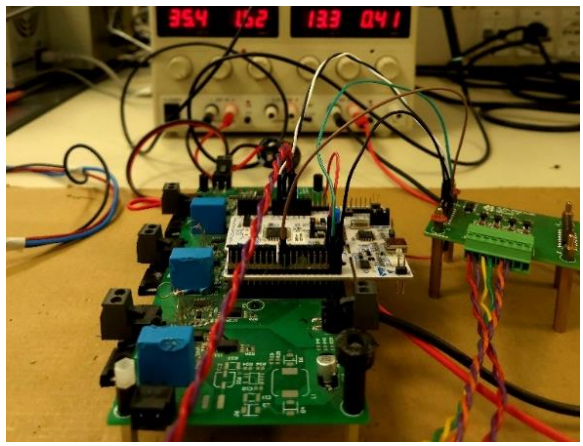


Figure 6. A DC/DC converter under test at UniPR

3.3.3 Testing of multi-source ESS driven by the iEMCS (T4.3)

The iEMCSs developed during the project were tested firstly by assuming concentrated battery pack and supercapacitor module, each of which supplying one of the two DTP-PMSM windings [16]; this simplified configuration enabled verifying the effectiveness of the iEMCS in charging/discharging the different energy storage units through the DTP-PMSM torque imbalance. Subsequently, the concentrated battery and supercapacitor modules have been split into multiple modules and integrated into the MMC-BP and MMC-SC, respectively. In this regard, suitable DC-DC converters have been designed and tested to interface batteries or supercapacitors with the corresponding MMC cells to prevent fast current variations and ripple on the latter.

An additional topology proposed during project activities considers a battery pack as the main bus source feeding an MMC [20]. An H-bridge topology of each cell was proposed, where the capacitor acts as an energy buffer connected to the first leg of the bridge, while supercapacitors were added to the second leg acting as voltage regulators for the capacitors. The proposed solution enabled solving the well-known MMC problem of voltage balancing among capacitors. Furthermore, the proposed control structure enables modifying the power share coming from the battery, thus enabling a smart EMS.

3.3.4 Joint testing (T4.4)

Based on the different components, configurations, and control approaches proposed and tested during the project, the final EPCS architecture has been defined, assembled, and tested (Figure 1); this consists of the most effective combination among different possible alternatives, which

enables exploiting DTP-PMSM, batteries, and supercapacitors to the maximum extent. In more detail, the two MMCs have been integrated to each other to supply the DTP-PMSM through the iEMCS, which is driven by the eDCCS and, eventually, by the sCCS. The performance of the final EPCS has been verified during different eTug mission profiles, revealing its effectiveness in terms of performance (successful tracking of all the reference signals) and energy management (suitable power flow among battery-based, supercapacitor-based and capacitor-based cells, as well as between the two MMCs).

4. PROJECT RESULTS and OUTCOMES

All the NEPTUNE SOs resumed at the end of Section 1 were achieved throughout the project, as detailed in the following.

4.1 Design of a highly reliable and fault-tolerant EPS (SO1)

This SO has been achieved by the proposed EPCS, which shows an inherent fault-tolerant capability due its modular and multi-phase configuration. Particularly, during free-running, the eTug can be propelled by just one of the two three-phase DTP-PMSM windings, thus ensuring its safe operation in case of any fault of one or more phase windings. Regarding MMCs and CHBs, they can operate safely even in case of multiple cell faults; if these occur, the rated MMC branch voltage could be preserved by increasing the voltage of the healthy cells. Alternatively, the DTP-PMSM overall power demand can be split asymmetrically among the two three-phase DTP-PMSM windings to compensate for a reduced voltage capability. Regarding batteries and supercapacitors, they consist of a number of modules distributed within the MMC-BP and MMC-SC, respectively. Consequently, in case of any fault of one or more energy storage modules, the others can compensate for this drawback by delivering/absorbing the required excess energy. Additionally, the DC-link between the two MMCs enables transferring energy from battery to supercapacitor modules and vice versa; consequently, even if one of the two three-phase DTP-PMSM windings is faulty, the corresponding energy storage units can still deliver/absorb energy to/from the healthy winding through the DC-link.

4.2 Integration of energy storage systems in MMCs (SO2)

This SO has been achieved by the proposed MMC configurations, replacing some capacitor cells with either battery or supercapacitor ones, leading to the MMC-BP and MMC-SC architectures previously described. In particular, supercapacitor cells enable the decoupling between branch energy and voltage, namely the energy content of each MMC-SC branch can be varied by keeping its overall voltage constant. On the other hand, integrating battery cells into MMC-BP enables local voltage and power regulation (at branch level) without resorting to any circulating current, which is instead required by conventional and MMC-SC configurations. As a result, using both MMC-SC and MMC-BP enables adequate redundancy and fault-tolerant capability of the proposed EPCS. Also, the alternative CHB-based architecture exhibits the capability of integrating different energy sources, while retaining modularity and fault tolerance.

4.3 Integration of AC and DC charging features (SO3)

The proposed MMC-SC and MMC-BP ensure the achievement of this SO by enabling charging the energy storage units in different ways, either in AC, DC, or both. In particular, the three-phase AC connection of each MMC can be usefully switched from the three-phase DTP-PMSM winding to a three-phase AC charging facility (Figure 1); in this case, MMC branch inductances perform a suitable smoothing action on charging currents, enabling recharging batteries and/or supercapacitors properly. Alternatively, batteries and/or supercapacitors can be recharged through the DC-link, which can be connected to a DC charging facility available in the port area (Figure 1). More specifically, DC-link voltage can be varied in a wide range by inserting/bypassing cells as needed, thus complying with different DC charging voltage and power ratings. AC and DC charging can even occur simultaneously, thus ensuring fast charging times, even in case of reduced charging power rates from the single charging sources.

4.4 Development of an integrated EMS (SO4)

This SO is fulfilled by the iEMCS developed within the project, which is able to split the overall eTug power/torque demand among the two three-phase DTP-PMSM windings as needed, by complying with all the operating constraints simultaneously. Different versions of the iEMCS have been developed within the project, one of which consists of processing the overall DTP-PMSM torque demand by appropriate low-pass filters to determine its sharing rate between W-BP and W-SC, thus leading to a certain torque imbalance [19]. This is further refined in accordance with supercapacitor energy content, namely the torque share of W-SC is reduced/increased if supercapacitors need to be less or more discharged. In this regard, it is worth noting that such a torque share could be even reversed (i.e. of the opposite sign compared to the overall torque demand) in case supercapacitors need to be charged during the propulsion stage, e.g. when the eTug reaches its steady-state speed. Similar considerations apply during AC charging, namely the power share between MMC-BP and MMC-SC can be set suitably in accordance with batteries and supercapacitors' energy content, as well as AC charging features and availability. Once both the overall torque/power and its imbalance have been defined, DTP-PMSM reference currents and voltages are computed and processed by the MMC-BP and MMC-SC control systems; the former has the task of managing DC charging directly, while both suppressing any branch and leg energy imbalance, ensuring adequate voltage and energy capability of supercapacitor and capacitor cells. This goal is accomplished through appropriate energy and current loops, but also by suitable PWM patterns. As a result, the proposed iEMCS combines both DTP-PMSM and energy storage control tasks.

4.5 Devising a smart recharge management (SO5)

This SO has been achieved by formulating the optimization problem using discrete graph-based optimization. Each node represents a pick-up or release location of the eTug, or, alternatively, a charging facility. These locations are connected by multiple edges, representing discrete towing speeds and the related energy and efficiency costs. Once the problem has been put in this form, it can be solved optimally

by known algorithms.

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

The outcomes of NEPTUNE are very promising and suggest potential extensions and further validation of the proposed EPCS configuration. In particular, the inherent modularity and flexibility of the proposed EPCS enables its application to different kinds of vessels, even those requiring a relative low power demand (few tens of kW). These features also enable integrating energy storage units different from those considered in the project (i.e. batteries and supercapacitors), as well as renewable energy sources eventually onboard; in this regard, the use of fuel cells is surely worth of investigation, especially if hydrogen will be widespread in port areas.

Regarding the MMC and CHB converters developed during the project, they enable different charging modes, which may occur even simultaneously and at variable rated voltage/power: this feature seems particularly relevant in the incoming scenario, in which different kinds of charging infrastructures will be available according to the specific port area and/or country.

Last but not least, the modularity of the electric propulsion motor could be investigated further, by using, for example, different kinds of electrical machines (e.g. permanent magnet, synchronous reluctance and/or induction machines) to make a hybrid electric motor for each propeller; this will benefit from the advantages of each specific module at different operating conditions, thus increasing its overall performance compared to mono-type solutions.

In conclusion, given all the previous considerations, NEPTUNE represented a first important step towards vessel electrification through a highly-integrated design, management and control approach. Further developments will surely occur, which may be subject of future proposals at national and/or international calls for project.

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