Abstract — Coarse and accurate power accounting methods for ship electric propulsion are observed and compared. For the purpose of analysis, the propulsion system has been separated into two units, namely the ship load and the motor drive. In the load model, variation of such factors like static and dynamic hull resistance and efficiency is explored while the supply characteristics, drive loading, propeller speed, and transmission are included to the factors responsible for the drive power consumption. A case study of the pro-ecological BalticSWATH vessel is described where the brake power dependence on the vessel velocity is estimated within the broad efficiency variation range at different methods of electrical drive organisation and control.

I. INTRODUCTION

The ship designs are now involved in a great penetration of on-board electrical and electronic devices. The evident trend is towards complete ship electrification, where the electrical systems become the parts of both the auxiliary and the propulsion units. Though a steam turbine, gas turbine, or diesel engine continue to play the role of the prime mover, for most ships electric propulsion becomes the more and more appropriate solution. Developers of boats, yachts, warships, icebreakers, and cruise vessels are becoming aware about the new possibilities that could take great benefits of motor drives thanks to advances in the fields of power electronics, electrical motors, fast microcontrollers, and digital technologies. Introduction of electric propulsion into water transportation leads, among other benefits, to the reduction of the environment pollution and the improvement of overall life quality standards.

One of the main troubles for a vessel designer concerns the power requirement for electric propulsion. Nowadays, motor driven systems account for about 40% of global energy demand and consume near 70% of generated electrical energy being the largest end-use of electricity [1]. Among them, three-phase squirrel-cage induction motors are used in more than 90% of the industrial motor driven systems. Since electrical energy is an important resource for all the ship processes, the shipbuilding sector now pays special attention to the main challenge of electric propulsion systems — reduction of their losses in order to effectively apply the onboard energy resources, including batteries and fuel cells among others. Except that electric propulsion offers the great energy saving potential, counted between 20% and 30%, it promises significant decrease of waste and emissions as well.

Power consumption of the ship prime movers varies considerably from vendor to vendor. To decrease power losses, propulsion manufacturers focus on such key factors as:

- optimal component selection making the primary use of low-loss parts and components
- aerodynamics improvement by using more efficient cooling systems and changing the fan and cover designs
- increasing the manufacturing quality by improving assembly techniques
- enhancement of operating conditions by searching the best loading profile, power quality, and thermal conditions
- optimal control across the full running velocity range

To increase the energy saving potential, observation of the full propulsion chain is required, including propellers, transmissions, motors, converters, supply, and system performance. In contrast to power requirement of a single drive which is usually quite simple to estimate at steady conditions, the power of multi-drive combinations in dynamics may not be so easy to find because the ship has a variety of very different operating conditions and the network energy consumption changes frequently in a wide range. As the drive power design is complex, certain estimates of multiple component combinations are required in order to attain energy savings in propelling.

On the basis of many experimental tests and with the help of pertaining dimensionless ship parameters multiple methods have been established for accounting the needed propulsion power [2]. In practice, however, these calculations based on experience and rules of thumb are becoming inadequate without verification [3]. In the most cases, the problem consists in impossibility to achieve proper similarity between the simulated prototype and the full-scale ship. Even the measurement of the power consumption and power output in test conditions can rarely give exact and dependable energy values. Since the propulsion losses represent a vector of innumerable different factors, it is challenging to simulate operation of each part separately with following their combining.

In this study an attempt to partly overcome the above problem is made. To estimate the total power consumption, multiple propulsion system parts have been taken into notice. For the purpose of analysis, the propulsion system has been separated into two units, namely ship load and motor drive. The load performance is affected by variation of such factors as system design, hull efficiency, control methods, process requirements, operating times, and maintenance while factors responsible for the drive power consumption include the supply characteristics, drive loading, propeller speed, converters, and transmission. In the following sections, the power and torque requirements are discussed. Basing on the factors affected the ship thrust force, the power of the BalticSWATH vessel propulsion is accounted and analysed within the broad efficiency variation range.
II. POWER AND TORQUE REQUIREMENTS

By definition [2], [4], the effective power $P_E$ required to tow the vessel is equal to the product of the total thrust force $F$ opposed to the vessel movement and its velocity $v$:

$$ P_E = Fv. \tag{1} $$

The agent employed to move a vessel is a propeller, sometimes two and sometimes more than two. In all cases the necessary propeller power $P$ required to move the vessel is normally greater than the pertaining effective power (Fig. 1).

$$ P = \frac{P_E}{\eta}, \tag{2} $$

where the total propulsive energy conversion efficiency $\eta$ represents the ratio of the output power of the propeller and the input electrical power consumed by the propeller mover from the onboard supply grid. In energy terms [3], [5], the total efficiency is composed of as minimum six main components,

$$ \eta = \eta_c \eta_m \eta_G \eta_S \eta_p \eta_H, \tag{3} $$

where

- $\eta_c$ – efficiency of power electronic converter supplying the electrical mover (0.65 to 0.99),
- $\eta_m$ – mover efficiency, electrical motor in our case (0.45 to 0.97),
- $\eta_G$ – transmission efficiency of the gearbox (0.95 to 0.97),
- $\eta_S$ – shaft line efficiency (0.97 to 0.98),
- $\eta_p$ – efficiency of the propeller, the least efficient part of the vessel drive train, which value is about 0.7 – 0.75 at the design speed,
- $\eta_H$ – hull efficiency defined as the ratio of the effective power for a hull with appendages to the thrust power developed by propellers (0.98 to 1.4),
- $t$ – thrust deduction fraction measured experimentally (0.1 to 0.3),
- $w$ – wake fraction, the vessel design parameter (0.2 to 0.45).

As the first approximation, the constant propulsive efficiency level is sometimes taken, for example 0.55 for the diesel-electric propulsion [6]. In [3], this efficiency is ranged from 0.55 to 0.75.

Nevertheless, the propulsive efficiency is a variable parameter strictly dependent on the loading conditions. As its maximum locates typically around a load of 0.7 – 0.85 [7], [8], it is advantageous to design the system such that the operation point lies on the load curve to the right of maximum, in order that the efficiency will first increase as the speed is reduced and then decrease. This can extend the useful range of variable speed operation in a system. To this aim the manufacturer should be consulted on the system maximum efficiency point [9].

It is important [7] that the ship propulsion efficiency drops notably and quickly as the load becomes lower than 0.50 of the nominal value. As well, the efficiency depends on the propulsion power level.

One example of the propulsive efficiency as a function of the propulsion power in megawatt power range is shown in [6]. Such drop in efficiency during the speed reduction reduces the economical benefits of the ship control because of increasing consumed power.

Another example illustrating the importance of giving close attention to the efficiency can be found in [10]. An average electrical machine consumes its capital cost in energy in less than 2 months. Premising on a typical fourteen-year life of an electrical motor, the lifetime cost savings for such machines are in the order of 3 – 4 times the purchase cost. Therefore a single percentage point in efficiency increase will save the lifetime energy cost generally equivalent to the purchase price of the motor.

The power delivered to the propeller from the input of the reduction gear is as follows:

$$ P_D = P \eta_G \eta_S. \tag{4} $$

When determining the required propeller mover power, it is a normal practice to add some extra power margin (so-called sea margin), which is usually about 0.15 of the propeller design power. However, for the large container vessels, 0.2…0.3 may sometimes be applied. Besides the sea margin, a so named engine margin of some 0.10…0.15 is added also. In [11] both these margins are combined to the service allowance of 0.25…0.35 recommended for determination of the installed propeller mover power. Commonly, such corrective factors are estimated on the basis of previous similar installations.

The propeller torque

$$ T_0 = \frac{P_D}{\omega_0}, \tag{5} $$

depends on the propeller angular speed $\omega_0$ (rate of revolution) (5 to 30 rad/s [12]). When accounting the torque, it is a practice to choose 0.03…0.07 higher rates rather than a designed value.

The torque on the propeller mover shaft is as follows:

$$ T = \frac{P}{\omega}, \tag{6} $$

where $\omega$ is the shaft angular speed (60 to 250 rad/s [12]). The speed of the propeller rotation is about 10…20 times smaller than the propeller mover speed, which is usually quite high (several thousand rpm for gas and steam turbines and some smaller for electrical machines).

In practice, for example [13], the gearbox ratio is selected as a trade-off between the requirement of the operation at the highest speed at reduced torque and volume and the need to limit the speed to minimize iron losses and to simplify gearbox design and realisation.
III. ANALYSIS OF THE SHIP THRUST FORCE

The power for the ship propelling is directly related to the resistance a hull experiences when moving. In the design procedure, a ship is treated as an internal mass acted on the total thrust force. An interaction between the propeller and the ship hull is expressed according to the traditional force procedure, a ship is treated as an internal mass acted on the some 0.8 of the static resistance of the average merchant ship, shallow waters and heavy sea, under wave disturbance and for high-speed ships [5], [6]. It is increased when sailing in the static resistance for low-speed ships, and up to 0.4 – 0.6 weather influence, and falls in a calm sea.

The air resistance usually amounts about 0.02 of the static resistance, but can be as much as 0.1 for container ships. For a ship steaming into a 10 m/s wind, the static hull resistance may be increased by up to 0.25 – 0.30.

In the steady state, it is enough to rely on the static force balance in (7). But when accurate manoeuvring of the vehicle is critical, the above steady-state assumption does not suffice. At dynamic positioning, the load varies substantially. This sudden load variation causes a continuous disturbance for the electrical system and the prime movers. As a ship under acceleration is subjected to larger load than during free sailing, the transient behaviour of the propulsion system needs to be considered. As follows from (7), the thrust required from the propeller will be higher as it takes some time before the propeller has reached its new speed level. As well, the reversed character of the propeller is of the major importance. From the dynamics viewpoint, the electric propulsion systems, compared to the diesel and turbine propulsions, can certainly improve the characteristics of manoeuvrability and dynamic positioning of the ship, particularly required in the area nearby the harbours, when a ship docks, and to reduce crash stop time/space.

As shown in [3], because of reversing and dynamics, the relation curve of counter-torque and velocity become significantly different from initial quadratic ratio occupying three quadrants of the torque/velocity reference frame. Following (1) – (4), the power requirement is thus not proportional to the cubed speed as in the ideal propeller law (8). Actual studies show that the power and vessel speed relationship is normally seen with a higher power than three [5]. A reasonable relationship is usually as follows: for large high-speed ships like containers the index of power reaches 4.5; for medium-sized, medium-speed ships (feeder containers, reefers, Ro-Ro, etc.) this index is 4.0; for low-speed (tankers and bulk carriers) and small ships it is about 3.5. The power required can be proportional up to the vessel velocity raised to the 6th power. The propeller law cannot be applied when the ship is sailing against the current, a strong wind, and waves that give rise to a heavier propeller running than when running in calm weather.

IV. CASE STUDY: POWER ESTIMATES FOR BALTICSWATH

The system under the observation is the pro-ecological vessel BalticSWATH with variable draft. Vessel data taken for accounting are as follows: waterline length of 7 m, wetted surface area of 20 m², equivalent air surface of 30 m². Many non-linear coefficients used in the model were generally derived from experimental measurements on the propeller in basins and given in the form of abacus and diagrams. The following constants have been chosen: $C_l = 0.0003$, $C_d = 1$, $\rho = 1020$, $\rho_A = 1.2$. The skin and residual resistance coefficients $C_F$, $C_R$ have been preliminary scaled from experimental data of a series of SWATH vessels published in [6]. Their dependence on the velocity is shown in Fig. 2.
Using (7), (8) and (9), the static hull resistance $C$ and the total thrust force $F$ versus the vessel velocity were obtained as shown in Fig. 2 as well. Basing on (1) and (2), the brake power was calculated as a complex function of velocity and total propulsive efficiency (3). As a first approximation, the total propulsive efficiency $\eta$ was obtained roughly for the variable efficiency of the propeller [6] at constant motor efficiency of 0.96, gear efficiency of 0.97, and power converter efficiency of 0.97. It is traced in Fig. 3 as the uppermost curve. Respective power trace $P$ is in Fig. 3 as the lowermost curve.

Fig. 2. Skin (CF), residual (CR), and static hull (C) resistance coefficients and thrust force ($F$) with respect to velocity.

As the next step, it was taken into consideration that the motor efficiency $\eta_M$ strongly depends on the load and speed levels [18]. Induction motor efficiency dependence of the torque has been acquired from [19] and recalculated into the efficiency versus velocity relation for the nominal ship velocity of 7 m/s basing on the quadratic torque-speed ratio (6). Respective more accurate propulsion efficiency curve $\eta$ ($M$ var) is shown in Fig. 3 below the previous efficiency trace as well as the new, more accurate power curve $P$ at variable motor efficiency is placed above the previous trace.

Appreciating the same regarding the transmission efficiency $\eta_T$ with nominal value of 0.97 at 7 m/s, the third pair of propulsion efficiency $\eta$ ($G$ var) and power at variable gear efficiency curves is also drawn in Fig. 3.

Efficiency of the power converter $\eta_C$ is associated with conduction losses and switching losses that as well depend on the circuit and operation conditions. It was shown in [18] that, for drives with the size of some kilowatts, the converter losses only constitute a small fraction of the total drive losses. As the drive size increases, the converter loss fraction increases as well and, for a 100 kW motor drive, the converter losses and motor losses are almost equal at nominal load. Similarly to the motors and gears, converter efficiency is reduced along with the frequency reduction due to the voltage pulsating, discontinuous currents, and cooling problems as well as with the frequency increase due to the switching losses [20]. As a result, the fourth set of propulsion efficiency $\eta$ ($S$ var) and power curves appears in Fig. 3.

In total, an essential growth of the consumed power along with the velocity increase is watched.

### V. Energy Saving Potentials

To evaluate an energy growth tendency, separate the full velocity range of the ship between two areas shown in Fig. 3, namely the lower sub-range (area for manoeuvring) and the upper sub-range (area for racing under the free sailing). In both areas the velocity can be doubled: in the former from the halved to the nominal level (3.75 – 7.5 m/s) and backward and in the latter from the nominal to the double level (7.5 – 15 m/s). As Fig. 3 illustrates, in both areas the requested power growth resulted from more and more accurate calculations is estimated at over 5 times, from 9 to 5 times in the first case and from 8 to 32 times in the second case. It is remarkable that the choice of the power accounting procedure seems the most important in the second area where even very small change of parameters results in significant increase of the requested energy.

For this reason, as a first step to energy saving, a double-zone control topology is required for the propulsion covering two regions, namely the constant torque area and the constant power one [4]. While the ship resistance remains below the permissible level, the driving power is adjusted proportionally to the velocity providing the constant torque operation. In this constant torque region, the changing ship velocity weakly affects the torque production. To exceed the rated velocity, the torque should be restricted to keep the constant output power. Different from the constant torque region, in the constant power region the output torque decreases along with the increasing velocity. This means that any acceleration will be available only at the reduced resistance. Upon such an arrangement, electric propulsion can be used for manoeuvring in dock areas or for sailing when becalmed. If the ship needs to navigate faster, an auxiliary diesel-generator has to be used for onboard electric power generation. One such example developing the velocity up to 12 m/s with sail propulsion was reported in [13]. It is also relevant in the described project intended to establish the trans-boarder coastal shipping.

Particularly, in our case study once the residual resistance drops to zero, the desired power decreases twice thus providing the possibility to accelerate. In Fig. 4, the desired brake power $P_{\text{nom}}$ is restricted by 500 kW. While the residual coefficient remains insignificantly low, the water resistance $F_w$ ($C_w=0$) is keeping slightly above 2000 N and the ship velocity can approach 15 m/s at brake power $P$ ($C_w=0$) of around 200 kW. Upon the nominal loading $F_w$ of 7000 N, the velocity is restricted by 12.5 m/s and continuous to drop more with even higher loads.
The new methods of the load-dependent control of electric power supply optimisation procedures, such as the structural and constant power one. The second method relates to the reason why, as a first method for energy saving, the velocity greatly affects the consumed power. This is the speed, and transmission are the factors responsible for the supply characteristics, drive loading, propeller dynamic hull resistance and efficiency has to be accounted for the load model, variation of such factors as static and arrangement with two regions, namely constant torque region of the motor, gear, and supply is as high as 29 %. Hence, using the load-dependent control of the drive inverters, this value can be minimised to 17 %.

VI. CONCLUSION

For the purpose of energy analysis, the propulsion system should be separated into the ship load and the motor drive. In the load model, variation of such factors as static and dynamic hull resistance and efficiency has to be accounted for while the supply characteristics, drive loading, propeller speed, and transmission are the factors responsible for the drive power consumption. Efficiency dependence on the ship velocity greatly affects the consumed power. This is the reason why, as a first method for energy saving, the propulsion drive requires a double-zone structural arrangement with two regions, namely constant torque region and constant power one. The second method relates to the power supply optimisation procedures, such as the structural composition of power electronic converters and their control. The new methods of the load-dependent control of electric drive with discontinuous SVM algorithms appear the most engaging.

ACKNOWLEDGMENT

This research work has been supported by the Estonian Ministry of Education and Research (Project SF0140016111) and European Social Fund (project “Doctoral School of Energy and Geotechnology II”).

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