On Studying the Power Supply Quality problems due to Thruster Start-ups

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Abstract: The target of this paper is twofold: primarily to highlight the significant effect of certain power supply quality problems on the normal operation of the entire ship grid, namely inrush currents and voltage dips due to manoeuvring thruster motor starting-ups. At a second stage, the paper aims at recommending some amelioration of standardization status. Hence, the authors suggest the exploitation of existing experience on pulsed load standardizing, taking into account the resemblance between the systems. The study is enriched by actual case studies and simulations in PSCAD computer program.

Keywords: power quality, thruster, pulsed loads.

I. INTRODUCTION

It is more than two decades that auxiliary propulsion systems (the so-called thrusters) have been introduced in the aft or stern part of several ship types increasing their maneuverability and collision avoidance capabilities. Thus, nowadays, thruster systems installed especially in the bow of a ship, is an indispensable piece of equipment of hers, while it is a common practice that rotation is provided by an electric motor, often an asynchronous (induction) alternative current one.

This electric motor drive is of high power demands, in the order of 0.5 up to 2.5 MW, which increases considerably the electric power demands that the electric power generation set has to meet. Moreover, things are getting worse during starting-up of such huge electric power system, when -like any other motor- the thruster motor absorbs a transient “inrush current” of high values (varying, in general, between 4-7 times the rated current [1-3]).

Consecutively, during the inrush phenomenon (i.e. for approximately up to 15-20 s after its time zero) the thruster motor power demands in terms of active and reactive power are high, too. During this interval, the “transient power factor” is fairly low, as the reactive power required is significantly higher than in steady-state.

This high energy demand at a low power factor cannot be easily covered by the vessel’s generator sets leading to their possible overloading or even tripping. Furthermore, as a result of the transient inrush current, large voltage drops take place in the entire network, introducing “symmetrical” voltage dips to all three-phases. More specifically, in the bow thruster cases, the motors are installed far away from the generator plant (perhaps farther away than any other large power equipment), therefore the distribution cable is fairly long resulting to a rather large valued cable impedance which is added upon any other intervening impedance like that of a starting-autotransformer. Hence, during motor starting-up there is an increased voltage drop on this impedance, while of course there is a thermal stress on the cable itself. This stress worsens further, in case of repetitive starting-up of the motor and has to be taken into account during cable sizing at the design stage.

In most large scale applications the thruster propeller is a controllable pitch one and during starting-up the blade pitch is set to 0° in order to minimize the electric power demands. However, even this closed propeller has a significant moment of inertia which is added upon the motor’s one deteriorating even further the starting-up phenomenon. Due to this large valued inertia, occasionally voltage and/or frequency stability problems might be noticed [4]. Coming back to the starting-up procedure, as soon as the transients have decayed, the actual ship maneuvering operating mode begins, via varying the thruster’s blade angle. In this way, it is ensured that motor starting-up with its adverse phenomena is not repeated during the rest of the maneuvering mode. Still considering the possible behaviour of the thruster unit during maneuvering, the variations in the propeller’s pitch can result to significant power fluctuations in the power demands. Therefore, it can be argued that the thruster unit operation resembles that of a pulsed load, i.e. load that has large power demand for a very short interval followed by small power demand for fairly longer intervals.

On the other hand, the transient phenomenon described above is not thoroughly covered by most standard rules, as the only relevant limitation is that of the permissible transient voltage fluctuations.

Hence, the target of this paper is twofold: primarily to
highlight the significance of the power supply quality problems due to thruster motor starting-ups, namely inrush currents and voltage dips. On the other hand, the paper aims at not only recommending alleviating measures, but also some possible improvement of the current status in standards towards facing the problem even at the design stage of the ship system. From this point of view, the authors suggest the exploitation of the standardization experience on pulsed loads, considering the similarities between the two loading systems, as highlighted in a specific section. Thus, following the approach of standards on pulsed loads, the thruster electric power demands in both steady- and transient state of operation are compared with the capacity of the generators-in-operation. Two sets of case studies obtained from actual ship systems are presented accompanied by simulations in PSCAD environment (the computer program of Manitoba HVDC Research Center) [5] are used for analysis purposes.

II. THRUSTER ELECTRIC ASYNCHRONOUS MOTOR STARTING-UP

As it is well known there are two major types of induction (or asynchronous) machines, the squirrel cage and the wound rotor ones. Their main difference consists in that in the wound rotor case, the rotor resistance, and hence the motor performance, can variate via externally connected variable resistor units. Focusing on starting-up, where the rotor resistance plays a substantial role, external resistors can be connected, so that the motor absorbs a transient inrush current as equal as its rated value. However, this advantage of the wound rotor types, is compensated by the significantly higher cost. Therefore, several starting-up methods have been developed for the squirrel cage induction motors, a brief overview of which follows.

A. Direct-On-Line (DOL) starting-up

Transient inrush current is mainly due to the low impedance of the motor during its starting-up and the slip rotor resistance, in particular. Due to the highly inductive character of this impedance, a DC offset is also introduced. The mathematical explanation of this offset consists in the initial conditions of the differential equations introduced.

Eventually, as speed grows-up close to its nominal value, slip decreases, slip rotor resistance, and hence total motor impedance increases to its steady-state value. Moreover, as the current is of high value, a voltage dip occurs in the entire electric system, of magnitude even up to 20%, see Fig. 2.

Eventually, as speed grows-up close to its nominal value, slip decreases, rotor resistance and hence total motor impedance increases to its steady-state value. Due to the low impedance of highly inductive nature during this starting-up, the motor requires significantly larger amounts of active and especially reactive power, (i.e. a lot of energy at fairly low power factor) than in steady-state conditions. For all these reasons, DOL starting-up is not at all recommended for motors above 3 kW. An improved version of the DOL method, which is exploited in larger power motors, is that of the “Wye/Delta” (Y/D) starter. According to this method, initially the motor windings are connected in wye-connection resulting in smaller currents –but lower electromagnetic torque, too-, while as soon as steady-state speed has been reached, the winding connection changes into delta. It is worth noting that neither the Y/D starter, is not easily applicable to high power motors, either [1-3].

B. Starting-up via autotransformer

In this case, the motor starts-up via the intervention of an autotransformer connected in series to the motor with its power supply. The autotransformer ratio is adjusted by an on-load tap-changing mechanism offering, at starting-up a higher current capacity. This is achieved by connecting the motor on the auto-transformer secondary side, i.e. at a lower voltage level. As soon as the motor has reached its nominal operation speed, the tap changer resumes to the 1:1 ratio of the autotransformer, or alternatively a changeover switch completely by-passes the entire autotransformer. Anyhow, the main problem of this approach is that, the high-valued starting current entails a large voltage drop at the autotransformer impedance, worsening even further the voltage dip problem, which in turn delays even longer the motor to reach steady-state. Thus, for the same motor as before, starting-up time has increased by 450% compared to DOL (Fig. 3 and 4).
C. Starting-up via Autotransformer and Capacitor

The problems during starting-up via an autotransformer can be alleviated by installing an additional reactive power source i.e. a capacitor bank close to the motor. It is recommended that the capacitor rating is approximately 30% of the motor rated power[1]. In this way, steady-state is reached at almost the same time as DOL method (Fig. 5 and 6). It is worth noting that when steady-state is reached, towards 12 s, see Fig. 6, a current spike is observed in current waveform, due to autotransformer tap changing.

However, this solution is not appealing in terms of both cost and space requirements considering the two auxiliary components (autotransformer and capacitor) needed only during the critical period of starting-up.

D. Soft Starting via power electronic devices

This method, which is fairly new, is based on progressively increasing the output voltage of the generator in a linear manner by using power electronic devices – soft starters or power converters with soft starting capabilities. The proportional augmentation of the voltage applied to the motor input, can be explicitly expressed as:

\[ V_{\text{rms}} = \begin{cases} 0, & \text{if } t < 0 \\ K_v t, & \text{if } t > 0 \end{cases} \]

(1)

where

- \( t \): motor starting-up time
- \( K_v \): voltage increment gradient

However, up-to-date soft starting devices although not space demanding nor noisy, are pretty costly especially in the case of high power applications, while due to their power electronic switching, power supply quality problems due to harmonic pollution can be emerged [2].

E. AVR Soft-Starting

This method has been initially introduced in a previous paper [1] and can only be applied in cases of a motor supplied by a dedicated generator [2]. More specifically, the method is based on progressively increasing the output voltage of the dedicated generator, in a manner similar to the one soft starting devices do. This proportional augmentation of generator voltage is achieved by properly controlling its AVR. However, this procedure has to be carefully initiated, as two factors have to be taken into account:
• The voltage output has to start by a non-zero value, $V_o$, so that no voltage collapse occurs. $V_o$ is recommended to be in the order of 30% of the rated voltage [1-2].
• A de-magnetisation procedure has to be done first, so that no remanence flux in the airgap spoils the initialisation of the AVR.

AVR technology, nowadays offers solutions readily available to both difficulties. Thus, the generator rms terminal voltage, $V_{rms}$ can be set during the motor starting-up as a ramp-like time expression:

$$
V_{rms} = \begin{cases} 
0, & \text{if } t<0 \\
V_o + K_v t, & \text{if } t>0
\end{cases}
$$

where
- $t$: motor starting-up time
- $V_o$: initial rms terminal voltage
- $K_v$: voltage increment gradient

i.e. slightly different from (1), only in terms of $V_o$.

In contrast to the other methods, which focus on modifying the power supply to the motor, AVR-soft-starting refers to the power produced by the generator. In motor thruster case studies, the dedicated generator is often a shaft generator which can be programmed as described above [1-2]. In limited applications, though, the dedicated generator can be a conventional generator intentionally de-synchronized from the parallel operation of all the others, so that AVR soft starting is performed. AVR-soft-starting is also more favourable in terms of cost and space savings than using soft starters [2]. Regarding duration of starting-up, this can be adjusted to be within acceptable time limits, namely less than 50 sec, see Fig. 7.

Figure 7. Speed building-up during starting-up of a 1.0 MW induction motor via AVR-soft starting-up

III. STARTING – UP OF THRUSTERS DRIVEN BY INDUCTION MOTORS

Taking into consideration the alternative starting-up methods of induction motors, two major alternative configurations are used for starting-up an electric driven thrusters unit.

On the one hand, the combination of a squirrel cage induction motor along with controllable pitch propeller is used. Initially the pitch is set to 0, so that the total inertia and consequently the inrush phenomenon is as minimum as possible during starting-up. Moreover, manoeuvring is attained via varying only the propeller pitch, without resorting to repetitive starting-up, which, as a matter of fact is not easily allowed by the manufacturers, as it leads to temporary equipment over-heating.

On the other hand, the second configuration comprises a wound rotor induction motor along with variable resistors and a fixed pitch propeller. As already mentioned, in this case, the inrush phenomenon due to the transient current is mild (the current is controlled so that its rated value is not exceeded). Furthermore, in this case with fixed pitch, manoeuvring is performed via consecutive starting and stopping the motor; as starting current does not exceed its rated value, no over-heating is endangered.

IV. RELEVANT STANDARDS

Several Power Supply Quality related issues emerged with the extensive electrification of most ship systems and the advent of All Electric Ship concept have not been incorporated yet into standards, at least in a clear manner as pointed out in [7]. The problems during thruster starting-up can be included in this category, too as explained in the following.

More specifically, the phenomenon of large power motor starting-up, seen as a voltage dip, is partially covered by the standardized limits of transient voltage fluctuations, i.e. the maximum permissible voltage dip along its corresponding duration within a fundamental period, see Table I. Considering that the most significant problem caused by the thruster motor starting-up is the voltage dip, provoking malfunction to a series of other equipment, the related standards are a fairly good starting point of discussion. Almost all standards set limits on these transient voltage fluctuations (maximum tolerance with respect to the rated value as well as maximum duration).

Thus, according to [8]: “A voltage transient is a sudden but temporary change in the peak amplitude of the voltage, which exceeds the user voltage tolerance limits. Typical time duration for voltage transients is between a fraction of a cycle and 2 seconds for both 60Hz and 400Hz systems. Transients are usually the result of changes in load. The reaction of the prime mover, alternator and associated controls to that change defines the recovery time. Voltage recovery times can be shorter than the original disturbance that caused the transient. A typical example of this, is voltage recovery during the start of a large motor load.”

According to this approach, no restrictions on the transient peak load current, neither on the corresponding power demands (in terms of active and reactive power) are cited.
On the other hand, compliance with these voltage norms is verified as described in the following [8]: “when the generator is running at no load, at nominal voltage, and the specified sudden load is switched on, the instantaneous voltage drop at the generator terminals shall not be more than 15% of the generator's nominal voltage. The generator voltage shall be restored to within ±3% of the rated voltage within 1.5 sec. Concerning the sudden load applied, although not officially written it is 60% of the generator capacity.”

<table>
<thead>
<tr>
<th>Standard/rule</th>
<th>VOLTAGE TRANSIENT*</th>
<th>VOLTAGE SPIKE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS (2005)</td>
<td>±20% (1.5s)</td>
<td>No</td>
</tr>
<tr>
<td>BV (2003)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DNV (2001)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRS (2002)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RINA (2005)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LRS (2001)</td>
<td>+20%, -15% (1.5s)</td>
<td>No</td>
</tr>
<tr>
<td>IEEE 45-1998</td>
<td>±12% (2s)</td>
<td>±2500V (380V – 600V)</td>
</tr>
<tr>
<td>STANAG 1008 (Ed.9), USA MIL-Std-1399</td>
<td>±16% (2s)</td>
<td>2.5kV, 440V</td>
</tr>
<tr>
<td></td>
<td>[±22% (2s)]</td>
<td>1kV, 115V</td>
</tr>
<tr>
<td></td>
<td>18-35V, 24Vdc</td>
<td>0.6kV, 24Vdc</td>
</tr>
</tbody>
</table>

* Permissible transient frequency variation is ±10% (5s) in all rules

After the authors’ suggestion, the best choice of “a sudden load” for assessing this generator set transient response would be the thruster electric motor, considering that in most cases, this is the largest motor installed onboard, being of equivalent capacity to that of the ship generators. Furthermore, taking also into account that the starting-up procedure (followed by a corresponding stopping) could be repeated more than once during manoeuvring operation, it can be argued that this “thruster” operation has a behaviour resembling that of a pulsed load. This is further discussed in the following section.

B. The thruster as a pulsed – load. Standardization issues

A pulsed load is “a repetitive random or cyclic load that imposes time-varying power requirements on the system that result in amplitude modulation in voltage and frequency” [9,10]. Although, the term refers either to certain navigation systems (e.g. sonars or radars) or to sophisticated weapon systems, its definition as mentioned above does not exclude any other load with the features noted (i.e. “repetitive high power”). Hence, the occasionally repetitive starting-up procedure of a thruster motor, can be considered to be a specific-type pulsed load. Moreover, the resemblance is improved considering that like the other pulsed loads [9,10], thruster motors are supplied via auxiliary power interface units, see section II, so that the related power quality problems are minimized.

Nevertheless, what is important is that for this type of loads there are certain standards, which can be used as the grounds for further discussion. Therefore, a brief citation of the standards on pulsed loads is made, followed by a case study. Thus, it is stipulated that “Pulsed loads should not exceed the limits specified in the equations below since that will cause voltage and frequency modulations exceeding the limits of this power supply standard. If such a load can not be avoided, the power supply design authority is to be consulted so corrective action can be determined.” [9,10], see also Fig. 12:

\[
P_{\text{pulse}} < 0.25 \times S_{\text{supply}} \quad \text{and} \quad Q_{\text{pulse}} < 0.065 \times S_{\text{supply}}
\]

(3)

where \( P_{\text{pulse}}, Q_{\text{pulse}} \) = active, reactive power of the pulsed load respectively, while \( S_{\text{supply}} = \) full rated apparent power of the supply during pulsed load operation.
Limitations of equation (3) are set, so that the variations of voltage and frequency are well confined within the following modulation limits:

\[
\Delta \frac{V}{V_{\text{nominal}}} \leq \pm 2.5\% \quad \text{and} \quad \Delta f/\Delta f_{\text{nominal}} \leq \pm 0.5\% \quad (4)
\]

which, are stricter than the transient fluctuations tabulated in Table I, as they refer to the quasi-steady-state modulation phenomenon.

If the thruster motor is to be considered a pulsed load, it is more appropriate to consider \(P_{\text{Pulse}}\) and \(Q_{\text{Pulse}}\) equal to its transient power demands. Depending on the configuration discussed in section II, this could be either several times the rated values (in case of squirrel cage rotor with single starting-up followed by propeller pitch variations [3]) or almost equal to the rated thruster motor power (in case of the wound rotor, where repetitive starting-up during maneuvering occurs). From the power generation point of view, the generator sets must have the capacity to meet the motor demands withstanding any related problems e.g. frequency or voltage stability problems.

V. CASE STUDIES

The rules discussed above, regarding a thruster as a pulsed load, have been examined in two different case studies obtained from actual ship cases, namely:

A. A Car/passenger ferry with a bow-thruster motor of 1.0 MW/440V (power factor=0.9 inductive), of squirrel cage type, supplied by a dedicated shaft generator 1.4 MVA/440V.

B. An LNG carrier with a bow-thruster motor of 1875 kW/6.6 kV (power factor=0.8 inductive), of squirrel cage type, supplied by two synchronized steam- and one stand-by generator of 4312.5 kVA/6.6 kV each.

In both study cases, power quality problems during starting-up have been noticed and alternative schemes have been investigated. These alternatives include combinations of power generators, supplying the thruster motors, as well as the auxiliary starting-up interfaces, so that the adversity of the related power quality problems is alleviated. In all cases, the criteria set in equation (3) for both the transient and steady-state (i.e. rated) power demands of the thruster motors have been used. All simulations are performed in PSCAD computer program.

More specifically, concerning case study A, in Figure 13, a representative comparison among several starting methods is made.

In this case study, four alternative power starting-up interfaces have been considered for investigation, namely:

A1. Direct On Line case, which evidently could not be applied considering the motor rated power,

A2. Power Supply via an autotransformer with two-step tap changer,

A3. Power supply via the combination of an autotransformer with a capacitor bank,

A4. The dedicated shaft generator operates in AVR-soft starting mode.

In Table II the thruster power demands with respect to the operating generators rated capacity, are presented in two different columns. In the first column, the worst power demands at (nominal) steady-state conditions, i.e. rated motor power along with any interface power supply (i.e. capacitor) is compared to the rated generator power. In the second column, the corresponding transient power demands of the thruster, as obtained from the simulations, are presented. The inappropriate selection of the generator capacity is emerged in all sub-cases, regardless if interest is focused on steady-state rated values of the thruster or transient-state ones. The limits of equation (3) are exceeded; hence the grid suffers from a significant voltage dip, which the generator can not compensate. On the other hand, the motor succeeds in starting up only in sub-cases A3 and A4. In particular, sub-case A2 is proven marginally unsuccessful, as the motor reaches its nominal speed slightly after 48 s, see Figure 13f, i.e. when its thermal limits have been exceeded and the over-current relay should trip [1]. In contrast, sub-case A4, is marginally successful from the motor thermal limits point of view.

Regarding case study B, seven alternative combinations of synchronized generators (modeled with their complete dynamic model along with their speed governors and AVR’s), as well as starting-up interfaces have been considered:

B1: One steam turbine generator 4312.5 kVA, along with an autotransformer with two-step tap changer,

B2: Two steam turbine generators (2x4312.5 kVA), along with an autotransformer with two-step tap changer,

B3i: Two steam turbine generators (2x4312.5 kVA), along with an autotransformer with three-scale tap changer,

B3ii: Two steam turbine generators, along with autotransformer with two-step tap changer and a capacitor of 500 kVar,

B3iii: Two steam turbine generators 2x4312.5 kVA, along with an autotransformer with three-step tap changer and a capacitor of 300 kVar,
The electric motor does not succeed in starting rotating as the generator is not capable of providing the energy required. The exact power demands of the motor are determined by considering the generator to be ideal sources in the simulations.
### Table III. Case study B (LNG-carrier)) (figures underlined exceed the limits of equation (3))

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Nominal Power Demands from the Generator(s) (Motor Rated Values: 1875 kW, 1406.25 kVAR)</th>
<th>Transient State Demands from the Generator(s) (Starting-up Motor Demands: 3.45 MW, 2.588 MVAr)</th>
<th>Minimum Voltage and Voltage Dip at Generator Terminals (in % of Rated Value)</th>
<th>Minimum Frequency and Maximum Frequency Dip (in % of Rated Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1: 1 steam-turbine generator 4312.5 kVA + autotransformer with 2-step tap changer (unsuccessful)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Active Power $P_{\text{thruster}}$ /Supply</td>
<td>Reactive Power $Q_{\text{thruster}}$ /Supply</td>
<td>Active Power $P_{\text{thruster}}$ /Supply</td>
<td>Reactive Power $Q_{\text{thruster}}$ /Supply</td>
</tr>
<tr>
<td>B2: 2 steam-turbine generators 2x4312.5 kVA + autotransformer with 2-step tap changer</td>
<td>43.48% &gt; 25%</td>
<td>32.61% &gt; 6.5%</td>
<td>80% &gt; 25%*</td>
<td>60% &gt; 6.5%*</td>
</tr>
<tr>
<td>B3: 2 steam-turbine generators 2x4312.5 kVA + autotransformer with 3-step tap changer</td>
<td>21.73%</td>
<td>16.30% &gt; 6.5%</td>
<td>7.54%</td>
<td>20.29% &gt; 6.5%</td>
</tr>
<tr>
<td>B3i: 2 steam-turbine generators 2x4312.5 kVA + autotransformer with 2-step tap changer + capacitor 500 kVAR</td>
<td>21.73%</td>
<td>10.50% &gt; 6.5%</td>
<td>8.12%</td>
<td>18.55% &gt; 6.5%</td>
</tr>
<tr>
<td>B3ii: 2 steam-turbine generators 2x4312.5 kVA + autotransformer with 3-step tap changer + capacitor 300 kVAR</td>
<td>21.73%</td>
<td>12.80% &gt; 6.5%</td>
<td>5.22%</td>
<td>13.33% &gt; 6.5%</td>
</tr>
<tr>
<td>B3iii: 2 steam-turbine generators 2x4312.5 kVA + autotransformer with 2-step tap changer + capacitor 300 kVAR</td>
<td>21.73%</td>
<td>12.80% &gt; 6.5%</td>
<td>8.12%</td>
<td>19.36% &gt; 6.5%</td>
</tr>
<tr>
<td>B3iv: 2 steam-turbine generators 2x4312.5 kVA + autotransformer with 2-step tap changer + capacitor 300 kVAR</td>
<td>21.73%</td>
<td>10.86% &gt; 6.5%</td>
<td>5.02%</td>
<td>15.30% &gt; 6.5%</td>
</tr>
</tbody>
</table>

* The electric motor does not succeed in starting rotating as the generator is not capable of providing the energy required. The exact power demands of the motor are determined by considering the generators to be ideal sources in the simulations.

**B3iv:** Two steam turbine generators 2x4312.5 kVA, along with an autotransformer with two-step tap changer and a capacitor of 300 kVAR.

**B4:** Two steam turbine generators synchronized and one stand-by generator (3x4312.5 kVA) along with an autotransformer with two-step tap changer. The stand-by unit is to be synchronized prior to thruster starting-up.

The corresponding simulation results are tabulated in Table III. Like in case A, the first column includes the comparison of rated power demands of the thruster system along with any capacitor power supply with respect to the operating generator apparent power. The second column presents the corresponding transient power demands of the thruster motor, as provided by the simulations. The last two columns correspond to the worst voltage and frequency dips occurred during the starting-up procedure; they are measured at the main generator bus-bar.

It can be seen, that like in case A, even if the rated power of the thruster is used, the problematic operation is deduced. Therefore, in all cases, where divergences of power demands from the limits of equation (3) are noticed, significant voltage and frequency dips occur. With the exception of sub-case B1, where the thruster motor fails to start-up due to insufficient power redundancy on behalf of the (only in this sub-case) generator, the active power restriction is met in all cases, whereas the reactive power one is not. Hence, it is plausible to argue that numerical
limits in equation (3) need some reconsideration. Further, the limits of voltage and frequency dips in (4) are, in certain cases, but not the limits of Table I. It is also noted that the ratios of thruster power demands over the supplying generator rated capacity, can be used as classification indices, indicating how effective each alternative solution is. Considering that the optimum solution is the one resulting in minimum values of voltage and frequency dips, several combinations between the transient power demands are sought, see Table IV. Thus, in Table IV, it is proven that ranking according to the “sum” or the “product” of transient power demands coincides with that of the dips. It is underlined, that while these transient power demands of the thruster motors are provided by their manufacturer [3], the dips are assessed via simulations of the entire ship grid operation.

Regarding the alternatives investigated, further conclusions can be drawn. Thus, power redundancy does not necessarily lead to the optimum solution. More specifically, synchronizing an extra generator (sub-case B4) can be less favorable solution than that of the combination of two generators along with an auto-transformer with 3-step tap changer (sub-cases B3i and B3ii). Similarly, an alternative with a large capacitor bank, besides being more expensive and more space demanding, can be less appealing than a combination of an autotransformer with increased step number in its tap changer along with a smaller capacitor unit (sub-case B3iii versus B3ii).

VI. CONCLUSIONS

This paper deals with highlighting the significance of the maneuvering thruster start-ups in the electric power quality of the entire ship grid. It is further shown, that the existing standardization status is not sufficient and has to be improved. This argumentation is enriched by presenting the analysis results of two actual ship case studies with troublesome thruster operation, namely a car-passerger ferry and an LNG carrier.

Thus, the authors, on the one hand, recommend that the voltage-transient recovery test of the generators is performed by considering a thruster start-up to be the sudden-load specified by the standards.

On the other hand, it is recommended to exploit the experience on pulsed loads standardization, where numerical limits of the load power demands with respect to supplying generator capacity exist. These power ratios compared to the corresponding limits can be used as a means of qualitative assessment that a problematic operation of the entire grid is expected. Although, it is shown that thruster units and pulsed loads have similarities, and, hence these limits could be the same, still their numerical values could be modified to thruster units.

Moreover, the ratios of the load power demands with respect to supplying generator capacity could be used as an index for quantitative evaluation of the adverse effect the thruster load provokes on the normal operating condition of the ship grid. Through this approach, alternative power supplying schemes could be evaluated and compared, too.

VII. ACKNOWLEDGEMENTS

The authors wish to express their gratitude towards MARANGAS MARITIME Inc. and its personnel for their valuable assistance offered during this work in many ways. But for their help, this work would not have been accomplished.

VIII. REFERENCES


Table IV. Classification of alternative starting-up methods

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Cases</th>
<th>Active Power Pthruster /Supply</th>
<th>Reactive power Qthruster /Supply</th>
<th>(Pthruster /Supply) + (Qthruster /Supply)</th>
<th>Voltage Dip DV</th>
<th>Frequency Dip DF</th>
</tr>
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<td>1</td>
<td>B3ii</td>
<td>5.22%</td>
<td>13.33%</td>
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<td>5.30%</td>
</tr>
<tr>
<td>2</td>
<td>B3i</td>
<td>5.10%</td>
<td>14.26%</td>
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<tr>
<td>3</td>
<td>B4</td>
<td>5.02%</td>
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<td>B3ii</td>
<td>8.12%</td>
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<td>7</td>
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<td>140.00%</td>
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