Facing safety challenges towards smart ships and ports

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Synopsis

Following the global concern and IMO directives, in particular for greener shipping, ships and ports tend to become more efficient in terms of environmental friendliness, energy consumption as well as services provided. This paper deals with facing the challenges emerged within this framework, as in the ship case, certain retrofitting works have to take place onboard a ship such as the installation of water ballast treatment systems, scrubbers, cold-ironing facilities, and LED lights. The paper discusses the necessity to perform a number of studies (e.g. harmonic distortion, short-circuit, arc-flash etc) so that major safety requirements are met, while on the other hand, the electric energy system has to be tuned to a significant extent so that it operates in an optimum manner which is most often interpreted as minimum fuel consumption and emissions. Further, the paper makes a similar discussion for the case of the ports.

Keywords: green shipping; water ballast treatment system; scrubber units; LED lights; short-circuit study; arc-flash study

1. Introduction

The global concern and the directives of IMO and EU for greener shipping, has made ships but also ports to accomplish their missions in a more environmental friendly manner.

Within this framework, certain retrofitting works have to take place onboard a ship such as the installation of the following equipment:

- ballast water treatment system (BWTS)
- exhaust gas cleaning systems ('scrubbers') to reduce emissions
- ship-to-shore power supply (or "cold ironing")
- replacing illuminating lights by modern ones of LED technology

Besides any problems in acquiring the additional space onboard and accomplishing all safety requirements (ABS 2014, ABS 2017, DNV-GL 2014, Lloyd's 2015), from the energy point of view, these challenges consist

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in properly covering the increased electric energy demands either by introducing load shedding (via preferential trip settings) schedule, or by installing additional power sources such as deck generators. These amendments to the power generation and distribution sub-systems actually entail a course of actions related to risk and safety analysis of the refurbished energy system which in most cases refers to a series of electrical engineering studies:

- updating short-circuit calculation study (IEC61363, 1998) so that the settings of the protection selectivity among all circuit breakers including the new ones are in good co-ordination.
- performing arc-flash study (IEEE 1584, 2018) focused on the new switchboards supplying energy to the new equipment installed. The objective of such an assessment is to estimate the incident energy that would be released when employees work near live equipment, to determine the necessary type of personal protective equipment (PPE) to limit potential injuries to a treatable level (2^{nd} degree burn), as well as to propose engineering solutions for arc flash hazard reduction.
- performing harmonic distortion study (IACS, 2016) ; most of the new systems operate in association with power electronic converters attaining optimum torque vs speed control at minimized losses. However, these converters provoke harmonic distortion to current and voltage waveforms which can have adverse impact upon electronic equipment.
- upgrading the power management system in order to perform an integrated optimal control and scheduling of the energy flows in the power system of the ship.

Thus, the paper outlines the necessity for these studies to be performed so major safety requirements are met, while on the other hand, the electric energy system has to be tuned to a significant extent so that it operates in an optimum manner which is most often interpreted as minimum fuel consumption and emissions.

Moreover, it is also discussed that within the augmented concern for the minimization of the impact of the maritime transportation upon the environment, ports have to re-design their missions providing besides ship berthing other advanced services, too, like:

- electric energy supply to ships and reefers exploiting the smart-grid concept in combination with deployment of Renewable Energy Sources and Energy Storage Systems (Kanellos,2018),
- advanced cargo handling services via cranes and/or pumps with minimized energy consumption exploiting the re-generative techniques through power electronic converters (Prousalidis et al 2019),
- supervisory monitoring and control of all energy transactions (Prousalidis et al 2019).

2. Ship optimized performance devices

The aforementioned systems aiming at optimizing the total ship performance are briefly discussed next, concentrating on their energy demands

2.1 Ballast Water Treatment Systems (BWTS's)

Ballast water treatment systems have already been or on the way to be installed in most ships like bulk carriers or tankers in an effort to minimize the adverse biological and environmental effects of mixing waters of different seas by neutralizing all living organisms within ballast water.

These systems comprise pumping and processing units that besides special arrangements onboard in terms of piping etc, introduce demands for extra energy supply from the electric generators. Considering that the additional energy amounts required are on the order of 50 up to 600 kW it is yielded that the 'as-built' generator operation plan, does not, quite often, suffice. Furthermore, most BWTS's are designed to operate during "cargo handling" operating mode and perhaps maneuvering, whereas their operation is not, in many cases, included within the "sea going" or the "anchoring in port" operating mode which provides some flexibility in scheduling the operation of generators. There is a limited number of alternatives to overcome this problem, namely:

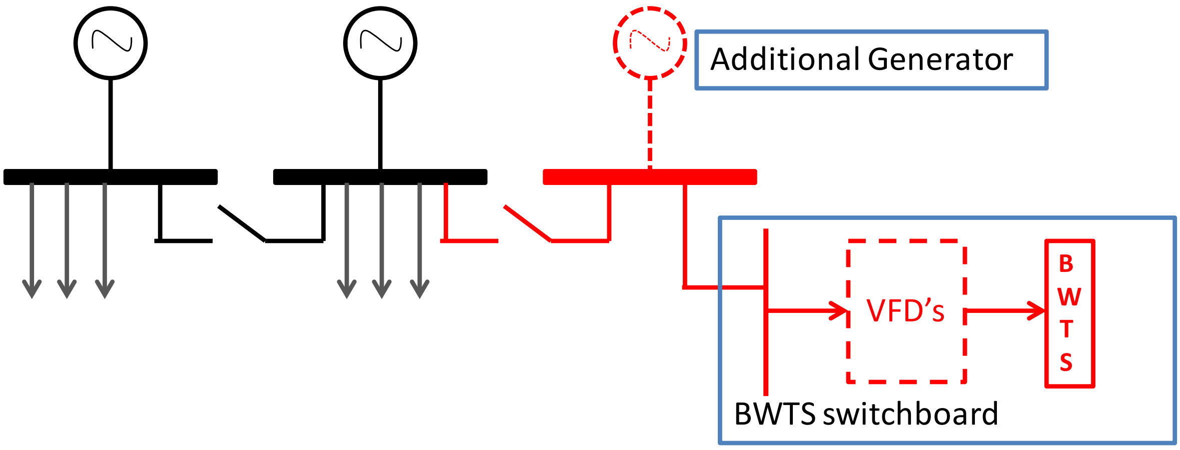

Figure 1: Retrofitted energy system to supply the BWTS *(retrofits in red, options in dashed lines)*

- Reconsidering the generator operation scheme (concentrating on the "sailing at sea" mode) by
  - Engaging any "stand-by" generator to participate in load sharing
  - Re-programming the 'preferential trip' schedule (only specific combinations of groups of loads are allowed to operate simultaneously according to a predefined scheme of interlocks)
- Installing additional generator (an additional generator is installed onboard, in most cases, due to space limitations, on the upper deck of the ship)

In an attempt to minimize the power demands of BWTS's the motor driven equipment are accompanied by Variable Frequency Drives (VFD's) which are supposed to decrease operation losses and increase efficiency. However the introduction of this interface provokes harmonic distortion; for instance, the harmonic spectrum of the converter input current both when motor runs and when it does not with the former being significantly greater than the latter, Fig.2. Moreover, small valued even ordered harmonics can be also noticed, which are mainly attributed to the internal DC link of the power converter and perhaps, to associated filter at the VFD input. An additional consideration is related to the harmonic voltage drop in the distribution power cables. More specifically, the necessary cabling of these systems could be fairly long, especially if specific cable routes have to be followed to minimize the safety risks. The longer the cabling, the greatest its impedance is and the greatest the (harmonic) voltage drop due to the highly distorted current of the VFD, while there are severe restrictions regarding the cable cross sectional areas that can penetrate in existing cable trays. Furthermore, as it is discussed later, the existence of power converter can have a side-effect upon the short-circuit study, too.

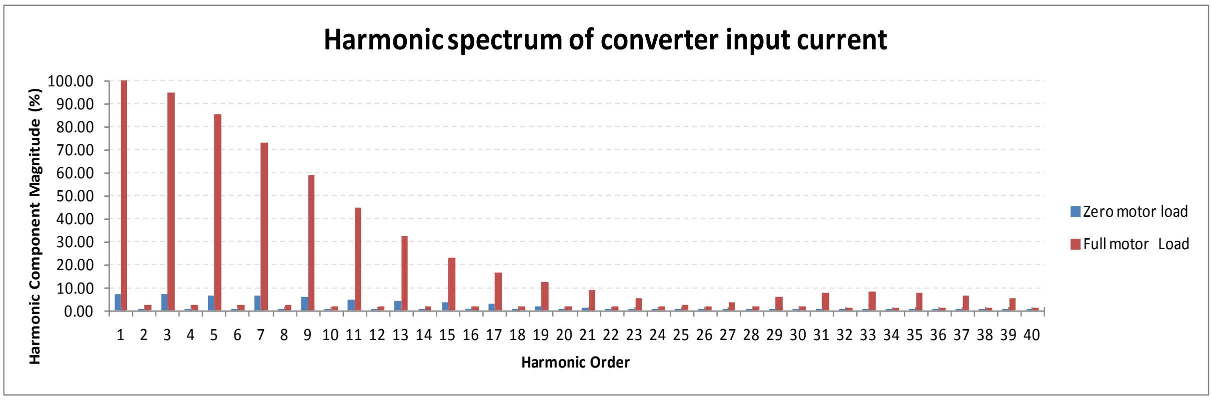

Figure 2. Harmonic spectrum of the input current of the power electronic converter motor supplying a motor. *(The fundamental component of the rated motor current is used as reference)*

2.2. Scrubber units

Following the directives of IMO and EU to decrease the atmospheric pollution provoked by maritime transportation, ships are being equipped with emission trapping units the most common of which are the scrubbers.

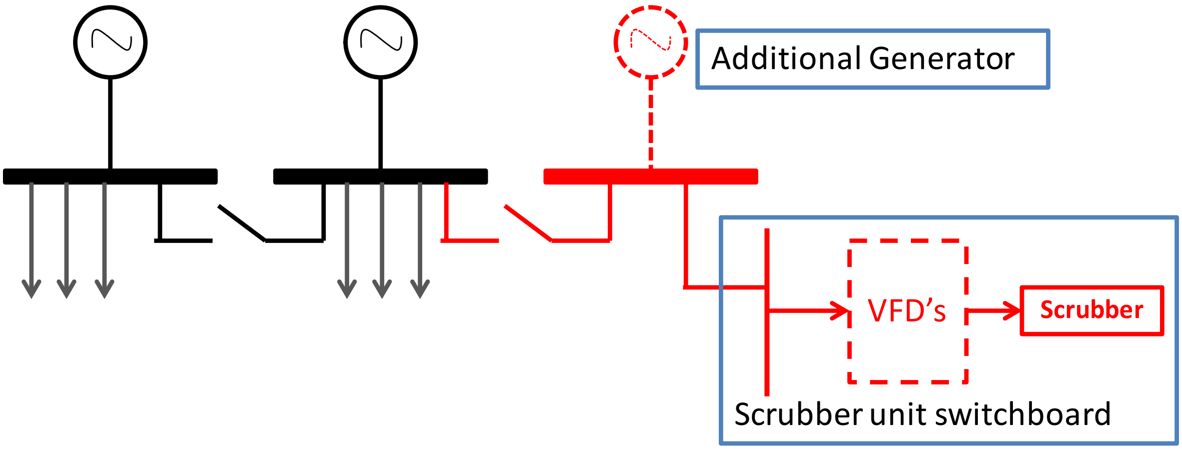

Figure 3: Retrofitted energy system to supply the scrubber unit *(retrofits in red, options in dashed lines)*

This retrofitting has some common points but also certain dissimilarities with the aforementioned one of BWTS's. More specifically, a scrubber unit comprises electromechanical equipment of a power demand varying between 100 and 500 kW, which, as deduced, cannot be easily covered by the existing ship generators unless, originally, they had been over-sized to a significant extent. Thus, in this case, too, there is a limited number of options to supersede the difficulty of the power supply problem of the new scrubber unit, with the installation of an additional generator being the most effective one, see Figure 3.

Of course, like in BWTS's, these power demands can be somehow decreased via the introduction of power electronic converters driving the electric motors engaged; all the side-effects related to the power converters (e.g. harmonic distortion, harmonic voltage drop etc) are valid in this case, too. On the other hand, unlike the BWTS's, the operation of scrubbers has to be on a more continuous basis, with some exceptions being in the port operating mode. Hence, it is concluded that power supply is by all means a very serious challenge that the retrofit engineering team has to face.

2.3 Ship to shore interconnection (Cold Ironing)

Cold ironing refers to complete shut-down of all ship engines (including generators) while at berth in ports and covering the electric power demands via a power interconnection with the mains of the port as supplied by the National Grid. It has been proven to be a most effective solution to eliminate the environmental footprint of ships in ports; the overall atmospheric solution is also reduced as the electricity of the National Grid is greener than that of ships as it is based on Renewable Energy Sources and more environmental friendly fuels like LNG.

It seems that investing in such a technology ship-owners tends to become eventually mandatory, considering that in certain ports like those in the State of California (USA) from 2021 all ships at berth must be in "cold-ironing" mode.

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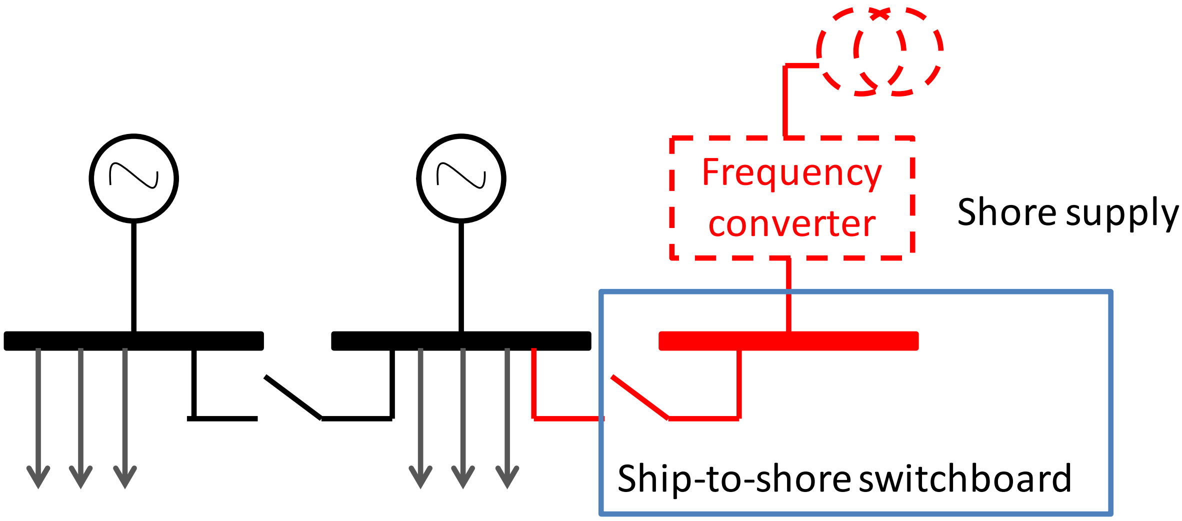

Figure 4: Retrofitted ship energy system for cold-ironing *(retrofits in red, options in dashed lines)*

This integration of ship-to-shore interconnection facility onboard a ship entails another retrofitting, this time in the existing shore-supply switchboard. The latter in most ships is designed to serve only during dry-docking providing electric power from shore to a complete dead ship, while of course in such an operating condition any synchronized operation of the ship generators with the port mains is meaningless. On the contrary, the new shore-to-ship switchboard must be treated as an "extra power supply" that can (and probably must) operate in synchronized mode with the ship generators so that no "black-out" during "switch-over from ship to port" takes place, see Figure 4. Moreover, the capacity of this switchboard must be able to meet all ship energy demands in "port operating" mode, e.g. hotel loads, galleys, accommodation, cargo handling, lighting, air conditioning etc which are, in general, greater than the dry-docking demands. Further implications both of technical and economical nature can be introduced if the power supply of the port is of different voltage and frequency compared to that of a ship. In this latter case, voltage transformers and frequency converters must escort the shore-switchboard retrofitting.

2.4 LED lights

LED technology has attained to provide lighting devices of high illuminating capacity but of low energy consumption. The latter actually refers only to active power demands and not the reactive ones which include among others harmonic distortion components. Thus, as it can be seen in Figure 5, where the measured harmonic spectrum of the current waveform absorbed by a representative LED bulb is depicted, the current has a significant distortion comprising odd-order harmonics which result in a THD equal to 172.2%. Moreover, while it is confirmed that the active power consumption is fairly low, the power factor is measured to be of very low value, too, being 0.478 inductive. This is reflected to high reactive and apparent power demands (being almost two times the active one), see Table 1.

Table 1: Indicative Power indices of a LED bulb *(Apparent power S is used as reference)*

Active Power	Reactive Power	Apparent Power	Power factor
P(%)	***Q(%)***	***S(%)***	***pf(-)***
47.80	87.8	100	0.478

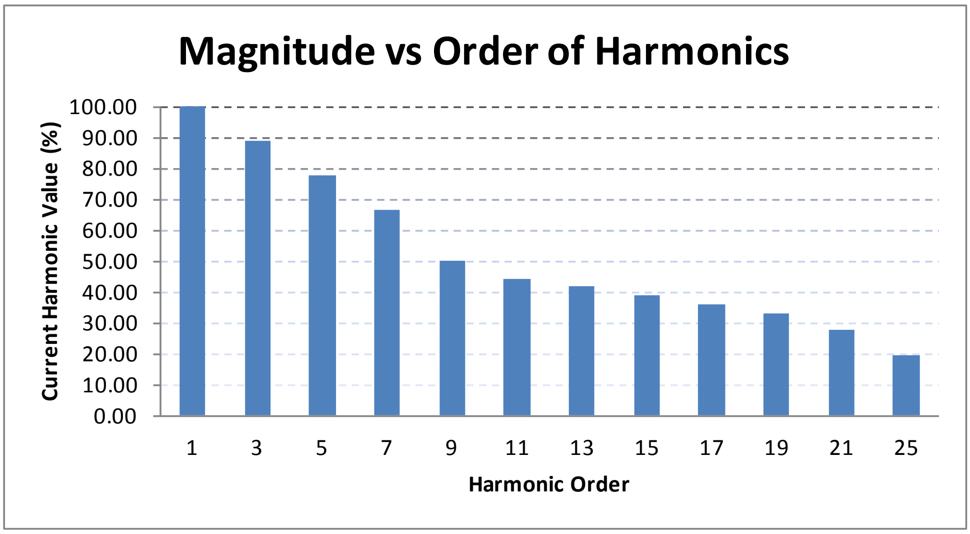

Figure 5. Harmonic spectrum of the current waveform of an energy saving LED light (THD=172.2%). Fundamental component is used as reference.

Hence, on the one hand, LED lighting is characterized by low energy demands in terms of active power, while on the other hand it introduces significant harmonic distortion which is translated into relatively high demands in terms of reactive and apparent power, as well as low (true) power factor.

Due to the small, in comparison with others, amounts of energy corresponding to lighting loads in most commercial ships, the aforementioned issue is not anticipated to provoke significant problems to the operation of most ship generators with the possible exception of cruise ships, where lighting is more predominant.

3. Additional electrical studies for ship electric energy systems

Considering the amendments discussed above and the implications introduced, the engineering team responsible must study thoroughly the retrofitted electric energy system. To this end, the following studies, namely:

- Short-circuit study
- Harmonic power flow analysis
- Arc flash study

help to assess better ship electric power system operation with the new devices. A brief description of these studies is made next.

3.1. Short circuit study

Short circuit study is performed in order to assess accurately the values of anticipated currents that will flow in case of a short –circuit. The values of these currents are used to rate the short-circuit breaking and making capacity of the circuit breakers, assess the forces that are developed during a short circuit, etc. According to standard IEC-61363 (IEC-61363-1, 1998) referring to short circuit analysis for ship electric networks, studying 3-phase short-circuits, which happen to be balanced faulted operating conditions, suffices providing results on the safe side.

As already mentioned, BWTS's and Scrubbers comprise motor driven equipment (mainly pumps) of fairly large capacity (well above 100 kW). The amendment in the entire electric grid due to these retrofits refers mainly to the installation of these rotating machinery which are considered active loads, and hence, according to IEC-61363 standard, they contribute to the short-circuits, and have to be considered in an updated short-circuit analysis. Moreover, according to the same standard, each motor of 100 kW and beyond must be modelled as a stand-alone piece of equipment.

The short-circuit currents calculated in this short-circuit study are also exploited in the arc-flash study which is required for the new switchboards as explained next.

It is worth noting however, that in the particular case, where the motors under discussion are driven by power electronic converters, then during a short-circuit fault, as pointed by IEC61363, *most probably* they are isolated and do not participate in the short –circuit. Hence, introducing a VFD can provide this additional benefit to the retrofit engineering team that the complexity of these motors and their VFD's do not contribute to the short circuit study. Still, a good argumentation based on the operation principle of the VFD would be required by the approval authority.

3.2. Harmonic power flow study

Currently, electric related standards for ship energy systems have rather vague limitations for harmonic distortion referring mainly to voltage one. More specifically, according to most classification rules, the THD of the voltage must not exceed 5% unless there are many power electronics converters installed where it can be up to 8%. Moreover, according to IACS/E24 rule, (IACS, 2016), the levels of harmonic distortion must be monitored on an annual basis. NATO's STANAG-1008, (STANAG-108, 2004) provides a rather more detailed description of the harmonic distortion problem setting limits for each harmonic of the voltage waveforms, while it stipulates that the harmonic power flow must be studied via simulations in dedicated computer packages (Hatzilau et al, 2002, Hatzilau et al, 2006, Prousalidis et al, 2003).

The calculated results of a harmonic load flow simulation consist of the active and reactive power flows in all distribution lines as well as the voltages in all buses. In order to perform such an analysis:

- All electric components of the ship energy system, e.g. distribution cables, transformers, generators, motors etc must be modelled via their harmonic models. It is substantial to model any existing filters (passive or active), too, (IEC 60092, 2016). In Appendix A, the harmonic impedance of most common components of ship electric networks are presented, in brief.
- The values of voltage and/or current harmonics of each separate component must be available (e.g. by VFD or LED light manufacturers, or by measurements) and be modelled most likely as harmonic voltage and/or current sources

Exploiting the results of harmonic analysis, besides assessing the harmonic distortion problem in the entire ship electric network, adverse consequences (e.g. false trippings, premature aging, failures, risen resonances) can be traced, too (Hatzilau et al, 2002, Hatzilau et al. 2006, Prousalidis et al 2003).

3.3. Arc-flash study

Arc flash is one of the most dangerous workplace hazards. Therefore, shipboard power system design and operation must take into consideration preventive and mitigating measures. In most cases, it is not practical to shut down electrical equipment to carry out field work. The objective of such an assessment is to estimate the incident energy that would be released when employees work on or near live equipment, to determine the necessary type of personal protective equipment (PPE) to limit potential injuries to a treatable level (2nd degree burn), as well as to propose engineering solutions for arc flash hazard reduction. Although available standards and regulations (OSHA, NFPA, IEEE) have been developed for the industrial sector, the majority of requirements is equally applicable to shipboard power systems.

The arc flash hazard analysis is a critical safety assessment for maintenance stuff. To perform such a study:

- Essential data should be collected, including electric network single-line diagram, power equipment electric characteristics, type of distribution boards, protective device types and settings, etc.
- The electric network model should be developed in appropriate power engineering simulation software.
- A short-circuit study should be carried out beforehand, to provide bolted fault currents at examined locations.

Based on IEEE 1584, the arcing fault current, the incident energy, and the arc flash protection boundary are calculated at each examined location. The arcing fault current flows through an electric arc plasma, also called fault resistance. The amount of energy impressed on a surface, at certain distance from the source, generated during an electric arc event is called incident energy. The arc flash boundary is an approach limit at a distance from exposed live parts, within which a person could receive a second-degree burn if an electrical arc flash were to occur.

Exploiting the above results and following the directions of NFPA 70E, proper personal protective equipment (PPE) is selected for personnel when live work is performed, warning labels are printed for each electrical equipment likely to require inspection, adjustment, maintenance or repair while energized, and solutions for arc flash hazard mitigation are proposed where the incident energy reaches extremely high values (> 40 cal/cm^2). The most common and practical incident energy reduction measures are the review of protection coordination throughout the electric network to reduce fault clearing time if possible, and the implementation of fast protection schemes (e.g. zone selective interlocking, bus differential protection, arc flash detection scheme). It is underlined that the safest approach is to avoid live work. This practice is strongly recommended whenever can be followed. However, it is not necessarily practical to shut down the process when field work has to be done.

4. New challenges in upgrading ports

Ports nowadays, being the transportation hubs, are also facing significant challenges in terms of providing innovative services of superior quality as well as high financial, environmental and societal impact. To this end, all ports tend to re-establish their strategic mission according to which they are subject to a transformation into smart energy hubs where electrification plays a key-role. In particular, the assets and services of the smart grid of a modern port can include, (Prousalidis et al 2019), see also Figure 6:

- *Cold Ironing facilities* supplying electricity to ships at berth
- *Reefer power supply* : reefers preserve their contents having high thermal inertia, which allows for non-continuous power supply with only short duty cycles
- *Port Lighting*: cutting edge LED technology provides high illumination services (of hot or cold like colors) at fairly low power demands
- *Cargo handling equipment:* mainly cranes and/or pumps with integrated regenerative braking capabilities have a low mean power demand on a daily basis as the lifting-down movements offset to a great extent the lifting-ups
- *Renewable energy sources*: Arrays of photo-voltaic cells (PV's) in possible combination with small scale wind-generators can be installed in appropriate areas (e.g. on top of buildings, in parking areas, etc) within the port jurisdiction producing green energy that can be consumed within the port or stored in batteries or directed to the main grid. Moreover, as wind potential is usually high in port extended areas port authorities can develop there offshore wind parks and integrate their operation with port electric system (Kanellos, 2017).
- *Energy storage systems*; mainly batteries which can be used either for buffering energy from any renewable energy sources installed in the port pr during off-peak hours or (bunkering and buffering)
- *Electric vehicle charging stations*: any electric vehicles either owned by the port authority and serving either internal transportation or belonging to travelers who park and charge simultaneously their electric vehicles in the parking areas of the port

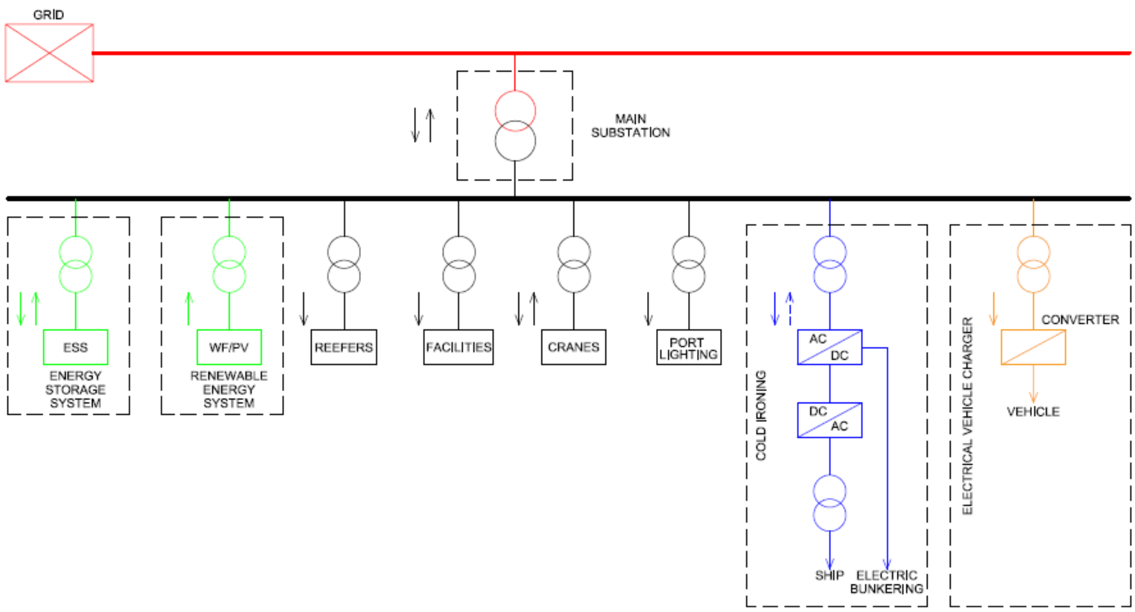

Figure 6. Power Distribution network of a modern port with bi-directional power flows

As all electro-mechanical equipment to be installed in the port jurisdiction is subject to the near-by hostile sea environment, it has to be of marine type, of increased Ingress Protection (IP)-level, i.e. referring to protection against dust and humidity, flame-retardancy etc.

Moreover, considering that the operation of most equipment engages the operation of power electronic converters (cranes, cold ironing, electric vehicles, RES's, ESS's, LED lights) enabling also bi-directional energy flow, the harmonic distortion problems in the port electric network can be significant.

Within this framework, all energy transactions in modern ports must be monitored and managed by a sophisticated energy management system of SCADA type with an integrated capability to supervise, control, protect and in the end bill the electric power flows within the port grid.

Thus, the port electric networks are subject to significant reformations an hence, certain studies similar to ship cases (i.e. short-circuit, harmonic power flow, arc-flash etc) have to be performed prior to any refurbishment.

5. Indicative Simulations - Calculations

Based on the discussion made above, some indicative case studies are presented next. Thus, Figure 7 presents the fault current for a three-phase fault at a 6.6 kV bus of an actual vessel before and after the installation of a 500 kW motor of a scrubber unit and a 150 kW motor operating for the water ballast treatment but not driven by VFDs. Furthermore, Table 3 shows the respective results of the arc-flash analysis performed with the PowerFactory software according to IEC 61363 and IEEE-1584. As can be observed, the two induction motors contribute to the short-circuit current for the first few cycles after the occurrence of the fault. This additional fault current and the associated energy released during an incident suffices to change the PPE category of the switchgear from 1 into 2.

Table 3: Arc-flash study for a 6.6 kV switchgear of an actual vessel

Quantity	Before the installation of BWTS and the scrubbers	After the installation of BWTS and the scrubbers
Arcing Current [kA]	6.049	6.184
Fault Clearing Time [s]	0.160	0.16
PPE category	1	2
Energy [J/cm2]	16.373	16.744
Working Distance [mm]	914	914
Flash Boundary [mm]	1654	1673

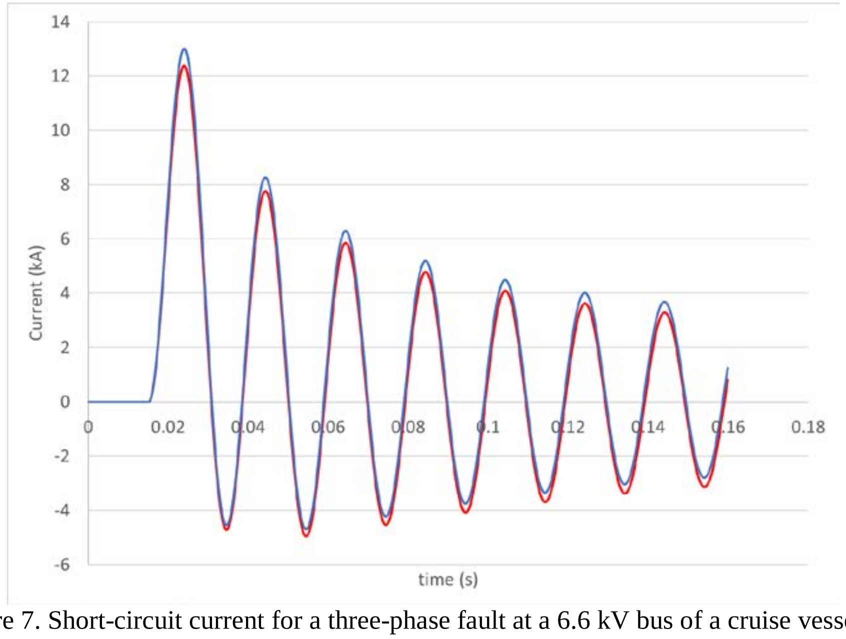

Figure 7. Short-circuit current for a three-phase fault at a 6.6 kV bus of a cruise vessel

On the other hand, as stated above, power electronic converters accompanying large induction motor can inject current harmonics in the vessel's power network. The total harmonic distortion (THD) of the input current of such a device directly depends on the operating point of the motor. Figure 8 presents the THD of the input current of a 500 kW induction motor driven by a VFD (comprising a diode rectifier in series with an inverter) as obtained by simulations via EMTP-RV software.

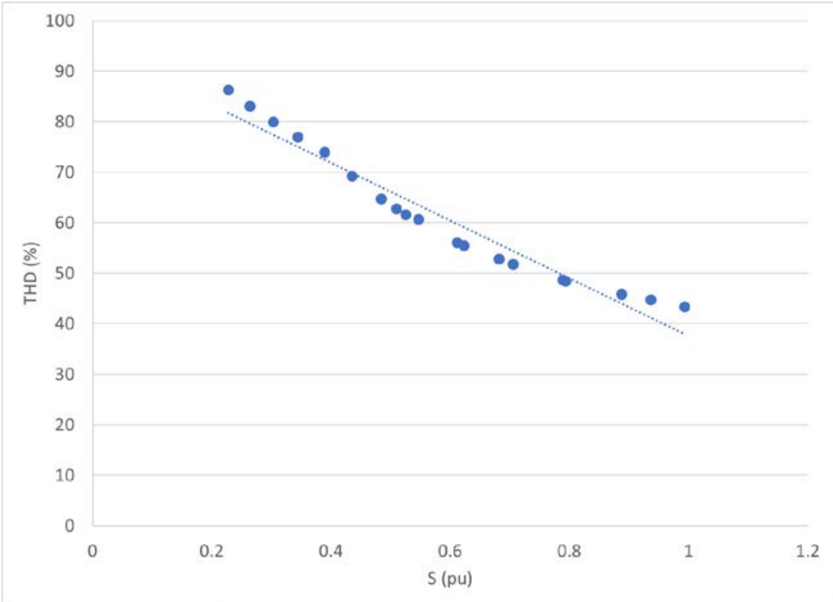

Figure 8. THD of the input current of a 500 kW induction motor driven by a diode rectifier VFD as a function of the operating power

Finally, Figure 9 shows the harmonic content of the current in a ship within 12 hours. In this case, the load consists of a 500 kW motor of the scrubber unit, a 150 kW motor for the water ballast treatment both driven by power electronic drives and 10 kW of LED lighting. The scrubber unit operates continually during the 12 hours while the BWTS is turned on and off 4 times and the LED lights are switched on after hour 6 operation. Both VFD's inject mainly 5th and 7th harmonic in the power network, while the LED light current contains all odd ordered harmonics in its spectrum.

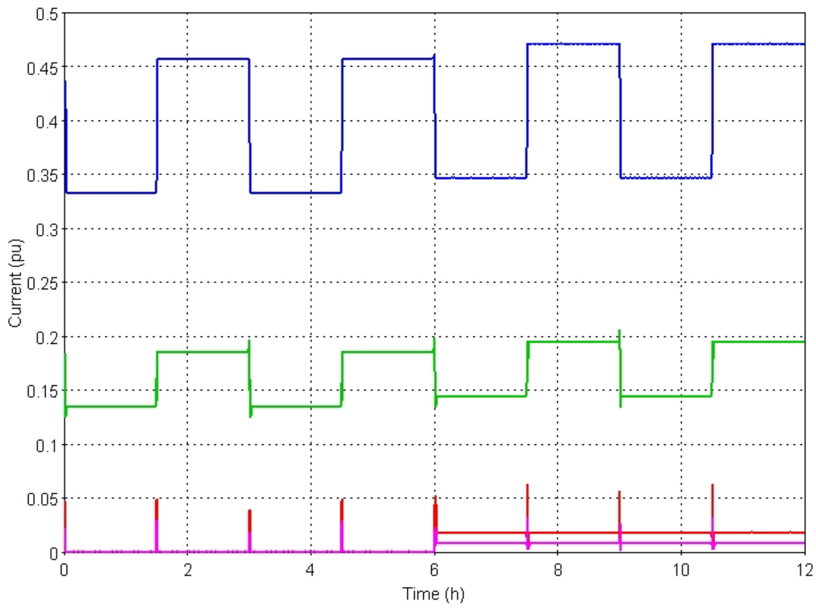

Figure 9. Harmonic content (red 3rd, blue 5th, green 7th, magenta 9th) of the current during 12 hours of a 500 kW scrubber motor, 150 kW water ballast motor and 10 kW LED lightning.

Thus, it is concluded that when the retrofitted motor equipment is accompanied by power electronic converters the latter on the one hand could eliminate any additional contribution of the additional electric motors to the short-circuit currents, and hence, no amendment to the PPE equipment against arc-flash is required, while, on the other hand, they introduce significant harmonic distortion, a rather serious power quality problem.

6. Conclusions

This paper deals with facing the challenges emerged when certain green shipping retrofitting works have to take place onboard a ship such as the installation of water ballast treatment systems, scrubbers, cold-ironing facilities, and LED lights. The paper discusses the necessity to perform a number of studies (e.g. harmonic distortion, short-circuit, arc-flash etc) so that major safety requirements are met, while on the other hand, the electric energy system has to be tuned to a significant extent so that it operates in an optimum manner which is most often interpreted as minimum fuel consumption and emissions. The discussion is enriched by indicative simulations showing that these retrofitting works can have some significant side-effects upon certain operating parameters of the ship electric network. It is also discussed that similar considerations must be performed in upgrading services provided by modern ports.

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Nomenclature

ABS	:	American Bureau of Shipping
BWTS	:	Ballast Water Treatment System
DNV-GL	:	Det Norkse Veritas – Germanischer Lloyd’s
ESS	:	Energy Storage System
EU	:	European Union
IACS	:	International Association of Classification societies
IEC	:	International Electrotechnical Com mittee
IEEE	:	Institute of Electrical and Electronic Engineers
IMO	:	International Maritime Organization
LED	:	Light Emitting Diode
P	:	Active Power
pf	:	Power Factor
PPE	:	Personal Protective Equipment
RES	:	Renewable Energy Sources
Q	:	Reactive Power
S	:	Apparent Power
SCADA	:	Supervisory, Control and Data Acquisition
THD	:	Total Harmonic Distortion
VFD	:	Variable Frequency Drive

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Appendix

Harmonic impedances of equipment at n-th order harmonic frequency are affected not only in terms of reactive components but also in terms of the resistive ones due to the skin effect. In particular (Whitelegg, 2016):

Harmonic impedance of cable

$$Z_n = \sqrt{n}(R + jX)$$

Harmonic impedance of transformer

$$Z_n = n(R + jX)$$

Harmonic impedance of synchronous generator

$$Z_n = \sqrt{n}R + jnX$$