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Physical Object-based Simulator of Ship's Electrical Power Plant and Its Application in MET Processes

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ABSTRACT: The paper deals with the analysis and practical verification of the possibilities of using the physical object-based simulator of the ship's electrical power plant for crew members MET (Maritime Education and Training) in the light of more and more demanding competencies. The analysis is based on experience gained from the operation of a new real ship power plant simulator built on the Faculty of Electrical Engineering at Gdynia Maritime University (FEE, GMU). Following the current curricula, this simulator is mainly used for ETO (Electro-Technical Officer) training. An important and worth emphasizing opportunity is to familiarize training participants with onboard challenges related to the safety operation and maintenance of a real electrical installation above 1kV.

1 INTRODUCTION

Maritime transport is common and, because of its relatively low costs, is developing dynamically. With technological progress, ships and other maritime objects are becoming increasingly complex, and therefore require a competent crew to operate them. Work on a ship can be divided into two complementary areas. One concerns the operation of technically efficient systems and devices which are often interconnected, and the other concerns maintaining their efficiency. Modern ships are of different types and are sometimes extremely complicated. Many newly built ships using the latest technologies, including electricity generation systems. One of the basic systems that are present on every type of ship is the power system, which provides the necessary electrical energy. The safety of navigation depends directly on its reliability. A painful example is the container ship m/v Dali, which, losing power due to a "blackout", caused a disaster in which several people died and the bridge in Baltimore was destroyed on March 26, 2024 [1].

The minimum competence of crew members, depending on their rank, is determined by the requirements specified in the IMO STCW 2010 convention [2]. They include competences in both the operation and maintenance of equipment in technical conditions. One of the elements of MET is the improvement of competences accepted by IMO regulations using various types of simulators. Currently, various types of technological solutions are used in the maritime education process to facilitate or support classes and enable them to consider various crises, starting with advanced navigation simulators (so-called mandatory simulators, in the STCW Code [2]), which fulfill perfectly their task. Simulators are increasingly being built for training ship engine operators. They are mentioned in the fundament of convention [2] in the part B-I/12 STCW code dedicated to the main and auxiliary machinery operation simulation, described as the recommended performance standard for non-mandatory types of simulation.

An example is the solution proposed by Texas A&M University in Galveston (USA) [3]. Similar solutions are available in other MET centres, which are based on complete computer simulation systems, where all push buttons, instrumentation and switches are virtual (touchscreen simulator), for example [4]. Another approach is the concept of building hybrid simulators, which include the use of real elements, such as control consoles, switchboards, in which only the front equipment corresponds to reality. An example is the ship engine simulator at the Faculty of Marine Engineering at GMU [5]. Yet another solution is that one important element of the system is real, and the remaining elements are in the area of computer simulation. An example is the Neptune System by Königsberg Maritime [6]. In this solution the simulator is dedicated to conducting courses for crew members on ships, and only one HV (high voltage) circuit breaker field is real and the rest of the system is in the virtual service area.

Another approach was maritime education based on real systems. One of the solutions dedicated to this problem were training ships, which were specially designed for this purpose. Historically, in Poland, special ships were used for this task in the 1980s, m/v Antoni Garnuszewski and m/s Kapitan Leduchowski. These ships fulfilled their role as merchant ships, but at the same time they were equipped with a so-called training ship engine room and a double bridge, one of which was a bridge used only for training purposes. On the other hand the training engine room was equipped with all the systems necessary for the operation of the ship, except for the main engine. It is worth emphasizing that this ship was equipped with high-voltage elements (3,3kV) such as a generator, loads and switchboard as part of the training power system. This solution allowed for good practical preparation not only of future navigating officers but also of mechanical and electrical officers. However, this model of education did not stand the test of time, especially in regarding to the engine crew, and as a consequence, practical education is based on currently available simulators and practice on ships. It should be noted that currently, in relation to ETO, apart from computer simulators, training is still based on physical stations where real operational problems related to the ship's electrical power system can be presented [7-10].

It is worth emphasizing the discussions on the use of virtual reality in simulators or the use of remote simulators located in the cloud and new challenges resulting from operating of future autonomous ships are continuosly developed [11].

Each solution has its advantages and disadvantages, but there is one common denominator, which is the purpose for which different types of simulators are used. The main purpose of simulators use is to prepare trainees as best as possible to operate ship systems and devices. However, as part of their duties, watchkeeping crew members not only operate the devices but are also responsible for maintaining them in good technical condition. In this case, despite the various virtual tools available, an important element of education is the contact of trainees with real devices. One of such positions in ship engines is the ETO, who rarely operates devices. However, its main task is to take care of the efficiency of devices in the broadest sense of the word electrical by conducting appropriate service, inspections and, in the event of damage, diagnostics and possibly repairs. Very often, ETO's start performing their tasks on devices that are already out of order. Therefore, ETO's need other competencies than just efficient service to perform their tasks. Often, in-depth knowledge is needed in relation to the construction and operating principles of systems and devices, not only electrical, but also mechanical, hydraulic, refrigeration or pneumatic, which are controlled by electrical systems (electronic or computer). The aforementioned preparation is difficult to implement based only on work with devices as part of internships on ships, especially in the field of electrical, electronic and control engineering. This mainly concerns the area of service, diagnostics and repairs. The minimum training requirements for ETO were specified only in the STCW 2010 convention [2], and they are mainly focused on defining competences in the field of maintaining the efficiency of electrical, electronic and control devices, including routine and ad hoc inspections and repairs. It should be remembered that the convention requirements also concern appropriate competencies in relation to the broadest sense of safety and environmental protection [12, 13].

It is worth noting that the STCW Convention defines minimum requirements and there are no formal obstacles to expanding the scope of competences within the curricula of individual MET units to meet new challenges resulting from technological development [14].

To meet new challenges and the specifics of ETO work, a physical simulator of a ship power plant was built at the GMU Faculty of Electrical Engineering. It is worth emphasizing that it can be a good supplement in the education of future marine engineers and navigators.

2 REAL ON BOARD JOB DESCRIPTION OF AN ELECTRO-TECHNICAL OFFICER

Work on a ship is significantly different from work on land. This translates into the selection of crew members not only in terms of substantive skills, but also a great deal of emphasis is placed on psychological, sociological, and health aspects. To evaluate the required competencies, it is not enough to consider the three functions and related 18 competencies in Table A-III-6 [2] but also we should to precise the relationship among them as well as some other factors being enclosed below. Three functions referred to the ETO operational level are: -Electrical, electronic, and control engineering at operational level (7 competencies); Maintenance and repair at operational level (5 competencies); -Controlling the operation of the ship and care for person on board at operational level (6 competencies).

At this point, it is worth noting that the STCW convention has a major inconvenience that applies to the entire document, in which the required educational and training tasks are given in tables without numerical references to the contents. This causes difficulties in developing detailed training programs.

In general, crew members must meet various challenges resulting from objective factors beyond their control. In the case of ETO, these include, among others (it should be emphasized that some of the factors listed below apply to all crew members)[15]:
- tendencies to limit the number of crews with the often increasing number and complexity of technical devices;
  - the result of this approach is a very frequent reduction of crew members responsible for electrical matters to one person, or one person operating several ships;
- in the case of a one-person crew, which is most often used, ETO must meet operational challenges without the direct possibility of consulting its substantive decisions;
- bureaucratic overgrowth expressed by a large number of reports;
- multilingual documentation;
- frequent changes of ship crews, much more frequent than employees in the land industry;
- full substantive availability upon embarkation, despite the fact that very often a given crew member is on a ship for the first time
- the impact of stress resulting from long-term separation from family and the need to be in the presence of random people;
- multinationality of crews
- difficult environmental conditions (tilts, vibrations, changes in temperature, humidity);
- required high reliability of equipment (safety of crew, environment, cargo);
- independence of the ship (no possibility of calling in external service at sea);
- the need for quick diagnosis and quick decision-making, resulting from the danger and variability of the situation at sea;

All this is superimposed on the general policy of many shipowners aimed at profit and thus looking for savings in the operating process on the costs of spare parts, maintenance, and repairs.

Considering the aforementioned and current technological requirements, the education and training process for ETO's at the level of minimum requirements defined in Tables A-III/6 and B-III/6 of the STCW convention is insufficient and it is reflected in much broader program proposals presented in the IMO 7.08 Electro-Technical Engineer [14] model course. However, it is worth mentioning here the need to return to the discussion on introducing the "Senior ETO" position at the management level to the STCW convention. An element of this discussion is the model course for ETOs and Senior ETOs developed within the IAMU (International Association of Maritime Universities) FY 2012 Research Project [16].

An inseparable element of maritime personnel education is internships, partly on ships. This also applies to ETO. It should be noted that during internships, the cadet does not have the opportunity to implement different variants of ship equipment operation. It should also be remembered that the quality of internships on ships may vary and depends on many objective and subjective factors. Hence, to guarantee minimum competences at FEE GMU, students are provided the opportunity to learn about the most realistic systems and situations occurring on ships, especially in relation to the electrical power system. This approach has been implemented since the 1980s.

3 STRUCTURE OF THE HISTORICAL SIMULATOR

The beginnings of maritime education in the electrical specialization on the FEE of GMU date back to 1954 [17]. From the beginning, great attention was paid to education based on modern devices and systems used in ship equipment. One of them was the first physical simulator of a ship power plant built, based on the main ship switchboard RG 103A type built in the 1980s. A simplified schematic diagram is presented in Figure 1. The model of the ship's power plant consists of the main switchboard RG 103A 400VAC 50Hz, located in the didactic room. The switchboard consists of individual generator fields, synchronization fields, and load fields. Three synchronous generators with a rated power of 27 kVA each, driven by 35 kW DC motors, are connected to the switchboard. The generators and the motors driving them were located in a separate room. The DC motor speed control system was built in such a way that it simulated the drive of a 4-stroke diesel engine (thyristor model of a combustion engine).

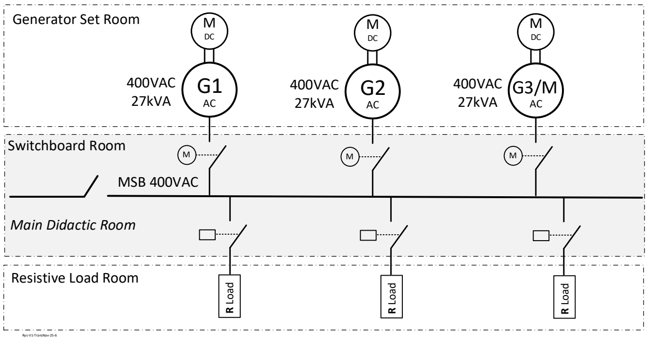

Figure 1. Simplified diagram of the historical simulator of a real ship power plant

The excitation current of the generators was controlled by thyristor voltage regulators of the TUR type and alternatively by a digital voltage regulator of the DECS200 type. Additionally, synchronous generator no. 3 had a system that allows it to be used as an inductive load as a separately excited motor. The main load was made up of power resistors located in an outdoor room that was well ventilated due to the heat released in the resistors. The power plant also had a Power TRAC network parameter monitoring system, as well as an automatic and remote control system for the power plant operation developed based on PLC (Programmable Logic Controller) [8][16]. The classes took place in the switchboard room, shown in Figure 2.

Figure 2. Historical didactic room with the main switchboard

The model built was limited to the cooperation of only three generators and a main switchboard with a voltage of 400V 50Hz. Over time, this constituted a significant limitation, hence the decision was made to build a new ship power plant simulator that would meet the challenges resulting from current technological progress.

4 STRUCTURE OF THE MODERN SIMULATOR POWER PLANT AND ITS APPLICATION

Based on the experience of operating the previous simulator and to meet the current challenges resulting from technological progress, the Department of Marine Electrical Power Engineering at GMU has built a new ship power plant simulator based on physical objects, which is a modern, autonomous electrical system characteristic of commercial seagoing ships. The electrical diagram of the simulator is shown in Figure 3. The individual parts of the simulator have been installed in four rooms. In the Generator Set Room (GSR) - there are units for generating electricity, together with the power supply and control system, as well as appropriate transformers. The simulator consists of four Generating Sets consisting of a synchronous generator 3x400 VAC, 50Hz with a rated power of 25 kVA driven by an asynchronous motor controlled by a Variable Speed Driver (VSD). The inverters are powered from the shore network, and this aspect has been omitted in the diagram in Figure 1 for simplicity. The control of the generators' rotational speed is carried out using VSD and this is a deviation from the real ship power plant, where generator sets usually consist of a synchronous generator driven by a combustion engine (auxiliary engine). The simulator is equipped with three generators, G1, G2 and G3/M, which can be used as an inductive load. An additional SG generator simulates a shaft generator. The generator room also contains High Voltage (HV) transformers such as TR1, TR2 3300 V/400V and Low Voltage (LV) TR3, TR4 400 V/230 V respectively. Additionally, this room contains a 10 kVA Emergency Generator Set. The general view of generators G1, G2, G3/M and SG is shown in Figure 4.

The electrical energy from the generator G1, G2, G3 and SG is sent to the appropriate main switchboards MSB 3x400 VAC 50 Hz located in a separate electric switchboard room (ESR), which is the main didactic place. The general view of MSB 3x400 VAC and 3x230 VAC placed in the ESR are presented in Figure 5.

The MSB 3x400 VAC, 50 Hz main switchboard consists of three sections. The first section can be connected to power from the G1 generator directly via the circuit breaker Br18, or indirectly via the HV switchboard and the circuit breaker Br 21.

The third important element of the simulator is the Resistive Load Room (RLR), located outside the building, where the power resistor units are placed. Each section is equipped with a set of resistors (R-Load), the values of which are appropriately switched on. This allows the load to be changed locally from the main switchboard MSB 400 remotely via Local Control Panel (LCP) located in a separate room C20.

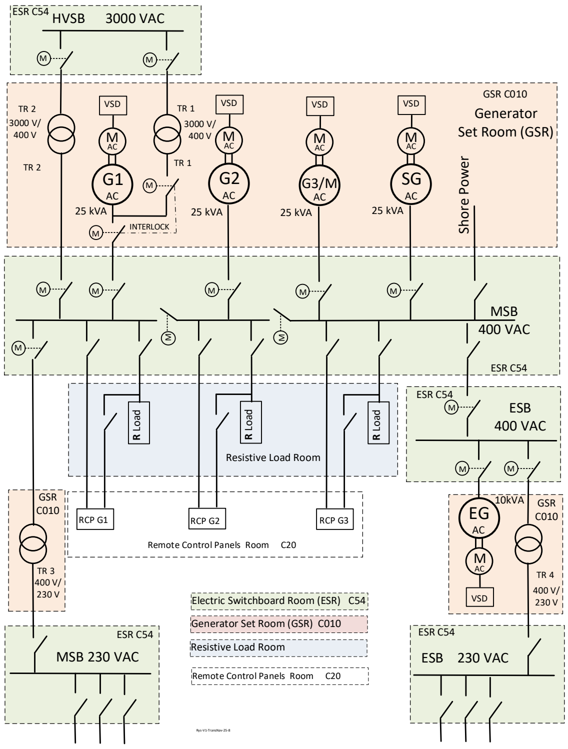

Figure 3. Simplified diagram of the modern simulator of a real ship power plant

Figure 4. Generator sets: G1, G2, G3/M and SG placed in GSR C010

Figure 5. Main switchboard 3x400 VAC and 3x230 VAC, 50Hz

Additionally, in order to obtain voltage above 1kV, two transformers 3x400 V/3x3,3 kV 50Hz were used, one of which TR 1 increases the voltage and supplies electrical energy to the High Voltage Switchboard HVSB 3x3 kV busbars, and the other TR 2 allows the HVSB 3x3,3 kV switchboard to be connected to the MSB 3x400 VAC switchboard. Additionally, two transformers were installed in the system to generate voltages of 3x400 V/3x230 V, 50Hz.

The individual generators supply power to the main low-voltage switchboard MSB 400 V/MSB 230 V, 50 Hz the emergency low-voltage switchboard ESB 400 V/ESB 230 V 50 Hz and the HV MSB 3300 V 50Hz switchboard.

Each generator is equipped with the PMS (Power Management System) system and is supervised by the EMOS 4 master monitoring and control system which gives opportunity for remote control of power plant This configuration allows the ship's power plant to be operated in the following modes:

– manual,
– semi-automatic,
– automatic,
– secure (manoeuvring),
– shaft (power supply from the shaft generator),
– with uneven power distribution.

It also allows the implementation of the following operating scenarios:

1. independent operation of individual generators G1, G2, G3, G4, G5 (individual);
2. synchronization and parallel operation of generators. Parallel operation of G1, G2 generators and use of G3 generator as a machine reactive inductive load;
3. synchronization of generators on the MSB3300V switchboard via 3300V/400V transformers;
4. operation of protection systems (switching off in the event of reverse power), operation of the Mayer system;
5. black-out (automatic start-up of the emergency generator and switching on the voltage on the emergency switchboard bars);
6. operation of the switchboard at a voltage higher than 1kV, including replacement of circuit breakers in compliance with all safety rules and principles.

The switchboard room contains the relevant OHS (Occupational Health and Safety) equipment for maintenance ship electrical installations supplied with a voltage higher than 1kV.

5 EXEMPLARY EXPERIMENT RESULTS

As an example, the procedure for synchronizing of synchronous generators will be presented and explained. We assume that the voltage in a given phase has a sinusoidal waveform, which can be described by the relationship (1):

$$u(t) = U_m \sin \omega t. \quad (1)$$

where: U_m and ω are a magnitude and a pulsation of the considered waveform, respectively.

Connecting a given generator to work in parallel with the system requires bringing about a state in which the instantaneous voltages of the corresponding lines will differ by an acceptably small value for a time sufficient to connect them. The activities that must be performed for this purpose are called synchronization.

It should be emphasized here that the term phase is not intentionally used to describe the wires, because the word phase is also used to define the angle assigned to the value of a given periodic signal, such as a sine wave.

The obvious condition is the correct connection of individual wires to the breaker, which means that the L1 wire of the generator must connect to the L1 wire of the system and so on for the other two wires to ensure the same direction of voltage rotation. This condition must be checked at the stage of construction, renovation or maintenance of the system. Additionally, before starting synchronization, the value of the generator voltages must be checked, which should be equal to the values of the voltages on the bars of the working system. The value of the generator voltages is automatically maintained at a constant level by the generator regulator. Hence, the voltage amplitudes in the individual, corresponding wires must be equal to the accepted tolerance.

Generator synchronization uses phenomena that occur between corresponding terminals on the breaker. And here it should be emphasized that there are voltage differences between the corresponding terminals, which should have minimal values (theoretically, it is best if the voltage differences are zero) before the breaker is closed.

On ships, where the generator power is at the MW level, two approaches can be distinguished. One can be described as quasi-static and the other as dynamic. In quasi-static, equal frequencies are achieved between the generator and the voltage on the switchboard rails. The static position of the synchroscope pointer corresponds to equal frequencies, while the position on the synchroscope scale corresponds to the phase shift angle between the voltages. Reducing the generator speed causes the pointer to move clockwise, and increasing it causes the pointer to stop at a correspondingly smaller phase shift. Repeating this procedure can lead to equal frequencies and a zero phase shift between the generator voltage and the switchboard rails, which is expressed by the position of the pointer on the synchroscope at "12 o'clock" position. This method directly refers to the classic synchronization conditions, which consist in the need to achieve equal frequencies and zero phase shift between them. It can be described similarly using a phasor diagram, which only makes sense for equal frequencies. It may have application in manual synchronization and is rather of no practical use on ships in semi-automatic and automatic synchronization. The quasi-static synchronization process can be summarized in the form of Table 1.

Table 1. The stages of the quasi-static synchronization process.

Check/Compare	Before switch on breaker	After switch on breaker
Correct connection of the wires L1, L2, L3	Mandatory: during commissioning and each time after repair and maintenance.	Not applicable.
Value of voltage	Mandatory: the voltage value on each and the corresponding lines (L1, L2, L3) on both sides must be within the permissible tolerance.	All corresponding voltages are equal.
Frequency	Mandatory: frequency of generator is equal the frequency of bus MSB.	All frequency are equal.
Fhase of voltages	Mandatory: phase of generator voltage is equal the phase of bus MSB.	All phases of voltages are equal.
Instantaneous voltage values for the corresponding lines (L1, L2, L3)	All instantaneous values of voltage are equal.	All instantaneous values of voltage are equal.

In the second approach, dynamic method of synchronizing ship generators, an absolute and necessary condition must be met, that the frequency of the voltages of the generator and the switchboard bars must differ slightly. A small difference in frequency is the most important element in the synchronization process, which is intentional and it is thanks to it that generators can be synchronized. It should be remembered that before the switch is closed, we only compare the instantaneous values of the generator voltages and the voltage on the switchboard bars. It should be emphasized that there is no physical sense in comparing the phases of electrical waveforms with different frequencies. Therefore, using a phasor diagram to explain the synchronization process is too much of an oversimplification. It should be remembered that a phasor diagram has physical meaning only for waveforms with the same frequency. Assuming that the voltage on the generator is designated $u_G(t)$ and on the switchgear bars $u_S(t)$, we can write:

$$u_G(t) = U_m \sin \omega_G t; \tag{2}$$

$$u_S(t) = U_m \sin \omega_S t. \tag{3}$$

The voltage difference at the circuit breaker terminals for a given line can be expressed by the following formula:

$$u_G(t) - u_S(t) = 2U_m \cos[(\omega_G + \omega_S)t/2] \sin[(\omega_G - \omega_S)t/2]. \tag{4}$$

This situation is illustrated by the waveforms in Figure 6.

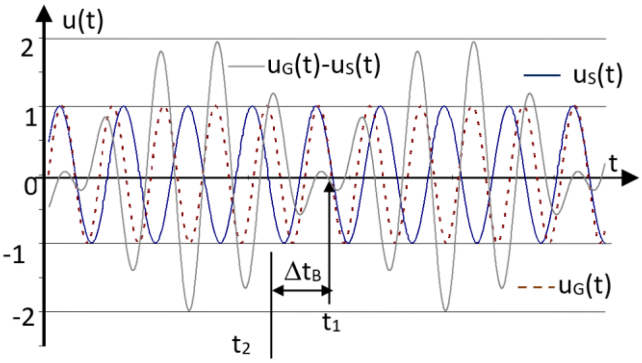

Figure 6. Voltage waveforms before connecting the generator to the switchboard bars

During synchronization, due to a sufficiently small frequency difference, the voltage difference between the breaker contacts is periodically sufficiently small and maintained for a sufficiently long time required to close the breaker. Such conditions occur cyclically with a period equal to half the frequency difference.

This is visible during synchronization by observing the appropriately connected bulbs and synchronizer. At the moment t1 shown in Figure 6, when the voltage difference between the contacts of the switch approaches zero, the bulbs go out, signalling the correct moment of switching on the switch (dark synchronization). Similarly, the synchronizer indicator shows "12 o'clock". However, the moment t2 of switching on the switch must take into account the necessary time of switching on the breaker ΔtB and the human reaction time during manual synchronization. During synchronization, it is also necessary to observe the rule that at the beginning the frequency of the synchronized generator should be set to a frequency higher than the voltage frequency on the switchboard bars and then gradually reduced to a value allowing synchronization to be carried out. The fulfilment of this condition is indicated by the direction of rotation of the synchronizer indicator. Rotating to the right (clockwise) indicates a higher frequency of the generator voltage than the frequency of the voltage on the switchboard bars. Such a procedure will allow, after switching on the breaker, immediate takeover of the load and basically excludes the activation of the reverse power protection. The procedure in automatic or semiautomatic synchronization systems is the same, except that it is carried out accordingly faster, because the element of perception and delays resulting from human reactions are excluded.

Figure 7 shows the interpretation of signals before connecting the generator to the switchboard rails. Three cases are presented. The obtained measurement results were recorded for the voltage frequency difference between the generator and the switchboard rails at the level of 0.2 Hz. For individual situations, attention was paid to the time course recorded on the oscilloscope and the corresponding state of the synchronizer and bulbs from manual synchronization was indicated.

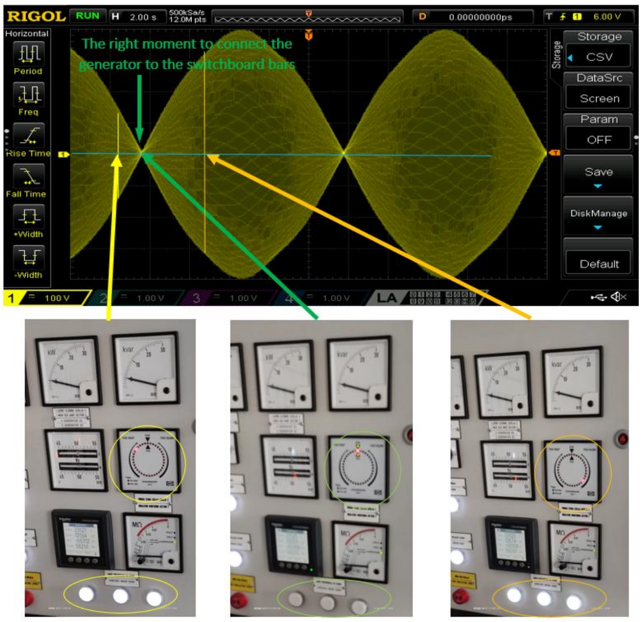

Figure 7. Graphical interpretation of signals and instrumentation before synchronization

The synchronization process can be summarized in the form of Table 2.

Table 2. The stages of the synchronization process.

Check/Compare	Before switch on breaker.	After switch on breaker.
Correct connection of the wires L1, L2, L3	Mandatory: during commissioning and each time after repair and maintenance.	Not applicable.
Value of voltage	Mandatory: the voltage value on each and the corresponding lines (L1, L2, L3) on both sides must be within the permissible tolerance.	All corresponding voltages are equal.
Frequency	Mandatory: 1. small difference,2. frequency of generator is slightly higher the frequency of bus MSB.	All frequency are equal.
Fhase of voltages	Not applicable.	All phases of voltages are equal.
Instantaneous voltage values for the corresponding lines (L1, L2, L3)	The difference between the instantaneous voltage values for corresponding lines (e.g. L1) changes cyclically with a frequency equal to half the difference in the frequencies of the generator and the MSB buses.	All instantaneous values of voltage are equal.

6 FINAL CONCLUSION

– a real ETO job description onboard of the ship is not dependent on the functions and competencies included in A-III/6 only, but also depends on interaction among them and other important environmental and social factors.
– the physical object-based simulator of a ship power plant gives the wider possibility for training under real conditions with underscoring the high voltage mission in MET processes.
– the example of experimental results confirm that a considered simulator creates better possibilities to understand the physical processes being observed in the real terms.
– aforementioned physical object-based simulator of a ship's electrical power plant is mainly dedicated to ETO's MET program, but it could also be very useful for training programs of watchkeeping officers and marine engineers as a real object training tool.

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