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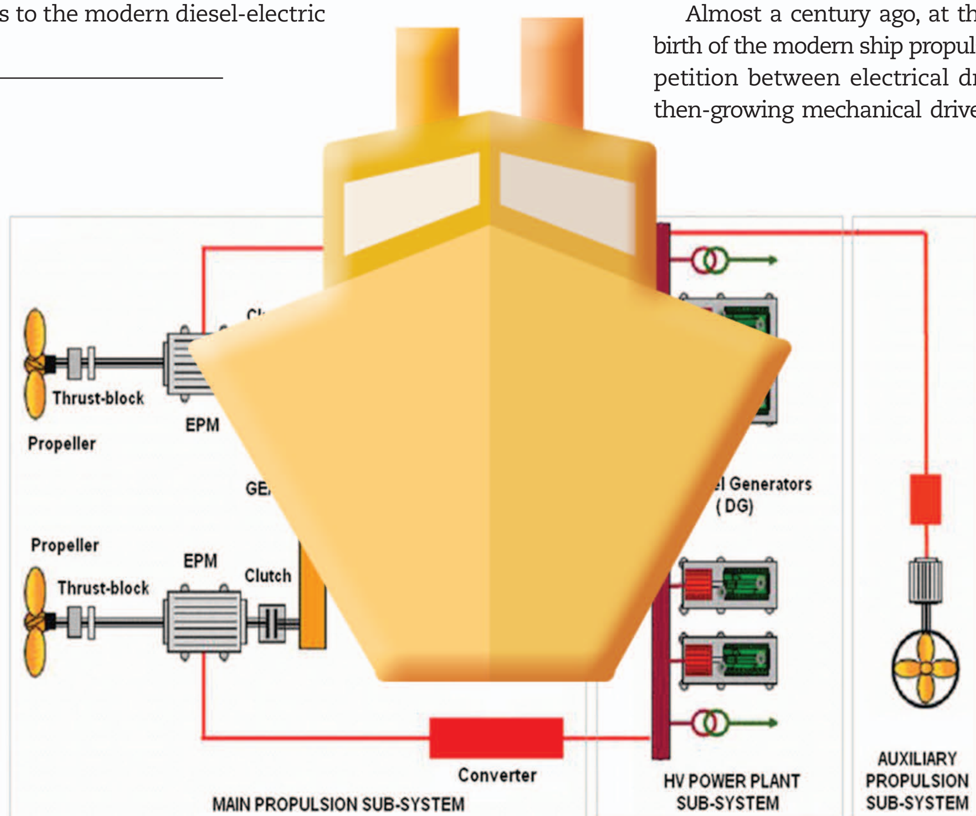
The Role of Voltage Controls in Modern All-Electric Ships

Toward the all electric ship.

SHIPS HAVE WITNESSED AN ASTOUNDING evolution in the last 200 years. The introduction of the combustion engine has started an ever-faster change, both in the performance and functionality given by the ships. From the steam-powered ships of the early 1800s to the modern diesel-electric ships, the improvements were significant and increasingly rapid. In particular, in the last 30 years, the design of ships has made a huge leap ahead, both in terms of efficiency of the entire vessel and new functions given to the owners. This is due to the progressive electrification that has occurred.

Almost a century ago, at the time of the birth of the modern ship propulsion, the competition between electrical drives and the then-growing mechanical drives was strong.



SHIP IMAGE LICENSED BY GRAPHIC STOCK.

The electric solution was seen as a valid contender, so, in 1912, the U.S. Navy built an experimental electrically powered collier. The promising results led to the production, a few years later, of a series of electric-powered warships that proved their worth in World War II. Some of these warships, using electric propulsion, consumed 20% less fuel compared to conventional vessels with turbine engines. The main issues of these first models were the electric propulsion size and weight; therefore, the idea was quickly abandoned.

The fast development in power electronics, which has led to the realization of devices capable of handling high currents, and the advancement in the electrical machine design (optimization through finite elements simulations), which has led to smaller and more torque-dense electric motors, have changed everything. These advancements have reduced the penalties associated with electric propulsion, making its introduction possible in large ships, thus totally revolutionizing the power system.

In addition to the electric propulsion adoption, the number of electric-powered devices that the owners are asking to install in these vessels has been increasing. This has been done with the aims of adding new functions, replacing mechanical or hydraulic drives (with more efficient, safe, and easy-to-operate electrical ones), saving space, and reducing the producedww noise and vibrations.

The result of this invasive adoption of electric powered equipment was the birth of the so-called all-electric ships (AESs). AESs feature an integrated power system (IPS), supplied by a set of generators that feed all shipboard loads, propulsion included. Electricity can be rerouted to wherever it is needed at the time, avoiding the use of separated internal combustion engines (ICEs) for propulsion and shipboard electric power (which is why it is called "integrated"), thus optimizing their size and consumption. The IPS can be considered equivalent to a land power grid, where generation, distribution, and utilization of the electric power exists in a limited, strongly constrained environment.

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The benefits of the AES concept are as follows:

- flexibility in space and weight allocation (short shafts, propulsion motors, and generators can be installed in different places)
- more degrees of freedom in the power system layout design
- podded-drive solution availability (no shafts, rudder removal)
- enhanced operating life (fewer mechanical components, less stress on prime movers)
- enhanced propeller dynamics
- increased overall efficiency [generators modularity, better management of heating, ventilation, and air conditioning (HVAC) systems]
- noise and vibration attenuation
- advanced automation and reduction of the crew
- increased survivability (generator sets distributed, better ship compartmentation)
- increased maintainability.

To give an idea of developments in technology that has accompanied the modern electrical applications on board, and, in particular, the marine propulsion systems, it is useful to consider the experience of the last 15 years in the construction of cruise ships. At that time, some designers of the most important shipyards have found themselves having to design the electrical system of a cruise ship with electric propulsion, starting from the blank page. Since then, several solutions have been designed and installed successfully in a succession of increasingly large and innovative projects, technological achievements, and continuous challenges. The most noticeable case is the Queen Mary II, which, with 86 MW of total propulsion power divided on four electric propellers and 112 MVA of alternators, holds the record for installed power of electrical drives and power plant on a ship.

In the field of the large cruise ships, the AES concept has become a standard, covering 100% of the construction made by the major shipyards in the world. The electric propulsion was adopted, in special cases, by other types of ships, such as ferries, oceanographic vessels, gas carriers, cable-/pipe-laying vessels, platform supply vessels and offshore oil and gas platforms, icebreakers, and megayachts.

The military, in which the mechanical propulsion solution is still widely used, deserves special mention. Much attention has recently been paid to electric propulsion, considering various types of navy vessels. This is clearly evidenced by the growing number of projects and works in progress regarding this type of propulsion in all the most technologically advanced navies.

All-Electric Ships Layout

The AES's power distribution typically uses alternating current (ac), thus directly benefiting from the technology transfer from land-based power plants. Nevertheless, direct current (dc) distribution is currently under evaluation for future electric ships, but currently this technology is still immature for extensive commercial use. However, the dc distribution is promising, and great innovations and advancements are expected in this field.

In an AES, the electric power is generated in two or more separate power stations, each of them presenting at least two generator sets. Each set is composed of a prime mover (typically a diesel engine), a synchronous machine, and all the subsystems required for their operation (fuel pumps, heat exchangers, automation, etc.). As can be seen in Figure 1, which shows the typical IPS layout of a cruise ship, the power stations feed separate busbars, which can be operated separately as well as connected by means of a conjunction breaker. The ship's loads are fed by the busbars, directly or by means of transformators, and are connected to one or another depending on considerations about fault tolerance and load balancing.

The subdivision of the power-generating capability into several parts, each completely separate from the others, is mandatory to assure the fault-tolerance level required by the current marine classification rules. Cruise or merchant ships conventionally adopt the simplest subdivision, implementing two separate power stations with two or three generator sets each. This solution allows for compliance with the rules with the least possible economic impact. In military ships, where the costs are not a primary issue, it is preferred to give priority to the survivability of the unit in combat condition, spreading multiple power stations all over the ship hull.

Power Quality

Ships' IPSs are a particular case of an islanded grid since they combine generation, distribution, and utilization of electric power in a single system without external energy inputs. AESs' power systems are characterized by high installed power and the presence of loads whose power can match the power of a single generator. Managing the variations in those loads' absorbed power while, at the same time, ensuring a high quality of power is challenging.

Moreover, in the common ship's IPS practice, generators are switched on and off following a logic that tries to minimize the fuel consumption. Doing that, frequent connection and disconnection transients are produced. An example of this practice is reported in Figure 2, where the start-up, load, unload, and shut-down of a single diesel generator during a maneuvering phase are shown. The most relevant traces are the green one, which is the generator's terminals voltage, and the orange one, which is the generator's active power. Observing the abscissa, where the time is reported at which the measure was made, it can be seen that the entire procedure occurs in less than 20 min. These continuous connection and disconnection transients act on a system where a lack of power-generating capability is present due to the nonsimultaneous presence online of all the generators. These facts, combined together, could lead to severe variations in the voltage and frequency when high power loads are used.

To respond to these solicitations and, at the same time, ensure the correct operation of the generating units, each generator set is equipped with a group of controllers. These range from security systems, which are essential to avoid

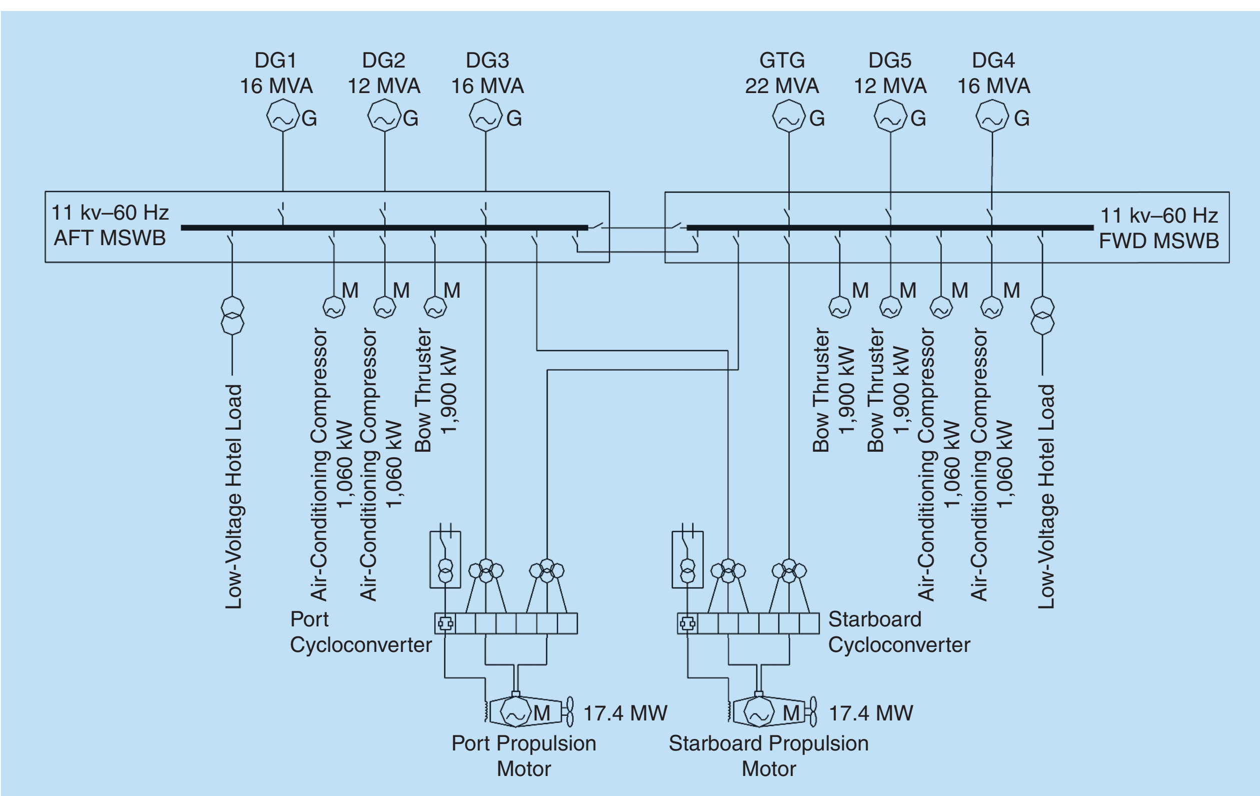

Figure 1. The typical IPS layout of an AES.

failures or hazardous situations, to regulators for the various quantities involved in the generator's functioning. Among these, the most relevant (since they affect the entire IPS's operation) are the automatic voltage regulator (AVR), which acts on the electric machine, and the speed governor (SG), which acts on the prime mover. Voltage and frequency real-time controls are of paramount importance for maintaining power quality during the IPS's operation. In islanded grids, such as a shipboard IPS, the absence of a connection to an infinite power bus implies the lack of a point in which the electric variables are kept constant regardless of the system's modifications (both in load and generation). Because of that, in an IPS generator, the voltage and frequency controls have a strong effect on all variables of the system, directly affecting the power quality.

In an IPS, the rated values of the frequency and voltage have to be maintained as well as in land electrical systems. The extension of the grid, its interconnection, and the high number of generators active at the same time on the land power system led to a particular management of the voltage and frequency variations that is not applicable on a small islanded grid. For this reason, the major marine classification rules impose peculiar voltage and frequency variation limits that must be respected in a shipboard power system. As an example, the limits given by the Lloyd's Register are the following:

- +6%, –10% permanent voltage variations
- ±20% voltage variations during transients with a recovery time of 1.5 s
- ±5% of the permanent frequency deviation from the rated value
- ±10% frequency variation during transients with a recovery time of 5 s.

Despite these limits being quite wide, both in magnitude and time, a careful voltage and frequency control design is still needed to obtain a fast and well-damped system's transient response.

Another very sensitive power quality issue in an IPS is the harmonic distortion. Power-electronic converters absorb distorted currents from the grid that cause voltage harmonic distortion, depending on the network impedances. This issue is relevant in a naval power system because of the high power of the converters (mainly the propulsion converters), which involves high-amplitude harmonic currents flowing in the IPS. To overcome this issue, some solutions are available: the classical are the use of harmonic filters or multipulse converters, while more advanced ones could be the use of new converters topologies (active front-end converters) or active filtering. Similarly to the previously stated voltage and frequency limits, the marine classification rules impose harmonic content limits for the voltage. Nevertheless, the discussion of this issue is outside the scope of this article, so it will not be addressed.

Voltage Regulation

Synchronous Machine

The electric machines traditionally used for shipboard power generation are of the wound-field synchronous type. Despite the presence of other types of machines capable of electric power generation with higher performance (e.g., permanent magnet synchronous machines), the robustness, ease of control, and long-term experience on these machines make them the most reasonable choice. Given the low maintenance required and the compactness of the excitation system's external hardware, the brushless rotating exciter is the

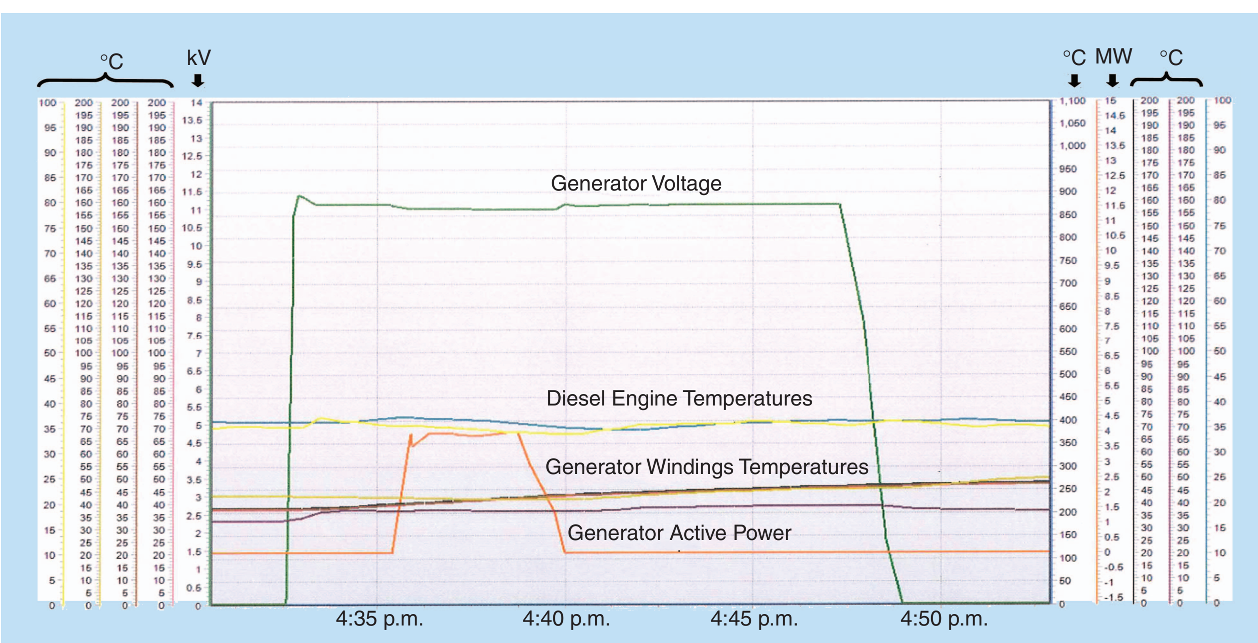

Figure 2. The ship's automation print screen of a generator's main variables during a maneuvering phase.

solution preferably adopted on ships. In this type of excitation system, an auxiliary synchronous machine (the exciter) is keyed on the alternator axis. The auxiliary machine has an inverted construction, with the stator on the rotating axis and the excitation winding on the external fixed structure. The exciter's stator windings are connected to a diode bridge rectifier, which is fixed on the rotating axis, and feed the field winding of the main alternator with dc. In this way, the rotating exciter acts as an amplifier and no sliding contacts are needed. Therefore, by means of the regulation of the voltage on the auxiliary machine excitation winding, the main machine's excitation can be controlled.

The major marine classification rules impose peculiar voltage and frequency variation limits that must be respected in a shipboard power system.

The rotating speed of the alternators is fixed by the ship's power system frequency, so the alternators are constructed in such a way that they are coupled with fixed-speed prime movers and directly feed the IPS.

Other types of generators are currently evaluated for marine applications, but their adoption is still extremely rare, mainly for cost reasons.

Automatic Voltage Regulators

Except for some particular cases that will be discussed later, generators are controlled in frequency (and, consequently, in active power) by SGs, and in voltage (and, hence, in reactive power, volt-ampere reactive (VAR) by AVRs. These regulators are usually set up in such a way that the regulation actions do not affect each other, fixing well-separated control bandwidths for frequency and voltage cycles. In the majority of cases, the frequency cycle, considering also the regulator, presents an equivalent time constant of 5–10 s. Conversely, the voltage regulation cycle is set with an equivalent time constant of 0.5–1 s, thus faster.

In some cases, the frequency (electromechanical) and voltage (electrical) cycles can interact. If high-regulation performances are required (e.g., in military ships), low inertia generator sets could be adopted together with high-bandwidth SGs. If this occurs, the two cycles cannot be defined as well separated, so a careful design is required due to the unexpected behavior that may arise from their interaction.

Being the fastest, the voltage cycle is the most relevant for the power quality goals. It is related to the main switchboard voltage, whose control determines the good or bad functioning of all the IPSs. As previously stated, the voltage is controlled by means of the AVR. The AVR is a device that senses the voltage in a defined point of the system (typically at the generator terminals) and regulates the input voltage of the generator's excitation system (or likewise the current) to reach and hold a preset reference voltage value. Figure 3 shows the connection of the AVR to the generator, while Figure 4 shows the typical voltage-control cycle. Usually, these devices are realized with simple proportional-integral-derivative (PID) [or even simpler proportional-integrative (PI)] regulators, but can also implement additional functions such as reactive power regulation and capability curves. If used, the reactive power control modifies the voltage reference input to regulate the reactive power generated/absorbed by the generator. This functionality allows the generator's power factor to be set and is mandatory to implement capability curves in the control system. With regard to these, capability curves are the limits in the active and reactive power that the generator must not exceed in steady state to prevent damaging itself (Figure 5). During transients, it is possible to overcome these limits, but only for a short amount of time. The reactive power control and the capability curves implementation are not mandatory, so the ship constructor (or equally the owner) may decide to use these functionalities or not, depending on their necessities.

Droop

When two or more generators are intended to be connected in parallel feeding the same busbar, some sort of decoupling between them must be adopted. Indeed, if the generators' voltage control loops measure the voltage in the same point (e.g., the main switchboard), the integral components of the AVR regulators may cause a dangerous reactive power exchange between the generators. This is due to the attempt to nullify different voltage

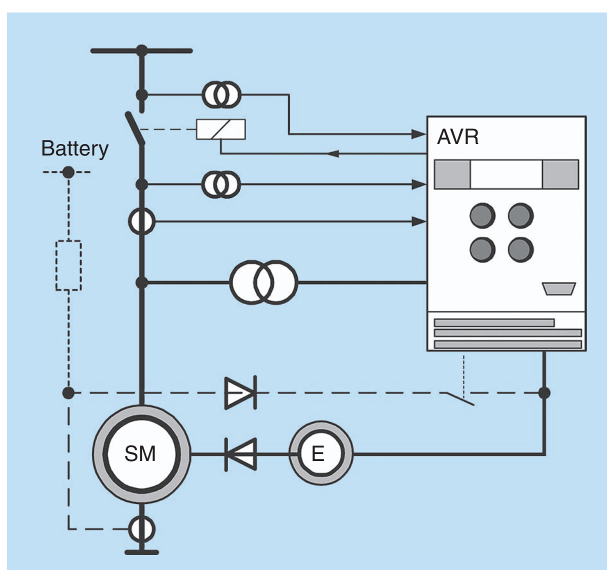

Figure 3. The AVR connection to the generator set (SM: generator; E: exciter).

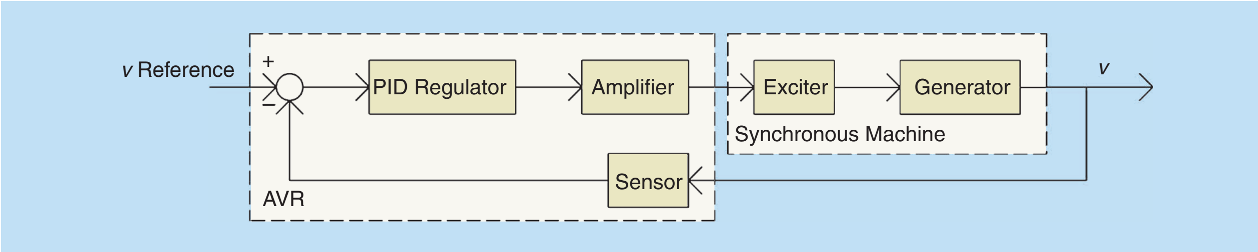

Figure 4. The voltage control cycle block scheme.

error levels in every AVR, caused only by sensors offsets that are not perfectly compensated (which is an impossible goal to reach). To avoid that, the only solution is the insertion of a decoupling element between the generators' terminals, where the voltage is sensed, and the common connection point of the system (which is the main switchboard in an IPS). This can be achieved in two different ways: the first is the interposition of a transformer, whose internal reactance decouples the generators each other; the second is the adoption of the voltage droop in the AVRs. In particular, the latter is the most adopted solution since transformers are not essential in shipboard power systems generators because of the voltage levels of the system (usually large ships' distribution voltages up to 11 kV are easily managed directly by the rotating electrical machines) and are space-consuming devices. (Space in ships is limited and must be reserved as much as possible for payload.)

The voltage droop technique implies the adoption of a negative feedback on the voltage regulator's input, depending on the reactive power generated by the alternator. By doing so, the steady-state voltage output lowers as the reactive power generated increases (Figure 6), introducing an equivalent inductive reactance (totally virtual) between the generator and the main switchboard. This enables a stable parallel operation without adding losses and weight, and without consuming space. Moreover, the droop mode imposes the steady-state VAR sharing between the paralleled alternators, allowing the change in the reactive power sharing distribution by the simple variation of the droop's constants of the generators.

Inverter-Based Generators

The advancements in power electronics made in recent years have unearthed the possibility to couple the alternators with ICEs, which are not dedicated solely to the generation purpose. In some cases, mostly in military ships, the propulsion is yet realized with ICEs, in particular, using gas turbines (GTs). This is due to the high speed requirements of these units, implying very high propulsion power requirements,

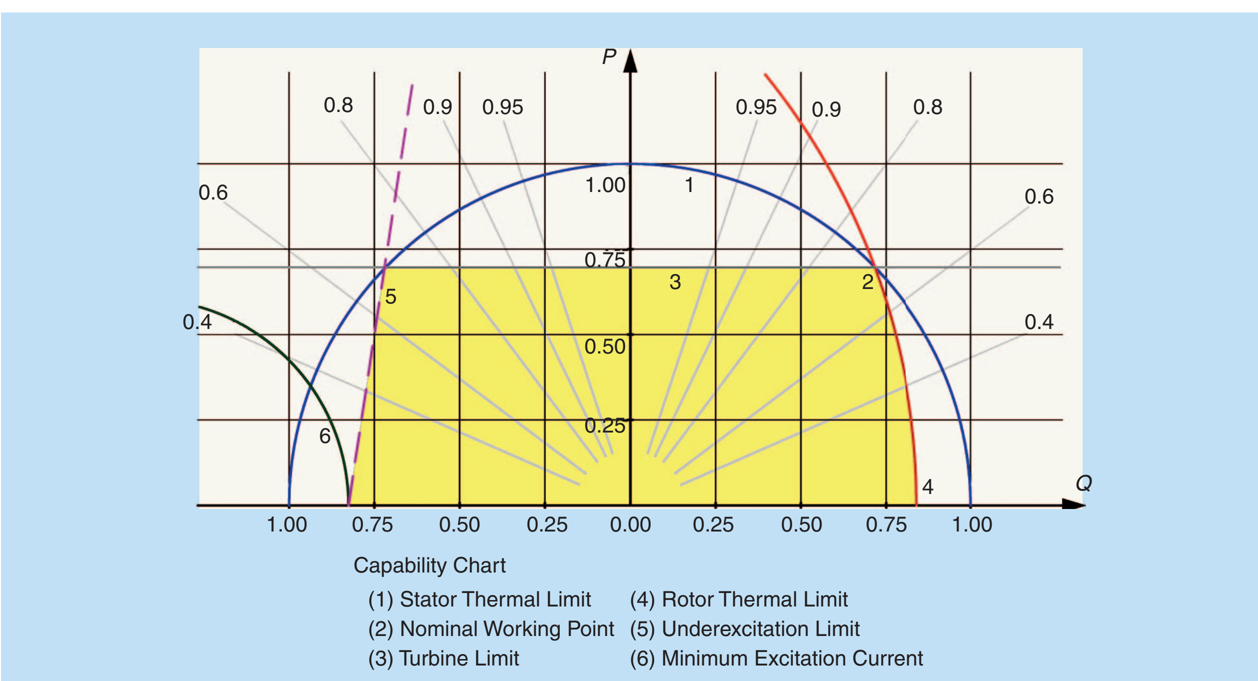

Figure 5. The region of admissible operating points.

which are hard to comply with using the all-electric solution. Because of the GT's poor efficiency at a low power output (which occurs during cruise speed conditions), it is not favorable to sail on the ICE's propulsion at low speeds. So, it is convenient (but not mandatory) for ships using GTs to have electric propulsion drives for cruising, with the ICE's propulsion reserved for high-speed navigation. This way, a hybrid propulsion system can be realized (Figure 7).

The electric propulsion motors, when high-speed propulsion is active but maximum speed is not required, could be operated as generators. In this way, the power difference between the propeller needs and the GT's rated value can be recovered and used to feed the ship's IPS in place of the diesel generators. This enables fuel savings when the GTs are on because their efficiency increases as the load increases, therefore making it better to turn off the other generators (if the power generated by the GT is sufficient) and feed all the ship's electric loads with them. Also, in case of a full gas turbine propulsion (e.g., a ship without hybrid electric propulsion), it is possible to insert electric machines on the shafts for the sole purpose of electric generation in cruise conditions (the so-called "shaft generators"). It is easy to see that the rotating speed of these prime movers cannot be fixed, as they vary with the propulsion load variations caused by the hydrodynamic interactions between the ship's hull, the propeller, and the water. Therefore, the direct connection of the

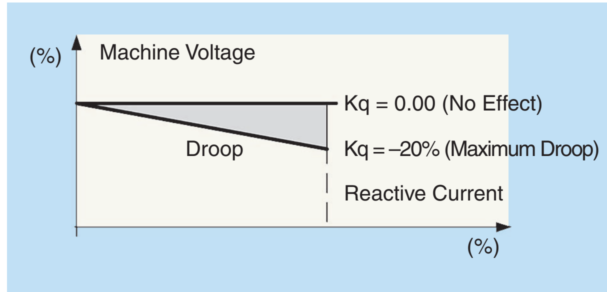

Figure 6. The reactive power-based voltage droop.

electric machines to the IPS is not possible because of the impossibility to maintain a fixed power system's frequency. Furthermore, some researchers have suggested that the use of variable-speed prime movers (for the generating systems) may be a way to improve the efficiency of the entire generator system, removing the constraints on the prime movers given by the fixed speed operation.

The solution to this issue is the insertion of a power-electronic converter between the electric machine and the ship's electric network, creating an inverter-based generator. The power-electronic device provides the frequency (and voltage if required) conversion from the variable-speed electric machine and the fixed frequency network. In the hybrid propulsion case, the same converter also operates as the propulsion drive, when the electric propulsion is required.

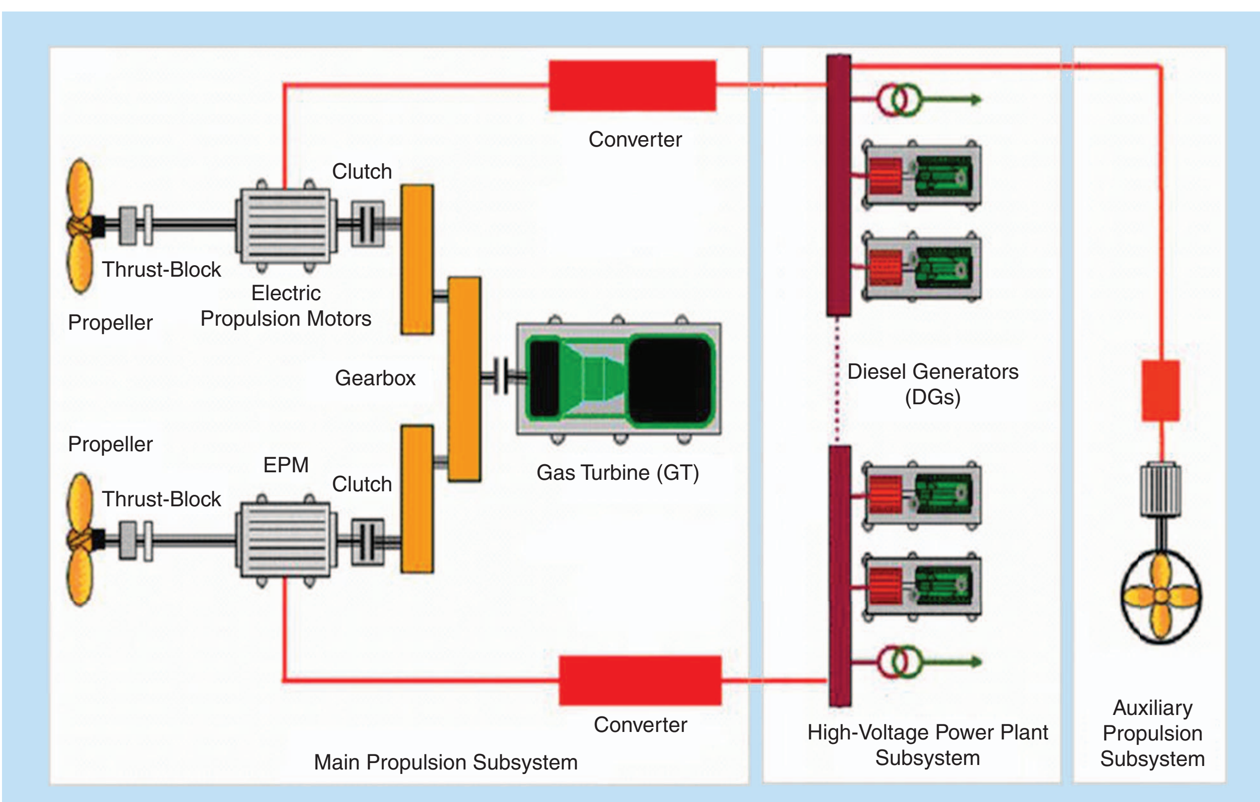

Figure 7. The ship hybrid propulsion system layout.

When the electric machine is operating as a generator, the converter must control the system's voltage and frequency, acting in place of the common AVRs and SGs, so appropriate regulators need to be adopted. The prime mover's SG is still present, but it operates following a reference that is totally independent from the IPS power and frequency management. As an example, in a shaft generator, the prime mover's speed will follow the propeller's needs and not the IPS's. In the inverter-based generators, AVRs can be either present or not, depending on the alternator technology or the designer choices. Indeed, having a power converter that is capable of managing the variations in the frequency and voltage on the alternator side, converting them in the ranges better suited for the IPS, it is possible to work with a fixed excitation system [e.g., a permanent magnet (PM) generator].

It is important to note that the converter could control its electric output variables with a bandwidth that is far greater than a common generator set. In fact, the power-electronic converter can impose, almost instantaneously, voltage and current vector variations at its terminals. (The time delay depends on the converter's commutation frequency.) Accordingly, it is necessary to implement voltage and frequency regulators that are tuned to the other generators of the system; otherwise, some issues can arise. If the inverter-based generator is set with a too-high regulation bandwidth (compared to the diesel generators), it will bear all the regulation actions necessary to withstand the IPS voltage and frequency transients. This behavior may be desired to some extent, giving as a result the partial freeing of the diesel generators from the fast transient responses, but it has an impact on the inverter generator itself, both on the prime mover and converter. In fact, these devices must be designed to bear the increase in solicitation without suffering. However, it must be noted that the prime mover, particularly in the case of shaft generators, is already heavily solicited by the mechanical stress due to the propeller operation; therefore, the addition of other solicitations due to the electric plant transients may be critical.

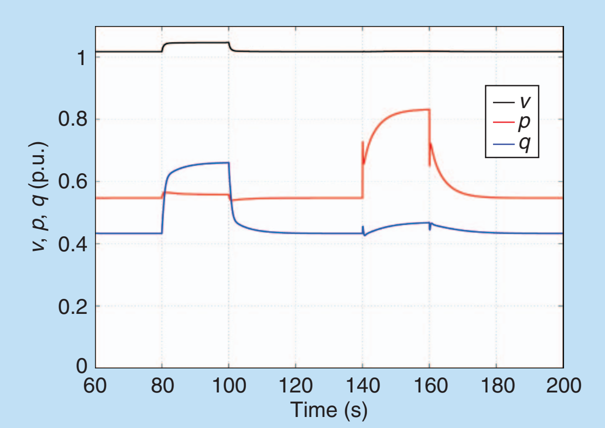

Figure 8. The inverter-based generator responses due to voltage and active power references step variations (±2%).

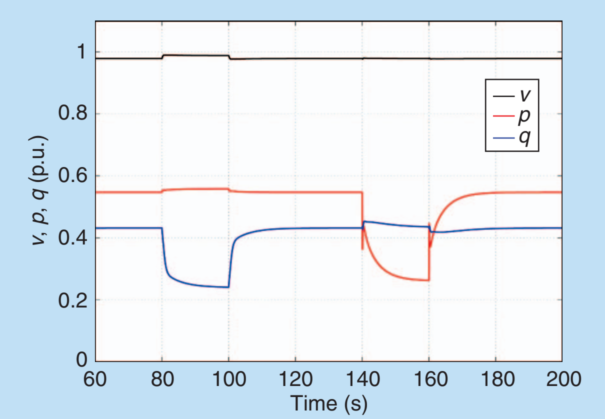

Figure 9. The diesel generator responses due to inverter-based generator references step variations.

As an example, Figures 8 and 9 show the simulation results regarding an entire IPS supplied by a shaft generator paralleled to a diesel generator. The system considered is the one shown in Figure 7. The shaft generator's voltage and frequency controls have been set in accordance to the diesel generator's AVR and SG settings to realize an equal sharing of active and reactive power between the two power sources. Figure 8 shows the voltage and power responses of the inverter-based generator due to references step variations. Figure 9 shows the corresponding responses of the paralleled diesel generator. As can be seen, the controllers' settings permit the same responses from both the generators, despite their different architecture.

Nevertheless, the differences in the voltage and frequency cycles between generators directly connected to the power system and inverter-based generators are relevant, even if they are tuned so that they respond with the same equivalent time constant. In fact, the direct-connected generator responds with an electromechanical-based cycle, while the inverter-based generator responds with a cycle, which is the composition of the electric machine's electromechanical cycle and the total electric cycle of the converter. These differences could cause unexpected interactions between the control cycles when the two types of generators are paralleled, unearthing instabilities and abnormal variations in the electric variables.

Master AVR

The previously explained voltage droop function, besides its utility in permitting a stable parallel operation of the generators and the definition of the VAR sharing between them, leads to a lowering in the main switchboard voltage when the reactive load increases. This reduction can usually reach a value of around 5% of the rated voltage at the rated reactive load, depending on the IPS designer choices. To avoid this, a master AVR (MAVR) could be introduced in the system. The MAVR is an additional AVR that senses and regulates the main switchboard's voltage. It works by varying the voltage references of all the generators to compensate the voltage decrease caused by the droop action, recovering the rated voltage on the switchboard. This recovery is set rather slow when compared to the AVR control cycle, occurring in about 10 s. Since the main switchboard is usually divided into two separable busbars, two MAVRs are required, one for each section. When the two busbars are connected by means of the interconnection switch, one of the two MAVRs goes into standby, leaving the control to the other, but remaining ready to return online if the busbars are separated again or if the other MAVR fails.

Despite being a useful feature, in some cases, it is not adopted for reasons both economic and technical. For the ship owners, it is an additional cost, requiring an additional device, sensors, and cables plus AVRs capable of being interfaced with the MAVR against a voltage drop under load that is of low entity. Nevertheless, the use of Master AVRs allows for increasing the power quality of the system and makes it easier to comply with the marine classification rules limits for the voltage deviations from the rated value, recovering the rated voltage in the steady state.

Multiple-Input, Multiple-Output Control (Wire)

As previously seen, the complexity of an IPS is rather high and the electric variables of the system are tightly coupled. Trying to control them separately is the simplest but a less effective way to approach the problem. In fact, the common practice is to control a multiple-input, multiple-output (MIMO) system with an array of separated, and noninteracting, single-input, single-output (SISO) controllers. It is evident that this approach could lead to the system's unexpected behavior in some conditions. Indeed, both the literature and ship owners' experiences report frequent power quality issues, from abnormal changes in voltage to blackouts. Even in the most modern and automated ships, these power quality issues are not unusual.

The reasons behind these unforeseen behaviors are the following:

- The poor information sharing between controllers (AVRs, MAVR, and SGs) makes it difficult to manage the dynamic interactions between them.
- No information is shared between the voltage controllers and the shipboard power management system (PMS).
- The shipboard automatic reactive power management is rather poor: for example, in some ships, harmonics filters are still manually operated.
- The droop mode is affected by voltage measurement errors, which determine the reactive power recirculation between alternators.
- No dynamic decoupling between different reactive power loops is assured by actual droop mode regulation.

An innovative approach to the ship power system's control could be the adoption of a voltage and VAR integrated regulator, substituting the standard SISO controllers with a MIMO controller that is capable of regulating the entire power system in a coordinated way.

This MIMO controller could acquire voltages and currents from generators and busbars and process these multiple inputs to calculate, for every point of interest, the active and reactive power. Such information, along with every generator capability curve, allows the regulator to fix the reactive power to be produced by each alternator to reach the reference voltage on the busbar. The dynamic interactions between the reactive control loops can be taken into account in a MIMO regulator, so the multiple outputs, consisting in the voltage references for the single generator's AVRs, can be dynamically decoupled. An example of a possible realization of this MIMO controller is the voltage and VAR integrated regulator reported in Figure 10, derived from land power systems.

An important advantage of the MIMO solutions is their ability to implement additional functionality. Full-digital over- and under-excitation limiter functions prevent alternator damage, thus allowing the transitory trespassing for transient network VAR demands. The full inverse time/current characteristic performs better than the simple threshold clipping used in the standard AVRs, improving the voltage quality. In addition, other functions recommended by the state-of-the-art standards can be easily implemented. Moreover, the controller can be realized with a fully redundant architecture and with automatic data loggers to improve the system's reliability and provide the tools for an understanding of the transient or fault situations that may occur during the life cycle of the ship.

Critical Issues and Advancements

Soft Start and Propulsion Motor Transformers Inrush Currents

As stated previously, power quality is a relevant issue in an IPS since the system is islanded from a stiff utility source. Some loads, such as propulsion motors, thrusters, or air conditioning compressors, have a rated power comparable with that of the generators, so their operation has a strong effect on the system. As an example, the transient measured during a sequential startup of two 2.2-MW thrusters on an IPS that has a total generator power of 88 MW can be seen in Figure 11. The voltage shows the typical shape of an asynchronous motor startup, presenting relevant sag at the motor connection, followed by a voltage peak. The former is caused by the high current absorption when the rotor accelerates from stationary condition, while the latter is caused by the drop in the motor current when the rated speed is reached. Similar transients also occur for ac compressors startup and, generally, for every high-power asynchronous machine installed on board. It is relevant to notice that, at the present moment, all of these motors are directly connected to the main switchboard and operated at a fixed speed and without a soft-start apparatus.

Although there are several systems that are capable of starting electrical machines at low power, thus reducing the starting procedure impact on the network, they are not commonly used. The simple star-delta starting method is avoided in these power systems because of the large disturbances that occur during the star-delta commutation.

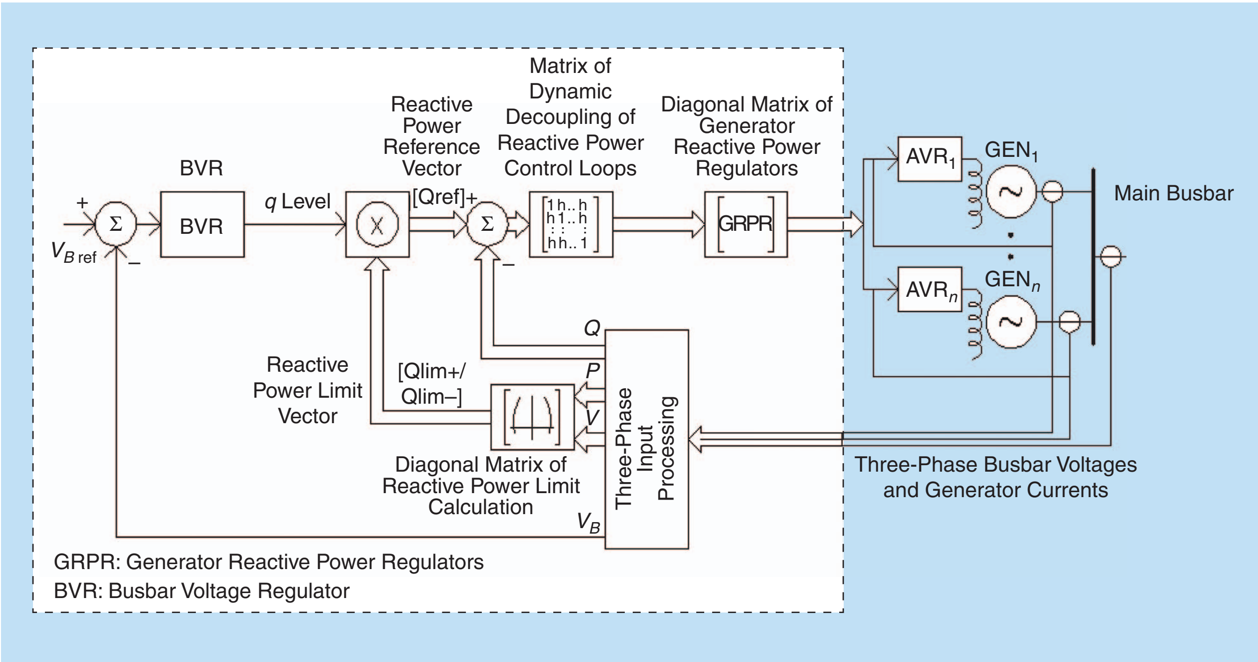

Figure 10. The possible architecture of an MIMO voltage and a reactive integrated regulator.

Also, autotransformers are rarely used because of the additional space and weight that they need compared with benefits, which are considered limited by the owners. A smart choice, which is presently not adopted, could be the use of the so-called "soft-starters." These are power-electronic devices that are capable of modifying the voltage module value at their output, applying at the motor a voltage ramp during the startup process instead of the step caused by the closing of a breaker.

The current advancements in power electronics have led to the appearance on the market of high-power motor starters that are capable of also starting high-power asynchronous machines (up to 2 MW at this time). Their introduction in an IPS could boost the power quality with a low economic impact and occupying little space on board. The last low-impact starting method is the adoption of a variable-frequency drive (VFD), in particular, one using pulse-width modulation (PWM). These drives are currently used for thruster motors when dynamic positioning is required but are also starting to be considered useful in standard applications. Extending this solution to all the high-power motors could be an effective way to gain better power quality because of the transient management improvement they provide. With a VFD, it is possible to strictly control both the voltage and the current absorbed by the electric machine.

Another advantage of PWM drives is energy savings with respect to motors directly connected to the grid, gained by operating propellers, fans, and pumps, in variable speed. The PWM solution seems to be the best from a voltage quality perspective, but it collides with the harmonic disturbances that such devices cause, which must be carefully evaluated. The transient response improvement must not be achieved at the price of insertion of big harmonic filters on the network because the capacitors included in them will cause the rise of short-circuit currents.

Regarding the propulsion motors, a soft start is already provided by the propulsion drive, which limits the impact of the propulsion power variations on the main busbar voltage. Nevertheless, the propulsion drive has a sensible impact on the IPS, mostly in a condition that is normally not considered: the no-load connection of the propulsion transformers to the busbar. In fact, when the propulsion is off, because it is not needed, the entire propulsion drive is disconnected from the network. In this way, the reactive power absorbed by the high-power propulsion transformers, which are mandatory to realize multipulse (12+) converters, is removed from the power balance, freeing the alternators from their generation. If the propulsion has to be turned on, these transformers must be reconnected to feed the propulsion drives. In this situation, their magnetic circuit needs to be re-energized, behaving essentially as a large inductance. Then, until the complete magnetization of the transformer's iron core, a large inrush current is drawn from the IPS, causing a sensible voltage sag (Figure 12).

To avoid this undesirable behavior, in certain cases, an auxiliary low-power transformer (called a magnetization transformer) is implemented. This transformer is connected in parallel with the main one and is controlled by the ship's automation. The magnetization transformer is connected before the connection of the main one and disconnected right after. Because of its low power output, it slowly energizes the main transformer iron, thus reducing the voltage sag on the main switchboard.

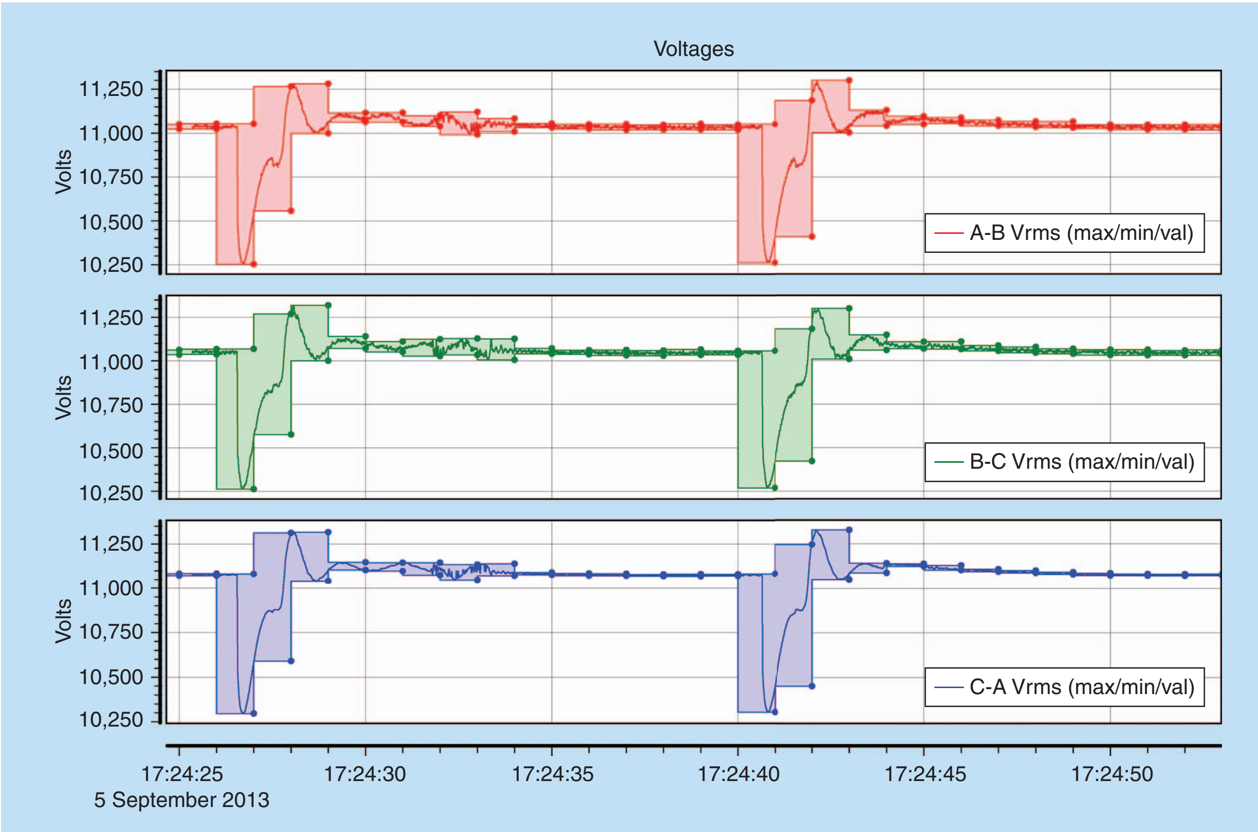

Figure 11. The main busbar voltage transients due to two 2.2-MW thrusters started up on an IPS with 88 MW total generator power.

Proper Disconnection of Generators

In the power systems of ships, the total generator power is divided into several generators, whose number and rated power is decided based on economic criteria. Indeed, to reduce the costs, usually the minimum number of generators is chosen that permits compliance with the rules and regulations of marine classification society. In particular, the rules provide that a ship must have at least two separable busbars and also impose that every portion of the power system that can be operated separately must fulfill its expected service even in case of the failure of one generator. Accordingly, shipbuilders today install four onboard generators (excluding the emergency power station), two for each power station, even in the biggest ships. The rated power of the single generator is chosen to have, in every ship's mode of operation, the highest efficiency. Generators have a maximum efficiency point around 85% of the rated power, and so, if the generator's ratings are properly chosen, an appropriate combination of running generators can be selected to achieve the minimum fuel consumption objective. In the past, the cost reduction was not as big of an issue for the shipbuilder (thus being a problem for the owner), so the use of six generators with different ratings was preferred. This was due to the greater ease in allocating the electric power in such a way that all of the generators can work close to their maximum efficiency point.

Given this, it is easy to comprehend that during normal operation of the ship, the generators are started and stopped frequently (as can also be seen in Figure 2), producing disturbances on the grid every time they are connected and disconnected. Connection disturbances are usually not an issue thanks to the automatic synchronizers that provide synchronization between the incoming generator and the busbar. By controlling the speed of the prime mover and the voltage of the alternator, the voltage and frequency differences as well as the phase shifts between the generator and the busbar are minimized before the breaker closing.

Conversely, generator disconnection is treated with less attention and can cause relevant disturbances that can be dangerous, especially for the disconnecting generator. In fact, while active power zeroing is achieved before every disconnection operation, zeroing of the reactive power is usually not carefully reached. Accordingly, the generator's breaker opens, interrupting a reactive current and causing overvoltage on the generator. An example is reported in Figure 13, which is a photo taken from a cruise ship's automation. As can be seen, at 8:07 p.m., there is a voltage spike (green trace), caused by the nonperfect zeroing of the generator's current (blue trace). This current is totally reactive since the generator is not producing active power anymore at the disconnection time (as can be seen examining the orange trace, which reaches the zero before the generator disconnection).

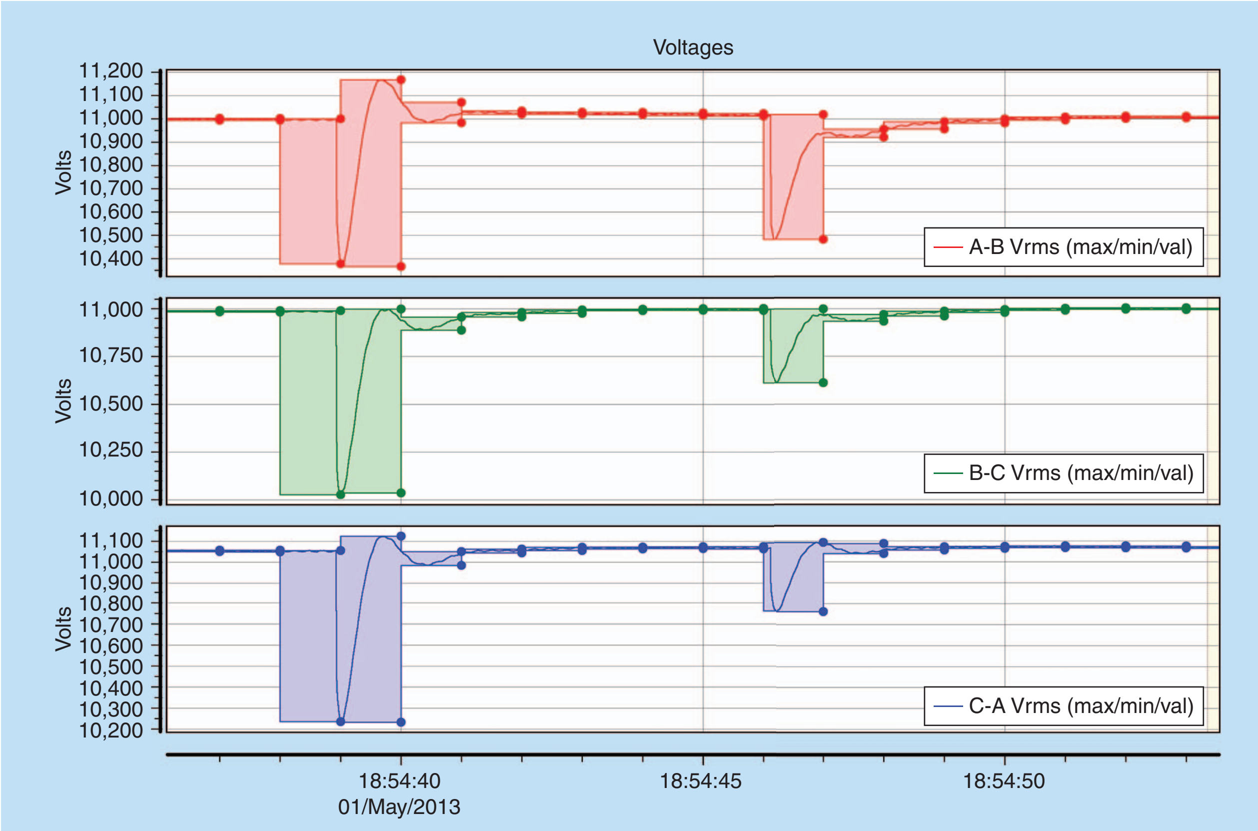

Figure 12. The main busbar voltage transients due to the propulsion transformer's inrush current.

AVR Settings (Capability Limits)

As previously stated, AVRs are endowed with some limiters to avoid generator damage. In particular, the AVRs must limit the voltage (equivalently the current) that they apply on the excitation circuit of the synchronous machine (the generator), with the aim of limiting the temperature that the excitation windings reach during this operation. The simplest way to do that is to set two or three time-based excitation voltage (or current) thresholds (Figure 14). The rated current can be maintained at steady state, whereas higher values can be reached in transient conditions. The transient excitation boost is essential to achieve an acceptable performance from the generator, provided that these higher currents are cut off (by the AVR) when they persist for too long. Thus, although it is not the best-performing solution (the best practice is the implementation of the entire machine's capability curve), the time thresholds implemented in the simplest AVRs are sufficient for the purpose.

A notable issue that can occur in excitation systems is the incorrect setting of these thresholds. The excitation voltage (and current) for both no-load and rated-load generator's conditions are the only data that can be found in datasheets (in some cases not even these), so the thresholds must be set accordingly to the competence of the personnel who install the AVR. An error in a transient excitation current threshold is dangerous due to the overtemperatures that it causes, but has little effect on the machine's lifespan because it lasts only a few seconds. A more harmful situation could arise when the steady-state current threshold is set incorrectly. In this case, the generator could work for a long time with an excitation current above the rated value, causing a rise in the excitation winding temperature to values that shorten the machine's insulation lifespan.

System Integration

So far, this article has confirmed the complexity of the system. The IPS is an interdependent system in which every component interacts with the others in multiple ways. Attempting to control this complex and interconnected system, which is MIMO, with an array of SISO controllers could be a harsh matter. If the regulators are set without paying attention to the interactions that could arise between them and the rest of the system, some problems, even serious, could occur. In fact, it is a common practice to allocate the design of electrical machines, regulators, and protection systems to different entities. These normally do not communicate among themselves, and they do not utilize complete models of the ship's IPS or perform transient's analysis and simulations (except for some special simplified cases). Moreover, the results of the design are often tested only after installation on board. In this way, the

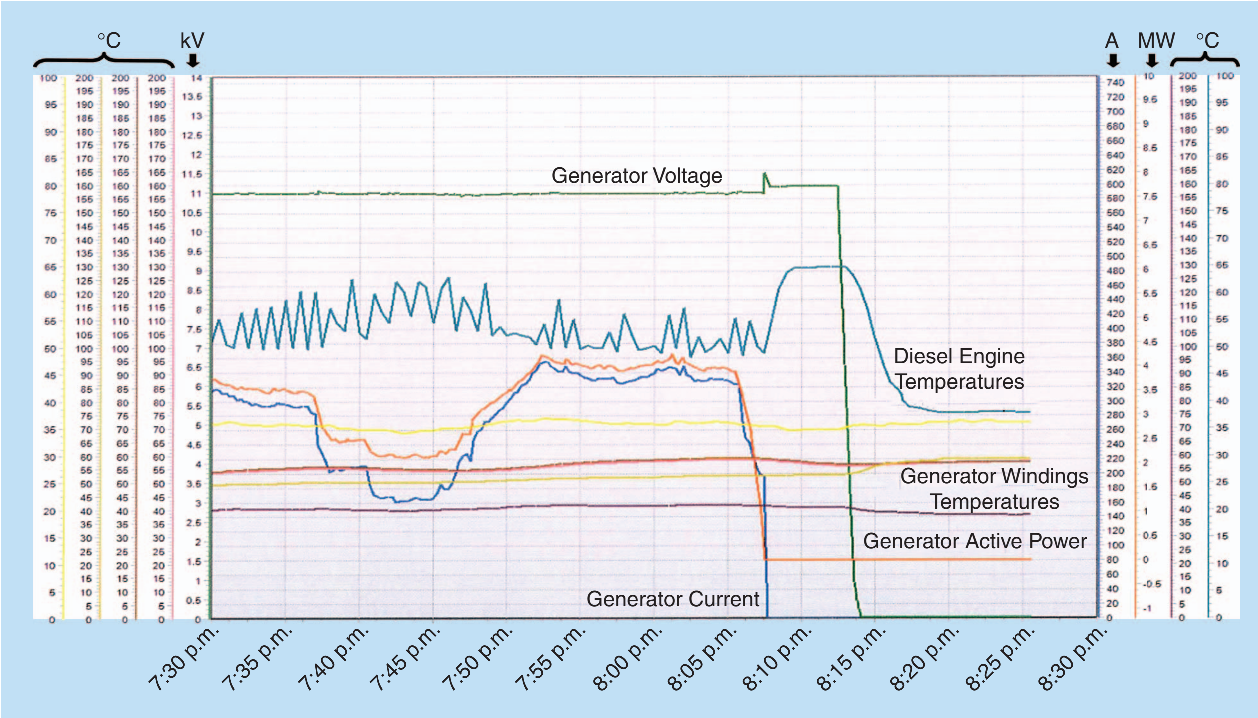

Figure 13. The ship's automation print screen of a generator's main variables during its disconnection.

complex interactions hidden in the system could not be analyzed and taken into account, which sometimes causes power quality problems (varying from important variations in the busbar voltage to blackouts).

With the aim of maintaining the correct operation of the IPS, three different main categories of devices are implemented: generator sets' controls (voltage and frequency regulators), the ship's PMS, and the protection devices (e.g., short circuit and overload relays, which control system's circuit breakers). Voltage and frequency controllers, such as the protection devices, are well known and are common to the land-based systems. The PMS, instead, is a peculiarity of the naval power systems. Since the IPS is an islanded grid and it is necessary to control the entire ship using as few crew members as possible, it is necessary to have an automation software that controls the IPS at every instant. The PMS makes it possible to:

- manage generators, high power loads, and automatic breakers of the power plant
- view and register system behavior
- manage the active and reactive power that flows in the IPS.

To achieve an optimal management of the entire IPS, and to obtain a fast and proper response to fault conditions, it is mandatory to design these three categories of devices as a coordinated ensemble.

An example of poor system integration is an electric incident that occurred on a cruise ship during sea trials. This incident quickly degenerated into a blackout, which is the most dangerous situation for an AES because it causes a complete loss of the ship's control. It is obvious that this situation could be fatal if the ship is maneuvering in a port when the blackout occurs. The subject of this situation had a common IPS architecture, with six generators connected in groups of three to two interconnected distribution switchboards. All of the users were fed by these two switchboards, directly (harmonic filters, high-power induction motors, and propulsion converters) or by means of transformers. The incident occurred during sea trials, when the ship was maneuvering in a channel.

The entire incident is shown in Figure 15, which provides the currents of the generators as well as the propulsion drive (two current traces for every propulsion converter due to the 24-pulse-drive architecture). Three generators were connected to the bus, together with two harmonic filters. The load was low, consisting mainly of the propulsion in low power mode (due to speed limitations in the channel), five thrusters

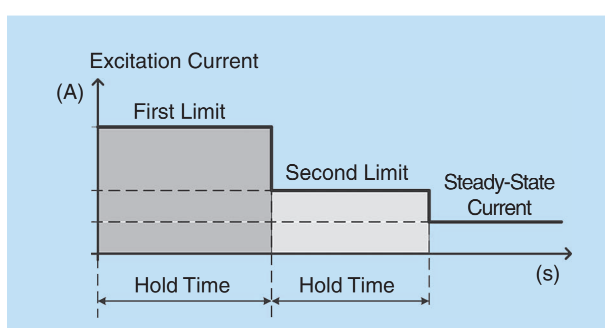

Figure 14. The AVR's time-based excitation current-limiting thresholds.

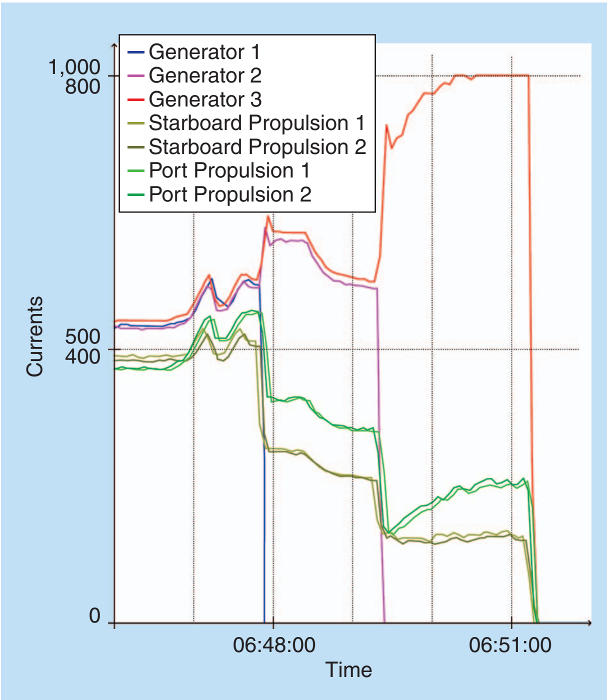

Figure 15. The experimental record of generator (1,000-A scale) and propulsion (800-A scale) currents during the incident leading to blackout.

in idle waiting for possible maneuvers, some air-conditioning compressors, and low hotel load (the ship was mainly unoccupied). The resulting power factor was quite low. One of the generators suddenly failed because of a lubrication fault, causing an automatic removal of one of the harmonic filters to avoid reactive power overcompensation. In a short amount of time, another generator failed because of the same lubrication problems (the lubrication circuit is in common to a group of generators). This caused the automatic removal of the remaining harmonic filter (along with its power factor correction function), which, in turn, caused overexcitation in the remaining generator. The PMS automation did not detect the reactive overload because of a sensor fault on the remaining generator, so it did not react to the situation. Moreover, it allowed a propulsion power increasing command, worsening the situation.

The increase in the reactive power required from the propulsion brought the remaining generator to saturation, and, as a consequence, the system voltage progressively dropped. At this point, protections operated, leading the system to the blackout. Analyzing what happened, it is obvious that the basic cause of the incident was the poor integration between the ship's control and protection systems. Indeed, the technological limitations of the equipment employed make it impossible to realize effective system integration. Fortunately, in the last few years, the trend is to increase the PMS managing functions, sensors, and actuators, acquiring more data from the system and acting more and more as an integrated platform management software, but there is still a long way to go.

Simulators

Today, system design is done by decomposing the IPS in little, noninteracting subsystems. As previously stated, this procedure can sometimes lead to incorrect design, discovered only when the ship is assembled, and then to expensive modifications to be done after the installation on board.

Software tools capable of simulating the behavior of the whole system are proving to be more and more a key feature that is essential for the IPS's accurate design. Obviously, the creation of an entire shipboard power system simulator is a difficult and time-consuming operation. Nevertheless, the possibility to experiment with different settings for the system's regulators and protections, and also to try different logic procedures to manage the loads, is worth the cost that the simulator creation implies.

In particular, it should be noticed that the use of a simulator permits one to know the system's responses when it is not yet assembled, in a short amount of time, and permits the same test conditions to be applied in every trial. The latter point is important because when tests on real systems are done, it is not possible to fix exactly the same conditions, meaning that sometimes the results are not comparable to each other. Moreover, the most relevant advantage of using a simulator is the possibility to run tests that would bring the system into dangerous conditions. In this way, it is possible to analyze particular situations (such as fault transients) without damaging the devices or creating harmful situations for the crew and the surroundings.

Realizing a single simulator that is capable of modeling the entire IPS function in every condition and for both short- and long-term dynamics is a harsh matter. A short-term-dynamics-tailored simulator will take a very long time to perform a long-term-dynamics simulation because of the computation of fast transients, which did not affect, to an appreciable extent, the long-term behavior. Likewise, a long-term-dynamics-tailored simulator cannot perform short-term simulations because of the removal of the fast dynamics, which is done with the aim of reducing the computational work. Accordingly, it is important to accurately define the scope of the simulator and then build it by applying the appropriate simplification hypotheses.

The proper solution could be the realization of a certain number of different simulators tailored to the needs of the designer. For example, short-term-dynamics simulators could be realized with the aim of studying the single component's behavior, while long-term-dynamics simulators could be realized to study an entire IPS's behavior. As an example, given the typical bandwidth of voltage control, a simulator customized for this study could be created using the hypothesis to consider only electromechanical transients. In doing so, several simplifications could be accomplished (some of them strong, e.g., totally algebraic load's network) to obtain a simplified simulator, which is faster than a complete one that is dynamic.

Before being used, a simulator must necessarily pass through a tuning and validation procedure. The mathematical

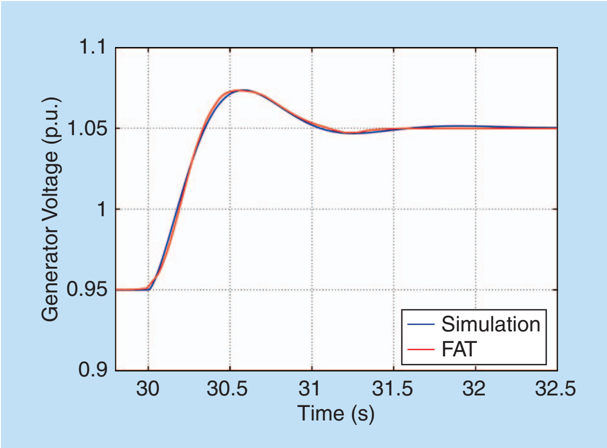

Figure 16. A diesel generator factory acceptance test (FAT) and simulation confrontation, no-load voltage reference step variation.

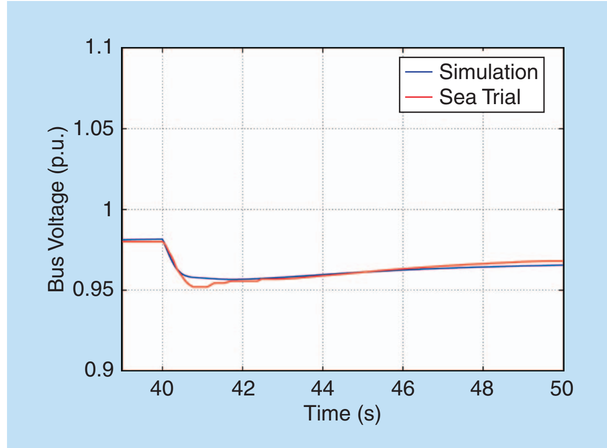

Figure 18. A sea trial and simulation confrontation of the generator's parallel operation, voltage transient due to one generator disconnection.

representation of the system's physics usually needs to be simplified to achieve reasonable simulation times and a low computational load. In addition, when a mathematical model is created, some less relevant phenomena are normally ignored because they do not significantly affect the system's behavior. Because of these facts, the simulation procedure leads to results that do not perfectly match reality. Hence, simulator tuning is mandatory and is done by means of some parameters' variations. The aim of this procedure is to reduce the differences between the simulation and reality as much as reasonably possible.

The tuning and validation procedure can be realized using some of the most common tests on the IPS's components that are normally done during the ship's construction. For example, the factory acceptance tests (FATs), done by the electrical machine's producers before the delivery, permit the tuning of the generators' and motors' models. As an example, Figures 16 and 17 show the results of a generator's model validation, which compares the voltage and frequency responses of the real system and the simulator when the same solicitations are applied. Conversely, Figures 18 and 19 show the comparison between the simulated and real variables, which is done using the parallel operation test results carried out during the sea trials. All of these simulations have been made using a software simulator created assuming the previously stated simplification hypothesis (electromechanical transient's simulation). Obviously, the tuning and validation procedures imply that the real system has already been built, making the simulator less useful for the design of the vessel since it can be validated only after the ship's construction. Despite that, once validated, the software can be effectively used for both new ships' design or for testing modifications on the constructed ship.

Important Simulator Applications

A first relevant application of an IPS simulator is to help in setting the generators' controllers. Indeed, it is possible to try different values for the AVR's and SG's parameters, applying the same loads and disturbances to the system,

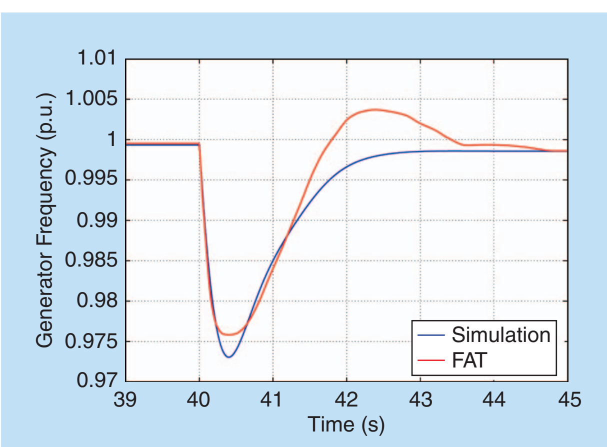

Figure 17. A diesel generator FAT and simulation confrontation, active load step variation.

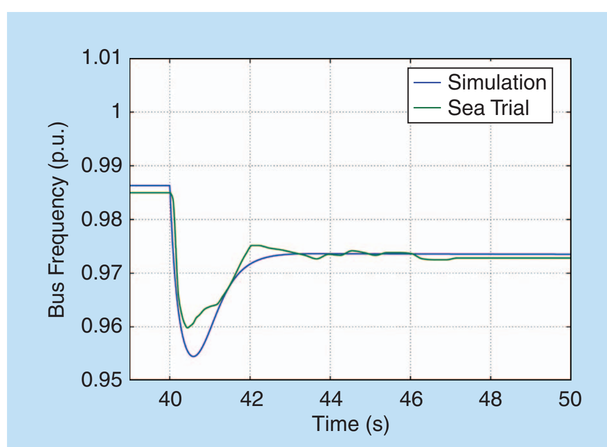

Figure 19. The sea trial and simulation confrontation of the generator's parallel operation, frequency transient due to one generator disconnection.

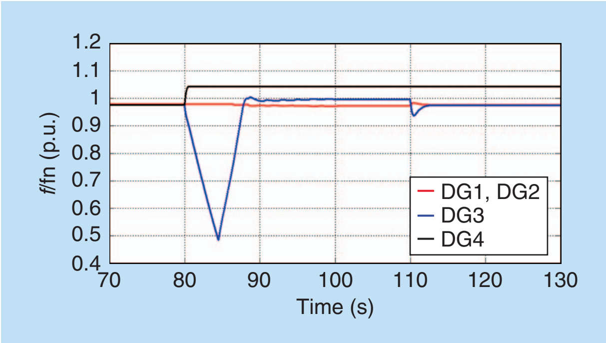

Figure 20. The simulated generator's frequency transients during an emergency reconfiguration procedure.

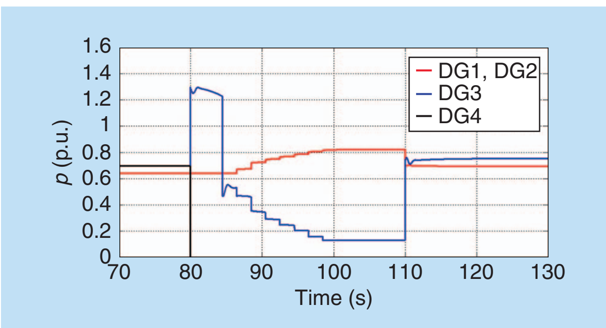

Figure 21. The simulated generator's active power transients during an emergency reconfiguration procedure.

and evaluate which is the best setting. In this way, it is possible to tailor the controllers to the particular IPS that has to be realized, achieving high performances. Also, by introducing the protections' logic in the simulation software, the behavior in fault condition can be assessed and the effects of the interactions between the protections, loads, and generators setting can be ascertained, limiting the system integration issues (like the one examined previously).

TABLE 1. Restoring the Operative Sequence.

Time (s)	Operation
80	Loss of diesel generator 4
84.5	Shut down of aft propulsion converter
86.5	Commutation of secondary switchboard (SSB) 2-2 from aft to fore low-voltage main switchboard (LVMSB)
88.5	Commutation of SSB 2-3 from aft to fore LVMSB
90.5	Commutation of SSB 2-6 from aft to fore LVMSB
92.5	Commutation of SSB 3-1 from aft to fore LVMSB
94.5	Commutation of SSB 3-5 from aft to fore LVMSB
96.5	Commutation of SSB 3-6 from aft to fore LVMSB
98.5	Commutation of SSB 1-2 from aft to fore LVMSB
110	Fore and aft propulsion converters power variation to a value of 70% for both
130	End of simulation

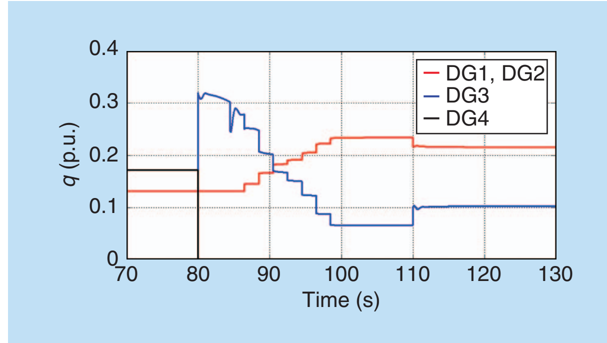

Figure 22. The simulated generator's reactive power transients during an emergency reconfiguration procedure.

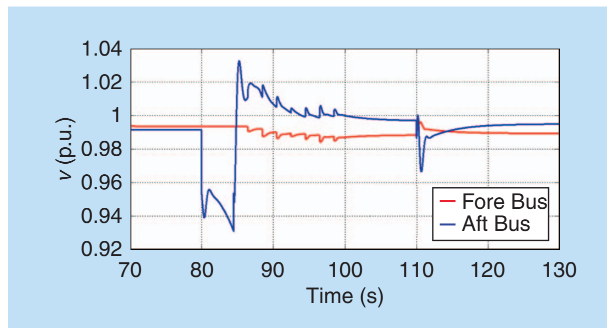

Figure 23. The simulated generator's busbar voltage transients during an emergency reconfiguration procedure.

Analyzing the simulations made for fault conditions (e.g., a generator loss), emergency actions can be defined, with the aim of maintaining the IPS in operative conditions. Various reconfiguration logics can be conceived, tested on the simulator, and compared, choosing between them with awareness. An example of a simulated reconfiguration procedure is reported in Figures 20–23. The ship's IPS is the one presented in Figure 7, endowed with hybrid propulsion. In the case examined here, the slow-speed propulsion is active, so the converters act as propulsion drives. The fault considered is the loss of one generator (DG4) on the IPS while loaded with propulsion drives and a series of low-voltage loads (LV Load). The two IPS busbars (fore and aft) are maintained separatly for the entire reconfiguration procedure (Table 1). As can be seen, the loss of the generator causes a fast frequency fall (Figure 20) because of the active power overload on the remaining generator (DG3, Figure 21). By temporarily removing the propulsion load and commutating some loads from a busbar to the other, a new sustainable configuration is reached. In this case, the power of the remaining generators is sufficient to reactivate the propulsion, even if at a reduced load.

The main variations in the busbars' voltages occur according to the reactive power variations (Figure 22), but one transient is to be noticed in particular: the first after the generator disconnection. As can be seen in Figure 23, after a little voltage recovery at 80 s, the voltage falls despite the almost constant reactive power load until the propulsion drive disconnection. This behavior is related to the frequency drop. Indeed, the rotating exciter output (which is the input of the main generator's excitation) depends on the rotating speed of the generator, and, under a certain limit, the frequency fall causes an exciter output drop that cannot be compensated by the AVR output rise (i.e., saturation of the excitation).

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Biographies

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Giovanni Giadrossi earned his M.S. degree in electronic engineering from the University of Trieste, Italy. He was a research fellow at the Italian National Research Council (CNR) and an assistant professor at the University of Trieste. In 1979, he joined the Department of Electrical Engineering, University of Trieste, as a full professor of electrical machines. He is active in the field of control systems applications of electrical machines and power systems. He is currently retired from teaching but is still cooperating with his former university group as research director for programs in the field of voltage control and medium-voltage dc power systems.

Giorgio Sulligoi earned his M.S. degree (with honors) in electrical engineering from the University of Trieste, Italy, in 2001 and his Ph.D. degree in electrical engineering from the University of Padua, Italy, in 2005. He spent an internship at Fincantieri Electric Systems Office, Trieste, and a semester as a visiting scholar at the University College of Cork, Ireland. In 2005, he joined MAI Control Systems, Milan, Italy, an Italian firm operating in the field of power stations and alternator voltage control systems. He joined the University of Trieste in 2007 as an assistant professor of electric power generation and control, where he was tenured in 2010 and appointed assistant professor of shipboard electrical power systems in 2012. He is the founder and director of the grid-connected and marine Electric Power Generation and Control laboratory at the Department of Engineering and Architecture. In 2013, he received the national qualification for the level of associate professor in electrical energy engineering. He has authored more than 70 scientific papers in the fields of shipboard power systems, all-electric ships, generator modeling, and voltage control. He is a Senior Member of the IEEE and a member of the Industry Applications Society, the Power Electronics Society, and the Power & Energy Society, where he serves in different technical and standard committees.