

Distributed Energy Resources On-Board Cruise Ships: Integration into the Ship Design Process

Giordano FLORE^{a,1}, Diego NERONI^a, Thomas LAMBERTI^b, Paola GUALENI^a,
Loredana MAGISTRI^b, Federico SILVESTRO^a and Andrea PIETRA^c

^a*University of Genova, Department of Electrical, Electronic, Telecommunication
Engineering and Naval Architecture (DITEN)*

^b*University of Genova, Department of Mechanical Engineering (DIME)*

^c*Fincantieri S.p.A, Merchant Ship Business Unit - Electrical Power System Department*

Abstract. An intense innovation activity is characterizing the energy system solutions on board ships, especially in the case of large passenger ships due to the significant total amount of installed power and the variegated typology of electrical loads. In the paper the solution of a distributed energy system will be considered for a 140.000+ GT cruise ship, in the perspective of a superior performance in terms of safety and energy efficiency. The target is to overcome the traditional concept of power generation based on large diesel Gensets located in few compartments. The innovative proposal is to integrate it, for the hotel needs, with a greater number of power generation units (but of a smaller size), properly distributed on board. For the application, a suitable reference cruise ship vessel will be considered, already characterized by LNG propulsion solution. Number, typology, size and integration on board of the generation units will be defined in relation with aspects of zonal independence, electrical load, weights, volumes, fuel tanks, supply systems, auxiliaries, with the minimum possible impact on commercially valuable space. In this perspective, fuel cells technology will be particularly taken into account. The critical issues in relation with the present safety rules and the whole ship design process will be addressed as a fundamental aspect.

Keywords. Ship Power System, Distributed Energy Resources, LNG, Fuel Cells, Microturbines, Design Process

1. Introduction

Electrical generation is a critical aspect on board any type of vessel and in the latest decade a consolidated trend towards all-electric ship design for large passenger ships can be identified. In this kind of vessels electrical power is used not only for on board services but for the main propulsion as well. Electrical generation on board is made up of large diesel generators (Genset), where chemical energy contained in fuels is converted into electricity through thermal transformations. The energy is used for both

¹ Paola Gualeni, Associate Professor, University of Genova, DITEN - Department of Naval Architecture, Electrical, Electronic and Telecommunication Engineering, Via Montallegro 1, 16145 Genova, Italy; E-mail: paola.gualeni@unige.it.

propulsion and hotel services, but gensets are localized in few engine rooms and the power is delivered through cables to all final users scattered on board. This design approach has some strong and very reasonable basis, allowing for example to delimit zones where safety related issues like fire can be identified as a significant hazard [1-2]. At the same time all outlet gases and inlet ventilation piping and casings are confined in a few astern zones. This choice is simple and safe at the same time.

However, the use of large diesel generators brings some criticalities [3], like production of large amount of NO_x, SO_x and CO₂ due to the inherent thermal transformations, low performance due to Carnot cycle limits, vibrations and noises due to mechanical components and difficult optimal management on the engines working point in different operational situations. In the perspective of a superior performance in terms of system efficiency, reliability, safety and environment protection, an innovative distributed power system has been investigated. The purpose is to overcome the traditional concept of power generation with installation of a greater number of small generating elements properly distributed on board and integrated each other through an appropriate electrical distribution grid. This design philosophy increases the system's flexibility, reliability and it can prevent the energy black-out on board also in emergency events like flooding and fire. This new design approach is applicable to highly specialized types of ships that require a large amount of electrical power nearly continuously available, as large passenger ships or ferry. It is simply not necessary onboard cargo ships, where the most volumes on board are occupied by cargo holds and the power demand is very small in relation with the propulsion power [4]. In these cases, a traditional approach is still the best solution.

2. New approach to design

As already mentioned in the present paper a new ship design concept has been developed. The challenge is to overcome the traditional system layout splitting the power production in a superior numbers of smaller generation units, to be located in each of the Main Vertical Zone (MVZ) already defined onboard that represent a suitable ship modularization for the purpose of the activity [5]. Engine room as traditionally conceived is modified, each MVZ has its own machinery space that is potentially independent from the others. Power generation distribution has strong positive attributes in terms of energy availability and delivery flexibility but it implied as well distribution of shortcomings like possible safety hazards and volume/area occupation onboard. This involves new guidelines to be considered and in the following a list of the design issues that have to be properly tackled with is given with brief comments [6-7-8].

Electrical power load analysis has to be developed for each MVZs. These have its areas with different main purposes and characteristics, systems, load users and they have an influence on the electric and thermic local balance which can be much different among MVZs. A global balance is now less meaningful and useful.

Power generation distribution is definitely more demanding in terms of ship areas and volume involved and it is more complicated to locate generation units on board.

Each technical room for Power Generation Unit (PGU) to be installed must be wide enough to accommodate generation units and its auxiliaries, with due care about the safety issues requirements. New "machinery" volumes have to be distributed on board influencing the traditional arrangement.

The weights of PGU are not all located in a few compartments on lower decks anymore, but they are now distributed in several “machinery” rooms located also at higher decks.

The new distribution of weights influences the ship attitude and stability. As described above it is likely that the Vertical Center of Gravity (VCG) moves up with negative impact on stability criteria.

Decks local strength must be assessed in all new machinery rooms.

Each PGU is to be integrated with the main electric power distribution grid to supply all ship energy demand and/or the local power demand only. From this perspective, the MVZ can be self-contained or connected to adjacent zones. This aspect depends on the selected electrical grid model.

Fuel supply system is a very critical aspect. In the case of fuel cells as PGU, the new technologies use LNG, methanol or hydrogen as fuel that are intrinsically more dangerous than diesel. International rules are more stringent for these low ignition fuels requiring double walled piping for fuel supply with inert gas between layers or appropriate air change. Safety rules requirements for tanks location are defined as well 2 m higher from base line and over B/5 distance from side for fuel storage. All these regulatory constraints limit the possible tanks locations on board: in particular the impossibility to install fuel tanks in the double bottom might imply an increment of ship center of gravity.

New exhaust “fluid” systems have to be designed. Each MVZ needs an exhaust fluid system treatment and an engine casing. As an example, the reformer system, necessary for hydrogen generation from LNG, produces carbon dioxide as a waste product that needs to be expelled. It worth reminding that fuel cells produce water that can be expelled locally or reused on board for hotel services or cogeneration.

The PGUs air supply system requires accurate design in order to minimize the loss of volumes to be destined for piping and casing.

Heat exchange and cogeneration actions in general became even more important to improve PGU overall efficiency. Each power source must be provided with heat exchangers with the specific aim to provide cogeneration at a local level.

The issue of noise & vibrations is to be discussed as well even though the selected technologies for PGUs are deemed to have a low impact in this perspective: fuel cells and energy storage by battery packs have no mechanical part and no vibrations or noise irradiation consequently. Small turbines or dual fuel engines can be simpler isolated than large generators now in use.

Safety is a critical aspect. Distributed engine rooms imply distributed hazards and safety measures to be replicated in every MVZ. Due to the kind of fuel (LNG and hydrogen) safety measures are even more severe. Just as examples of what just mentioned, each generation room must have its own fire insulation and fire systems; LNG tanks room must be protected by cofferdam and piping are double walled to prevent explosion or toxic leakage.

Continuity of service and reliability of the whole energy system is intrinsic in the innovative concept of a distributed system, and a single MVZ can help the adjacent zone in case of failure. The reliability and the need for maintenance of innovative technology like fuel cells in marine application are still to be supported by field data.

The use of LNG or hydrogen has also refueling issues. Nowadays few ports are equipped with LNG and/or H₂ bunkering facilities and, in any case, refueling actions must be carried out carefully.

A typical electric power load analysis on a modern cruise ship puts in evidence that about 70-80% of the total produced power is delivered to propulsion system, and the other 20-30% is used for accommodation services. From the analysis of the zonal load and the technology available at present, it appears that we have to focus our attention on hotel services only. With the current state of the art technology is not practically feasible to cover all the propulsion and hotel power demand in one solution.

The innovative approach integrates onboard new technologies, like dual fuel engines [9], gas turbines [10] or fuel cells [11]. The latter are very promising for future developments in the maritime field and its highly modular nature is suitable to the new enhanced configuration in the next years.

3. Application case and system design applications

The reference vessel considered in this application is a typical 140000 GRT Fincantieri cruise ship. The 22 knots design speed is provided by 2 fixed pitch propellers supplied by 2 electric engines located in an astern compartment. In navigation the total power demand, for both propulsion and hotel services (for 5600 passengers), is little less than 50 MW supplied by 4 diesel engines Tier II compliant located in two different astern engine rooms. As already mentioned, the installation of a Distributed Energy Resource (DER) system on board needs volumes for LNG fuel tanks storage, PGUs, fuel supply systems, inlet and outlet piping, casings and appropriate electric connections [9-10-11]. In order to DER installation, the reference ship needs preliminary deep transformations, such as:

- installation of 2 symmetrical azimuth units for main propulsion, in order to avoid rudders, stern thrusters and the 2 electrical propulsion engines [12-13];
- separation between hotel and propulsion electric power supply in order to reduce the main Gensets size and exploit them for propulsion supply only;
- replacement of the original 4 diesel engines with smaller 6 dual fuel engines Tier III compliant. This type of engines uses both LNG as main fuel and Marine Diesel Oil (MDO) for ignition phase only [14-15];
- installation of several LNG Type C tanks, as required for propulsion and for hotel services, in relation with the assumed range and endurance [16-17].

All these actions have the purpose to convert the reference ship in a LNG dual-fueled vessel [18-19-20], and to recover new precious volumes on board for the DER system elements. As previously described, PGUs installation is meant for hotel loads only. So, about 20-30% of the total energy amount needed on board needs to be covered by the innovative distributed energy system. The remaining 70-80% is loaded on the dual fuel engines. In the case studied, the hotel load is about 7 MW that is provided by the distributed system. The reference vessel is divided into 7 MVZs, numbered from bow to stern. In order to provide the zonal load through a homogeneous local size of the PGUs, it was considered to install a single 800 kW PGU in the first five MVZs and double 800 kW units in the last two MVZs, for a total of 9 PGUs connected with the main electric power distribution grid.

Due to the large amount of installed power generation, the physical proximity with the power loads, the island configuration, shipboard power systems can be defined as marine microgrids. In this context, it would be possible and useful to adopt some technologies and practices developed in recent years for terrestrial microgrids [21]. The

main objective is to guarantee the continuity, flexibility, reliability and sustainability of the service for an optimal management of the ship. A smart design of the shipboard power system associated with the implementation of (DER) can represent a disruptive technology in the perspective of increasing the ship's efficiency, reliability and decrease at the same time its environmental footprint.

The requirements of a power generation system for on-board DER are mainly: Power Density (PD-kW/l); Specific Power (SP-kW/kg); Noise & Vibrations and Cogeneration capabilities. Among the present available technologies [3], the ones that seems to better comply with the requirements are Fuel Cells (FC) and Micro Gas Turbine (mGT).

3.1. Power distribution system architecture

The power distribution system of the reference vessel can be defined as a radial configuration composed by a primary distribution in High Voltage (HV) (to this regard it is worthwhile mentioning that, in the shipbuilding field, a voltage above 1MW is already deemed as HV) and a secondary distribution in Low Voltage (LV), at 11 kV and 690 V, respectively. The primary distribution system presents two main buses where propulsion motors, compressors for heat ventilation and air conditioning system and thrusters are connected. On the other hand, the secondary distribution system in LV is composed by seven "accommodation substations" provided with 690V, 230V and 120V sections and two "galley substations" provided with 440 V, 230V and 120V sections. Finally, two "engine room substations" feed the auxiliary users in LV through 4 service sections, while the other two spare sections are connected to the other seven accommodation substations as back-up lines. Therefore, the total number of distribution transformers installed is equal to fifteen (i.e. excluding the transformers for the propulsion). In order to implement the DER into the shipboard power system, a new grid configuration similar to those adopted in terrestrial microgrids is proposed in Figure1. The Nine generation units are connected in LV to the accommodation and galley substations (e.g. one unit for each substation) in order to cover the zonal demand of power. Furthermore, the following changes are expected compared to the actual configuration:

- the accommodation substations, which are positioned in each main vertical zone (MVZ) of the ship, have been connected in LV in order to group these substations depending on both the load characteristics and the positions on board (e.g. MVZ 1-2, MVZ 3-4-5, MVZ 6-7). Moreover, also the two galley substations have been connected to each other (e.g. as proposed in red in Figure 1);
- as a consequence of the substations grouping, the total number of MV/LV transformers has been reduced from nine to four. Being these transformers used in case of failure of one unit of the DER, it has been possible to maintain the same rated power of those installed in the case study (i.e. 2.35 MVA);
- the backup safety lines from the engine room substation spare sections to accommodation substation can be deleted maintaining the same degree of reliability of the system due to both the installation of the DER and the interconnection lines between the substations.

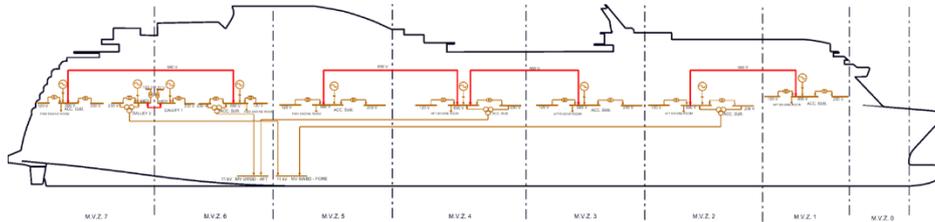


Figure1. Radial configuration of the grid with DER and MVZ grouping.

The flexibility and reliability of the whole system has been increased by introducing the DER and implementing the proposed grid configuration. However, it is to be noted that these improvements would require more complex and sophisticated power and energy management systems.

3.2. Description and installation of Microturbines system

The mGT technology considered for this application is a boxed system that incorporate the Turbine, the Compressors, the Combustion Chamber, the Heat Exchanger, the Current Conditioning System and all the smaller Auxiliary systems [22]. The mGTs power installation is composed by:

- the mGT,
- the mGT Fuel System,
- the mGT System controls
- the mGT High power electronics.

All the assessed systems are made by modular components composed by 100 or 200 kW turbines. The mGT system used is an 800 kW Capstone module [10], made of four 200 kW modules installed inside a compact enclosure of 65 m³ over a deck area of 22 m². mGTs can be directly fed by natural gas supplied by the LNG storage.

Kept in mind the issues exposed at paragraph 2, the microturbines based PGU system installation is described below. Microturbines, auxiliaries, voltage converters and inlet and outlet piping have been placed in a single A-60 insulated volume [23]. Each microturbine has its own 60 m² room, mainly located at deck 8 to reduce the outlet piping extension (as shown in orange in Figure 2). Three bilobed Type C tanks placed at deck 1 in MVZ 4 supply the all PGU systems: LNG is treated in a pre-tank room and it is distributed by double wall piping, exploiting the inside tank pressure itself [17-18]. Propulsion and hotel LNG tanks are independent from each other. For an endurance in terms of hours ranging between 100 and 200 hours about 600 m³ of LNG are provided for microturbines system only. Fresh air is taken from existing adjacent AC Stations while exhaust gas piping is routed through engine casing or near existing vertical large casing like stairs or lifts trunks [24].

Although the weight of each microturbine is about 20 tons, ship's Vertical Center of Gravity (VCG) is not significantly influenced. Major effect is due to the capacity tanks modification i.e. three Type C tanks on deck 1 and the elimination of the HFO form the double bottom. The combination the above described actions increases the VCG for about 0.30 m.



Figure 2. Distributed Microturbines system on board.

Orange: PGU room; red: fuel supply system; yellow: outlet piping; blue: inlet piping

3.3. Description and installation of Fuel Cells system (FC and Reformer)

Proton Exchange Membrane Fuel Cells (PEMFC) have been found as the most suitable FC technology for the short-medium terms ships applications [11]. PEMFC are characterized by good performances in terms of PD (0.24 kW/l), SP (0.29 kW/kg).

A typical Fuel Cell Power Installation is composed by:

- a Fuel Cell Power System,
- the FC Auxiliary Systems,
- the FC Control System,
- the DC Power Conversion and
- the FC Safety System

The list is exhaustive in all the necessary element. For sake of completes it is worth mentioning that at present IMO rules focus on FC Power Installation addressing only the following aspects:

- FC stack,
- the Primary Fuel Process Unit
- the Air Process Unit.

Future developments on international rules side are expected. The most voluminous and heavy component of the system is the Fuel Cell Power System made by Racks of Fuel Cell Stacks connected together to reach higher power. LNG supply has been considered for the FC system, even if PEMFCs require a pure hydrogen supply only. The main issue from the storage system is represented by the LNG reformer unit, indeed no marine system has been found on the market and an assessment on the performance of the main compact stationary applications Steam Reformer (SR) systems has been conducted. The high volume and weight required from the reformer is worsen by the large amount of fresh water required. A last consideration need to be done on the total efficiency. Even if the fuel cell efficiency is high, the total electrical efficiency results to be low (30%-36%). For this reason, cogeneration is important in order to enhance the total system efficiency [25-26].

In this solution, onboard location of reformers is a big challenge. Each reformer occupies about 60 m² area, the same as an 800 kW FC module, and a CO₂ outlet piping must be provided [27]. The total weight amount of what above mentioned is about 70 tons, and we must consider that a single FC produces about 12 tons per day of water as an electrochemical conversion product. FC and its own reformer are placed in the same 200 m² A-60 insulated room, to minimize hazards due to hydrogen piping supply, reduce the global number of risk sources and reduce the volumes demand. As a consequence, all system elements have been located on the lower decks, mainly at deck

3 and 4 (as shown in Figure 3). The driving criterion for location was the lower impact as possible on valuable areas form the commercial point of view on internal passenger cabins, crew cabins and technical areas have been modified. Fuel tanks are located in the same position described in the microturbines configuration, and its dimensions are pretty the same. LNG supply system is the same described in paragraph 3.2 and hydrogen piping is double walled anyway [18-24].

Each reformer for a PEMFC needs about 2 tons per hour water supply. Therefore, 2 daily water storage tanks are located in the double bottom and the main water flow comes from board fresh water-makers and a small part from FCs themselves. The reformer itself provide heat to start and supply the reforming reaction by taking a small percentage of LNG inlet to feed an internal burner. Cogeneration could be done by heat generated in the FC. Future considerations on weights distribution and stability implications will be made.

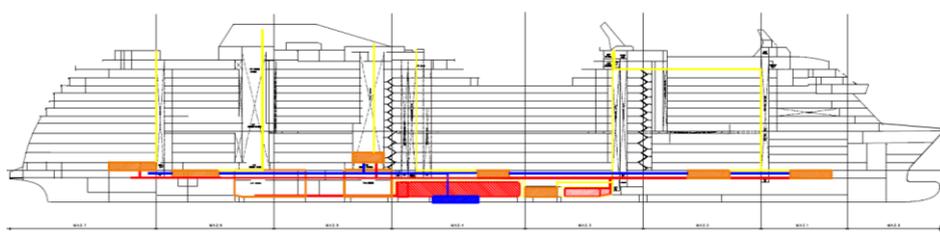


Figure 3. Distributed Fuel Cells system on board.

Orange: PGU room; red: fuel supply system; yellow: outlet piping; blue: water supply system

4. Future Developments

In the context of fuel cells technology, the scenario is wide and in continuous development. In the future, Solid Oxide Fuel Cells (SOFC) technology is likely to capture the attention in the marine applications.

SOFC are ceramic based fuel cells that works at high temperatures (800-1000 °C) and are believed to become the most suitable fuel cell type for marine applications, due to a number of factors:

- High electric efficiency (up to 60% only fuel cell, up to 70% in hybrid GT configurations);
- Good cogeneration (hot water or vapor) with higher efficiencies;
- MW size systems;
- Possibility to be directly fed with Natural Gas.

These positive characteristics are unfortunately in balance with some shortcomings i.e. fragility to vibrations (IBC ASCE class D, high seismic vulnerability), a present less mature technology and high cost also due to the limited number of system producers. Moreover, high temperatures and high thermal capacity require long start-ups and shut-down procedures that pose operations and safety issue. For these reasons, SOFC will probably find applications on-board ships in the medium-long period enabling the transition from medium power fuel cell systems based on PEMFC for auxiliary loads and small propulsion to high power SOFC able to propel the ship.

5. Final considerations

Microturbines and fuel cells technology implementation have different impacts on the ship design. In the short-term time, gas microturbine technology appears as the more mature and results in a lower system complexity. Microturbines have small impact in terms of areas on decks but they require big diameter air intake piping to work properly and consequently big exhaust gas piping, with a not negligible impact on internal volumes distribution and vertical openings.

The present PEMFC technology needs an external reformer to obtain hydrogen from LNG, therefore has a major impact in terms of areas on decks and weights, but piping impact is reduced. As a result of the application it has come out that FC solution requires about five times mGT solution area on board. The FCs solutions higher impact is due mainly to the reformer system. In the case of FCs, the major influence is on the spaces originally devoted to Crew Cabins and Hotel Services. This in turn can imply that a redistribution of spaces onboard is needed, in particular between passenger and crew cabins to maintain the original passengers/crew ratio.

In terms of energy management, microturbines have a better dynamic response to load increase and its optimal work point, with high efficiency, is on high load. FC system allows a better energy setting and splitting because of its efficiency is independent from power system dimensions. Their dynamic response is less performing and in case of variable load, batteries system is needed. In term of noise & vibrations FCs are an outstanding solution, with positive influences the passenger comfort, instead the microturbines acoustic emissions are about 65 dB.

It is worthwhile to stress again that a more complex energy system onboard calls for a higher attention to the ship energy management during ship operation. Therefore, a close collaboration between the shipyard and the owner is more and more advisable during the design phase, in the perspective of a ship superior energy efficiency deployed along the ship life.

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