

Research Article

PV Systems Installed in Marine Vessels: Technologies and Specifications

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Considerations are held about the specification in which the PV plants have to fulfill so that they can be installed on marine vessels. Initially, a brief description of the typical electrical grid of ships is presented, distinguishing the main parts, reporting the typical electrical magnitudes, and choosing the most preferable installation areas. The technical specifications, in which the PV plants have to be compatible with, are fully described. They are determined by the special marine environmental conditions, taking into consideration parameters like wind, humidity, shading, corrosion, and limited installation area. The work is carried out with the presentation of the most popular trends in the field of solar cell types and PV system technologies and their ability to keep up with the aforementioned specifications.

1. Introduction

Without doubt the last decade was the golden age of the photovoltaic systems. The large number of technological breakthroughs on the research areas of power electronics, photovoltaic (PV) panels, and microgrids made the use of PV panels feasible to numerous applications of modern life.

The PV systems of today generate electric power that ranges from W to MW. Small solar chargers for portable devices such as laptops, cell phones, and calculators are very popular. Single or arrays of PV panels produce electric power for street lights, advertising signs, isolated agricultural electric pumps, even small houses not connected to the utility grid. In addition, PV systems, wind power systems, batteries, fuel cell generators, and other renewable energy systems work together and organize reliable microgrids [1–4]. But the most common PV applications are the grid-tied ones, where single PV panels or large scale PV plants apply auxiliary electric power to the grid [4–7].

Despite their extended use at mainland applications, the PV systems presence in modern marine technology remains

limited, mainly working as suppliers to small lighthouses, buoys, and chargers for the batteries of small sailing yachts [8, 9]. The rising transport expenses due to the fuel prices, the increasing restrictions of CO₂ and nitric oxides NO_x emission due to new ecological policies, and generally the need for more eco-friendly transportation were the reasons that forced the marine companies to reexamine the systematic use of PV systems on large vessels [10–12].

The photovoltaic technology can indeed be a really cost-effective solution for ships. PV systems can act as ideal subsidiary power sources, independent from the vessel electromechanical settlement because they [13–15]

- (i) produce electric power without the need of transferred gas or liquid fuel,
- (ii) have no by-products such as gas emissions or noise,
- (iii) have low maintenance cost,
- (iv) have limited or no use of mechanical moving parts,
- (v) consist of few parts, with easy installation and fast replacement in case of aging or defectiveness,

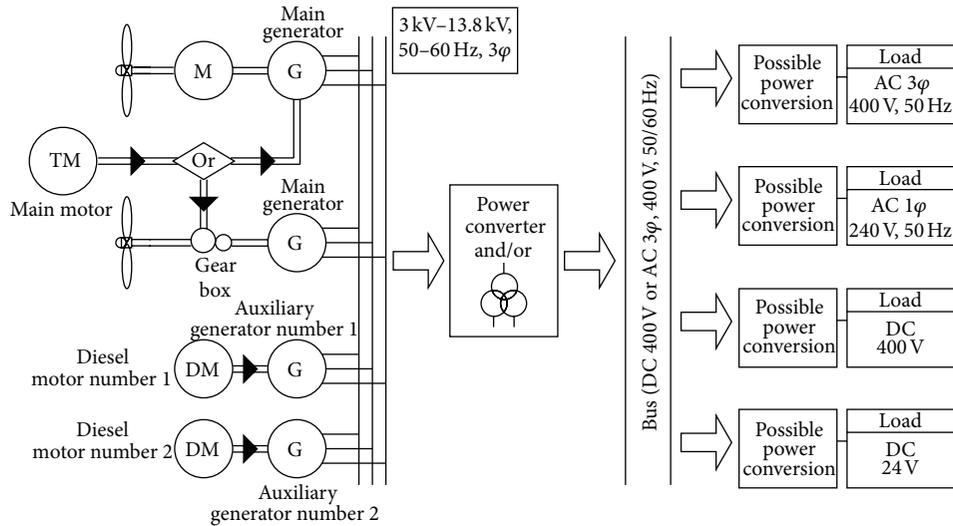


FIGURE 1: Diagram of a typical electrical system for a ship.

- (vi) have satisfactory life time with a warranted PV panel output power by the manufacturers, which usually cannot be less than the 80% of the nominal one after 25 years of operation,
- (vii) can be placed in small surfaces with no practical use such as roofs, walls, funnels, and superstructure,

In this paper, a research is held to give answers about how the most popular technologies of the mainland PV systems can be applied, and what specifications must be fulfilled in order to be appropriate for partially or fully electrical marine vessels.

2. The Electrical System of a Marine Vessel

Four separate areas can be distinguished in the electric system of a typical ship: the main propulsion engine, the generators, the main distribution bus, and the loads. In Figure 1, a diagram of a typical electrical system for a ship is presented.

A thermal motor consuming diesel or heavy fuel oil is used as a prime mover. Its rotational movement can be used either for both propulsion and electric generation, or exclusively for electric power generation.

In the first case, the generator is coupled to the shaft through a step-up gear. It is known to the worldwide bibliography as shaft generator; and according to its position, the type of coupling and the control equipment can be categorized into fourteen types [16, 17]. It aims not only to produce electric power for the ship but also, in certain cases, to operate as a propulsion motor and assist the main motor engine.

In the second case, the mechanical power of the thermal engine is dedicated only to drive the main generator. The generator simultaneously supplies the ship with electric power and drives an electric motor attached to the propeller. The propulsion system is known as integrated full electric propulsion (IFEP) configuration, and its main characteristic is that the shaft system is minimized, if not completely eliminated, that is, in the IFEP-pod case.

Besides the main generator, at least two additional auxiliary (diesel powered) electrical generators are connected to the electrical grid providing with electric energy. Additionally, in high load or breakdown cases (malfunction of main motor and/or main generator) they have to sustain the minimum operational standards of the vessel [18, 19].

According to the bibliography, the output voltages of the main and the diesel generators vary. Typical values of their magnitude and frequency are 3 kV, 3.3 kV, 4.16 kV, 6 kV, 6.6 kV, and 13.8 kV and 50 to 60 Hz [16, 20, 21]. With the help of power converters and transformers, the generated power is supplied to an internal bus that transfers the power in every load over the ship. The bus can be either AC or DC. The DC buses are more popular to modern naval ships while the AC ones to cargo and passenger ships. However, the research in progress investigates the most profitable solution for the large civil vessels. Typical values for a three-phase AC bus are the 400 V, 50 or 60 Hz and for a DC bus the 400 V.

The last part of the ship electrical system is the loads. Different types of loads are connected, but the most common are the DC 24 V and 400 V, the single-phase AC 230 V, 50 Hz, and the three-phase AC 400 V, 50 Hz loads.

Among the aforementioned parts of the vessel's electric system, the potential spots for the PV systems to be connected to the distribution buses along with the loads.

3. Technical Specifications for PV Systems in Marine Vessels

Even though the installation of PV plants to mainland is common and thoroughly examined, extra considerations must be done when they have to be installed on ships. The most important distinction between the mainland and marine PV applications is the environmental conditions, forcing PV systems to be more tolerant to extreme winds, high humidity, and salt.

The winds on a ship are characterized by their great mutability of direction and speed, a fact that has great impact to the orientations of the applied PV panels. The use of fixed tilt offers easy and strong embracement to the ship. The orientation is preferable to concur with the keel so as to help the vessel aerodynamic. But the fixed tilt results an important drawback. PV panels cannot fully exploit the sun radiation due to the variety of the ship routes and constantly changing latitude. PV plants with embedded tracking control system may offer more efficiency but have many mechanical moving parts which are vulnerable to ocean storms and are more expensive and need extra maintenance costs even higher than the ones of the corresponding on land systems. The golden mean is the use of PV panels placed tangentially to the ship surfaces. The air resistance of the PV panels to strong winds becomes negligible, and its incident solar radiation is hardly affected by the sailing routes. However, this type of orientation maximizes the necessary installation surface and stints the air flow behind the panels reducing the possibility of cooling.

The marine environment can be also harmful for both the electronics and the panels of a PV system. The high levels of humidity and salt can cause short-circuits and induce corrosion to the mechanical parts of the converters. The European Committee for Electro Technical Standardization (CENELEC) has developed an ingress protection rating (IP Code) that scales the electronic circuit protection levels from solid objects, materials, and liquids [22, 23]. According to this, the protection class of the converters embedded to the marine PV plants must be at least IP54 or IP54 W (especially the ones installed outside the ship's shell), making the ventilation weaker and the total cost higher.

To encounter the corrosion problems, the PV panel metallic frames must be specially constructed. Every metal surface must be galvanized or covered by special antirust coatings. High-quality metal must be used especially at fixing points (e.g., aluminium or V2A stainless steel). In addition, since any moisture penetration would result in cell degradation (especially in CIS cells) extra consideration must be done for the encapsulation materials (i.e., additional glass sheet as the front weatherproofing heat-strengthened, or -toughened safety glass) [24].

The installation of PV plants on a marine vessel is also under area restrictions. The systems must neither impede the cargo and human transfer nor cover places with financial impact such as deck, storage halls, and tanks. They also should be kept out of reach in order to prevent electrical shocks, as well as damage of PV panels and converters, keeping at the same time their maintenance work easy for the specialized staff. Thus, appropriate installation areas can be the unused roof and the facades of the superstructure, the funnel, the port, and the starboard, even the glazing and glass fronts.

Shading is another problem the PV systems are facing. The full or partial block of sun radiation in a cell or even a whole panel in a string grid not only decreases the efficiency but can also be harmful to the system. The phenomenon is known as hot spot and occurs when the shaded cells or panels stop acting as generators and become electric loads [24]. In land applications, shading is avoided by choosing open

installation areas. On the contrary, in marine applications the open spaces are limited, and the shades are more difficult to be predicted due to the continuous changes of the vessel orientation. For these reasons, the use of bypass diodes and smaller-scale installed PV systems are preferable.

There are two additional specifications that the smaller-scale installations meet. Firstly, PV plants on ships should be connected closely to crucial loads so as to minimize the distribution losses; and secondly, they have to produce dispersed electric power, to apply the necessary reserve for PV power generation.

Finally, the operational specifications of a PV system are the same for both the mainland and marine applications. Namely, the output characteristics ought to be compatible with the electric magnitudes on the installing points of the grid; high efficiency, and power factor are essential; maximum power point tracking (MPPT) and anti-islanding control are necessary.

4. Solar Cell Types

According to their structure, the solar cell types can be classified into two basic groups, the crystalline cells and thin films [24]. At crystalline cells, the raw material is silicon (Si), whose molecules are organized in crystalline grids. The orientation of the grid defines whether the cell is monocrystalline or polycrystalline [24, 25].

The monocrystalline solar cells (Mono c-Si) owe their name to their almost perfect single-crystal silicon structure. They are constructed by the Czochralski process [24], a special method according to which the polysilicon starting material is melted, specially cooled to monocrystal semiround or square bars and cut into wafers with wire saws. The use of almost pure silicon (an expensive raw material), the specialized production process, and the large amount of silicon losses during the construction of wafers rise to the top of the production cost. However, the monocrystalline solar cells have the longest estimated lifetime (over 30 years), the highest efficiency (15–18%), and power density (W/m^2) among the commercial cells [24, 25].

On the other hand, the polycrystalline cells (Poly c-Si) consist of crystal grids with different orientations. The aim of this difference is the massive production and the less controlled cooling method of silicon into cuboid form, which significantly diminish the production cost. As before, the wafers are formed by cutting the extracted silicon cubes or ingots with wire saws. The resulting square form of the wafers offers higher back plane cover than the square monocrystalline cells. The higher internal resistance at the vicinity of the multicrystalline structures decreases the overall efficiency of polycrystalline cells to 13–15% while their estimation life time exceeds the 25 years [24, 25].

In contrast to the aforementioned types of cells, thin films have no crystalline structure. They are constructed by applying thin layers of photoactive semiconductors on low-cost substrate (in most cases, glass). The most common raw materials are the amorphous silicon (a-Si), the copper indium diselenide (CIS), and cadmium telluride (CdTe), with the a-Si to be the most popular because of the low cost and

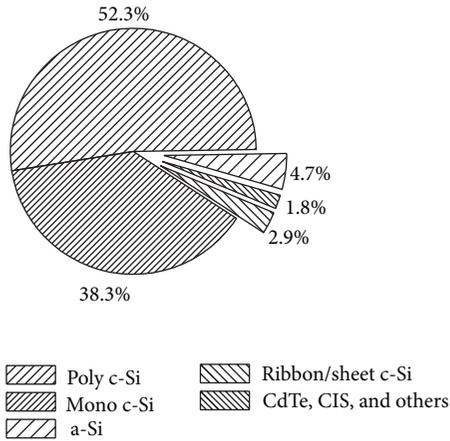


FIGURE 2: World trends of the most popular commercial PV cells at 2009 [26].

the lack of heavy metals. The cheap and small amount of raw material, the simple and low energy-cost production process, and finally the easy installation make thin films an attractive choice for mass production. Because of their cell form (long narrow strips) and their interconnection, thin film cells are less sensitive to shading and are able to construct cheaper and more transparent modules than the aforementioned cells. Counting on their ability to be installed in curved, even flexible, surfaces, thin films are perfect for PV plants installed in building facades and glazing and glass fronts. The main drawbacks are the low efficiency (a-Si: 5–7%, CIT: 9–11%, CdTe: 5–8.5%) [24, 25] and the least lifetime (20 years) which aim to the lack of crystalline structure. Though thin films offer better utilization of diffuse and low light and more favorable temperature coefficient, properties that the new technology of hybrid PV modules take advantage of.

In marine PV applications, the choice of the type of cells is related to the total cost and the type of installation surface. Crystalline cells are more appropriate for flat surfaces. They have low cost, high efficiency, and high power density that help them to fully exploit small installing areas. The selection of monocrystalline or polycrystalline is determined by the total budget and the available area. The thin film modules are more preferable for transparent surfaces like windows and glass facades, for curves, and shadowy places.

Finally, in Figure 2 the world trends of the most popular commercial PV cells at 2009 are presented [26].

5. PV System Technologies

The power of a PV plant is directly related to the number of the installed panels while their parallel and in series connection defines the output current and voltage. There are four main technologies for the interconnection of the PV panels and converters, which are presented in the following paragraphs, adjusted for marine applications.

The first technology is referred in the worldwide bibliography as centralized technology [7, 26–29]. It is one of the oldest ones, applied to PV plants with large amount of output

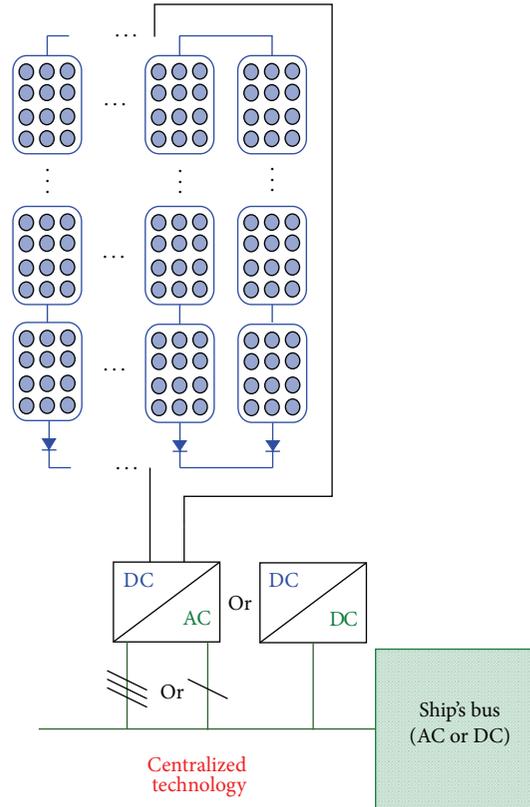


FIGURE 3: Centralized technology.

power. As it is shown in Figure 3, its main characteristic is the use of a single converter. The power is generated by parallel connected strings of panels. Each string ensures the necessary high DC voltage that drives the converter, while their parallel connection generates a high current. Extra characteristics of the centralized technology are the use of (a) a single maximum power point tracking (MPPT) control system and (b) diodes at the end of every string that block the reverse currents because of the shadings or in grid temperature differences.

The pros and the cons of the centralized technology at marine applications can be summarized as follows.

Advantages

- (i) Large amounts of electric power can be generated. Due to space limitations on vessels the power production cannot be equal to respective mainland applications (10 kW to 400 kW) but definitely overcame the 10 kW [7, 27].
- (ii) The string formation of panels offers satisfactory high DC voltage at the input of the converter, making needless extra voltage amplification (by the converter or transformer). The high DC is essential for the connection to the ship electric bus.
- (iii) The converter can be away of the PV grid, protected from humidity and dust.
- (iv) It can be applied both to single- and three-phase AC bus.

Disadvantages

- (i) Large installation areas are necessary.
- (ii) The PV panels are more likely to be shaded and stroke by hotspot phenomena.
- (iii) The single converter lacks of reserve, raising the risk of total system breakdown in case of a malfunction.
- (iv) Only the same type of PV panels can be installed.
- (v) There is high voltage at the connection point between PV grid and converter that results to
 - (a) higher risk of electroshock,
 - (b) higher cost of the wiring (special specifications for insulation and high power transfer),
 - (c) higher installation cost due to special protection and ground systems [26].
- (vi) The single MPPT control system cannot help each panel to operate at its maximum power, leading to reduced overall efficiency.
- (vii) The upgrade of the total installed power capacity is not feasible.
- (viii) High total cost.
- (ix) Lower efficiency in relation to other technologies.

Possible replacer of the aforementioned technology is the string technology [7, 26–29], which is popular in countries, pioneers of PV technology, such as Germany. Unlike centralized technology, the PV grid consists only of a single string that is attached to a converter, a characteristic that decreases the installed power capacity but gives many advantages to the new technology. A diagram of the string technology is presented in Figure 4.

Advantages

- (i) Because of the in series connection of the panels, there is not always necessary extra amplification of the converter’s input voltage.
- (ii) Less installation area needs but still considerable.
- (iii) Lower total cost than before.
- (iv) More effective MPPT control system since it is applied to smaller number of panels.
- (v) There is no need for blocking diodes.
- (vi) The upgrade of the installed power capacity is succeeded by installing more strings and converters to the bus without any further restriction by the precedent system design.
- (vii) Higher efficiency compared to the centralized technology.
- (viii) The converter can be away from the PV grid, protected from humidity and dust.
- (ix) It can be applied both to single- and three-phase AC bus.

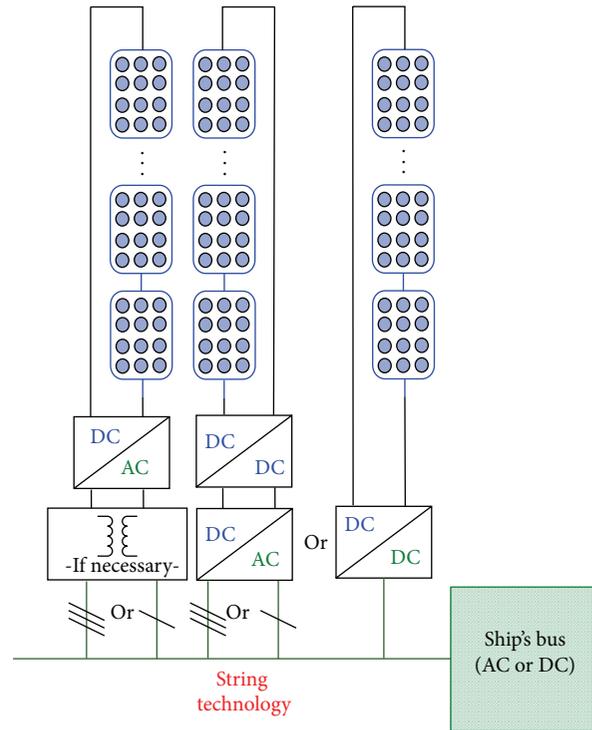


FIGURE 4: String technology.

Disadvantages

- (i) The problems of high DC voltage to the connection point between PV grid and converter and hotspot phenomena still remain.
- (ii) Only the same type of PV panels can be installed.
- (iii) Depending on the installed number of PV panels, the generated power from every string ranges between 0.7 kW and 3 kW.
- (iv) The multistring technology is an evolution of the string technology which lately gains ground on the world market. The power management that is offered is similar to the centralized technology without the disadvantages of the second. As it is presented at Figure 5 in the design requires multiple strings of panels with their respective converters, parallel connected to a single central converter.

Advantages

- (i) Similar power generation to centralized technology.
- (ii) More effective MPPT control system.
- (iii) Different types and numbers of panels can be installed at every string.
- (iv) The blocking diodes are not necessary.
- (v) The converter can be away from the PV grid, protected from humidity and dust.
- (vi) It can be applied both to single- and three-phase AC bus.

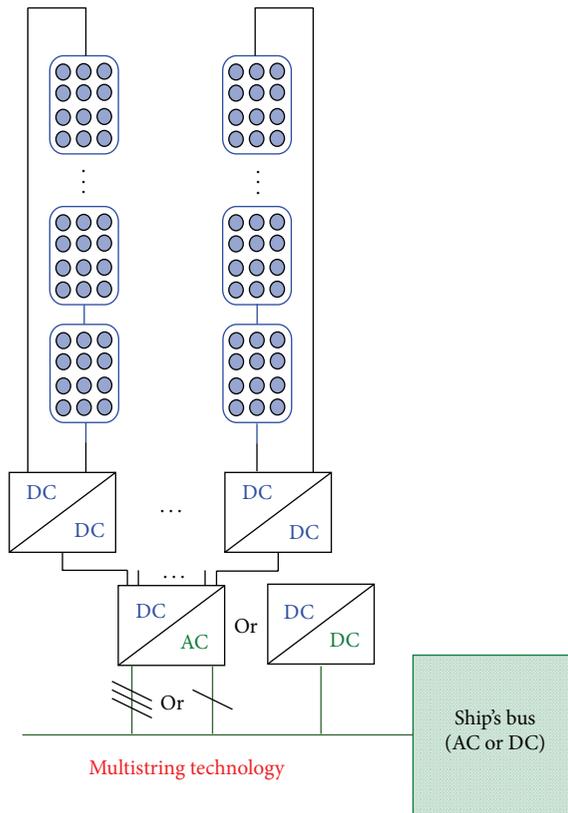


FIGURE 5: Multistring technology.

Disadvantages

- (i) The additional converter in every string increases the total cost
- (ii) The problems of high DC voltage to the connection point between PV grid and converters and hotspot phenomena still remain.
- (iii) Even if the system is tolerant during a string's converter breakdown, it cannot remain operational if the main converter is damaged.
- (iv) Large installation areas are necessary.
- (v) The last technology is called AC-PV module (in AC applications) or module-integrated converter (MIC) [7, 26–29] and is the newest one in the field of Residential PV applications. They are low power PV devices that are consisted of a single PV panel and a converter directly connected to the bus. The lack of PV arrays and the more effective control of every device (panel and converter) lead to higher total efficiency. The converter can be attached either to the support mechanism beside the panel or directly to its back side. The diagram of MIC technology is presented in Figure 6.

In comparison with the aforementioned technologies MIC have the following characteristics.

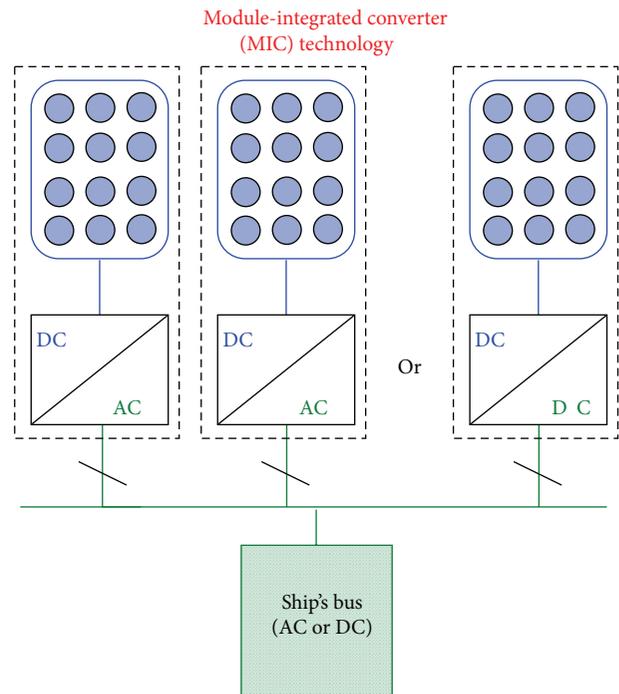


FIGURE 6: MIC technology.

Advantages

- (i) The one to one correspondence between panel and inverter offers the optimal MPPT control.
- (ii) The voltage at the connection point between panel and converter is low.
- (iii) Low total cost.
- (iv) The installation does not require special staff.
- (v) They demand the minimum installation area, making them ideal for marine applications, especially in PV plants integrated in windows and glass facades.
- (vi) Easily installed closely to crucial loads.
- (vii) The upgrade of the installed power capacity is succeeded by installing more modules to the bus without any further restriction by the precedent system design.
- (viii) A PV plant based on numerous MIC can generate power even when one or more converters fail to operate.
- (ix) The panels are free of hotspot risk.

Disadvantages

- (i) The MIC in mainland applications is dedicated for single-phase applications and the output voltage hardly overcomes the 300 V (without the use of transformer). However, in marine applications, they may have to be not only able of supplying three-phase loads but also reaching output voltages equal to 400 V (DC or AC).

- (ii) The maximum generated power is determined by the PV panel's nominal power. According to the present commercial technology, it cannot overcome the 350 W.
- (iii) Due to the placement near to the panel, the converter is exposed to extreme operational conditions (humidity, temperature) which decrease the lifetime and make the design specifications more difficult to succeed [29].
- (iv) It has lower efficiency compared to the other topologies. However, the last years, intensive research is being held to increase it.

6. Conclusions

The aim of this paper is the presentation of the most popular trends of the mainland PV technologies on the fields of solar cell types and the PV systems, and how they can be applied in ship applications. The electric grid of a typical marine vessel is described, the main parts are distinguished, the typical electric magnitudes are defined, and the preferable areas where the PV plants can be attached are spotted. The PV system must be tolerant to the special marine environmental conditions and especially the wind, humidity, shading, corrosion problems, and limited installation areas. The resulting restrictions are the parameters that define not only the type of the solar cells but also the applied PV system technology which refers to the interconnections types between panels and converters.

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