The advantages and challenges of DC collection grids for offshore floating PV

Oscar Delbeke, Jens D. Moschner, Johan Driesen

Abstract—**Offshore floating photovoltaics, tidal turbines and wave converters face similar challenges in terms of grid integration: electrical power must be transferred over long distances through a reliable and efficient grid connection. Whereas AC power collection systems are considered the industry standard for large-scale photovoltaics and (offshore) wind systems, a DC power collection grid may be more suitable for offshore floating photovoltaics. This work provides a qualitative discussion on the advantages and challenges tied to the grid integration of offshore floating PV systems through DC collection grids. The proposed advantages include reduced transmission and power conversion losses, improved power density, reliability, power quality, efficient integration with energy storage and high-voltage DC links, and flexibility in power flow control. Whereas many of these advantages apply onshore as well, this work argues that reduced transmission losses, improved power density and reliability benefits are more significant offshore. To unlock this potential however, challenges such as high capital costs, adequate protection, dynamic grid stability and lack of standards must be addressed.**

Keywords— **Direct Current, Floating Photovoltaics, Grid Integration, Offshore Floating PV (OFPV), Offshore Solar Power, Photovoltaics, Power Electronics.**

I. INTRODUCTION

THE accelerating adoption of renewable energy adds to the competition for space, as renewables have a lower power density than traditional thermal power stations. Regions with high energy demand are often those where land is scarce and expensive. At the same time, this is where the largest demand for renewable electricity will be, due to ongoing electrification. Ocean renewables emerge as promising technologies to supply the grid with renewable electricity without encroaching on valuable land.

Fig. 1. Example of an Offshore Floating PV system design, courtesy of SolarDuck [1]

Among these technologies, floating photovoltaics (FPV) is a recent addition. In the race towards a net-zero energy system, photovoltaics (PV) plays an essential role. According to the IEA's "World Energy Outlook 2023"[2], solar PV will become the largest source of electricity generation between 2030 and 2040. To scale up PV without escalating spatial competition with industry, housing, agricultural land or reserved nature, floating PV is gaining traction. The technology is already commercially viable for inshore use and has exceeded 5 GWp of installed capacity in 2022 [3].

Along with the pressing need for scale, the extraordinary decrease in PV module prices allow offshore floating PV (OFPV) to be considered, with several offshore solar pilots currently being tested [1], [4], [5]. So far, OFPV pilots have mostly focused on the survivability of structural designs and less on the electrical integration of such systems, despite many knowledge gaps existing in this field [6]. To enable an efficient and reliable electrical integration of OFPV, this work argues in favor of DC power collection systems, as PV modules are inherently DC sources. Inspiration is taken from research in PV, offshore wind and (shipboard) DC microgrids.

DC technology is benefitting from an R&D renaissance in recent years due to the accelerated integration of distributed renewable DC generators, widespread

Part of a special issue for ICOE 2024. Manuscript submitted 17 March 2025; Accepted 2 May 2025. Published 9 September 2025.

This work is funded by the European Union under Horizon Europe project no. 101135639 — Nautical SUNRISE.

O. Delbeke, J. D. Moschner and J. Driesen are with KU Leuven, Dept. ESAT – ELECTA, Kasteelpark Arenberg 10 bus 2445, 3001 Heverlee, Belgium and EnergyVille, Thor Park 8310, 3600 Genk, Belgium. (e-mail: oscar.delbeke@kuleuven.be).
Digital Object Identifier: https://doi.org/10.36688/imej.8.253-257

adoption of energy storage solutions [7], the expansion of consumer electronic DC loads, and the development of high-performance DC/DC converters with advanced semiconductors.

The work is built up as follows: Section II features a discussion on the main functions and requirements of an OFPV grid. Section III introduces a classical AC power collection grid for OFPV, inspired by utility-scale onshore PV systems and offshore wind farms. Section IV contrasts this approach with the introduction of two DC power collection grids. Section V then features a discussion of the main benefits of these options, whereas Section VI elaborates on the corresponding challenges. The conclusions of the work are highlighted in Section VII.

II. FUNCTION OF AN OFPV GRID

The OFPV power collection grid is the electrical interface between the floating PV converters and the high-voltage AC (HVAC) or high-voltage DC (HVDC) grid. When an offshore grid is already present, e.g., for accommodating wind farms, the floaters can also be connected to this transmission system [8], [9].

The OFPV grid must facilitate power conversion from the low-voltage DC output of PV modules to alternating current at a high voltage in the case of HVAC, or to the appropriate DC voltage for integration with an HVDC link. To accommodate the intermittency of the solar resource, it is essential that the power system is sufficiently flexible [2]. Thankfully, considerable expertise from offshore wind is readily applicable, as the electrical challenge downstream the PV inverter is similar to that of integrating offshore wind generators, albeit that the natural resource has a fundamentally different dynamic behavior.

However, as the share of renewables in the electricity grid increases, transmission system operators have also expressed their concern about decreasing system inertia, lower transient stability margin, resonance phenomena and the sufficiency of available generators to provide system services [10], [11]. As such, it is important that large-scale offshore solar farms also contribute to system stability and flexibility.

III. AC GRIDS FOR OFPV

The standard utility-scale approach to connect power from PV modules to the grid via an AC system features either central inverters - with or without power optimizers – or increasingly large (multi)string inverters to convert the direct current from PV strings to alternating current. While DC input voltages are in the range of 1000-1500 V, the output voltages of inverters are typically between 500 and 800 V. The AC voltage is then increased through typically two transformer stages to an appropriate level. The simplicity of this approach lies in the limited number of power conversion steps and the convenient use of transformers to step up the AC voltage efficiently and reliably. Both inverters and transformers have the benefit of considerable technology maturity.

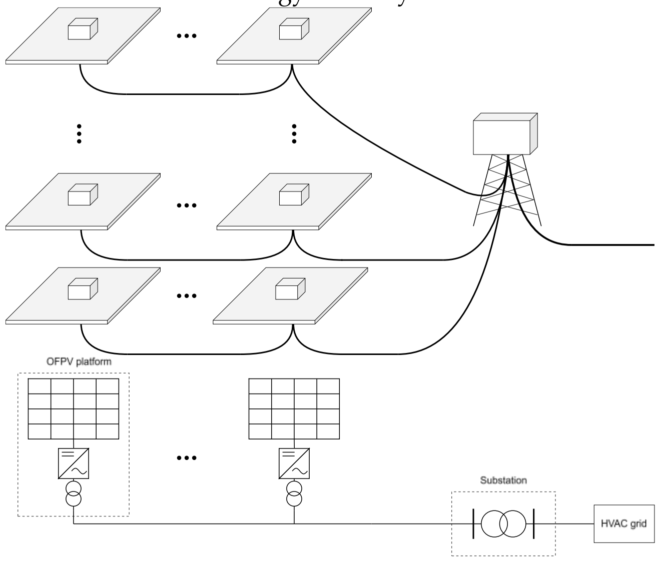

Fig. 2 AC grid for OFPV farms. An inverter converts DC power from the PV modules to AC, after which the voltage is stepped up by two transformers.

In an OFPV farm (Fig. 2), each floater or cluster of floaters needs its own inverter and transformer. The floaters are connected in strings, which are radially routed to a substation, where the voltage is again stepped up by a transformer to connect to the HVAC grid. Since distances between clusters amongst themselves and between clusters and a point of common coupling (PoCC) can be considerable, transmission at low voltage is not an option, as too much power would be dissipated in transmission losses. Since inverter output voltages typically do not exceed 800 V, installing a transformer on each of the platforms is essential to realize transmission at a sufficiently high voltage (33 and 66 kV are common in offshore wind). Nonetheless, installing a bulky line frequency transformer on every platform takes up a lot of space, especially since the floating clusters are likely to have a nominal power of less than 1 MWp. They are also adding considerable weight, for which buoyancy needs to be provided.

IV. DC GRIDS FOR OFPV

PV modules generate DC power, and coupling DC sources through a DC grid can inherently be more efficient than through an AC grid [12]. DC topologies have been considered before, also for floating PV [6]. The two following DC collection grid architectures are the most evident options. The first design is inspired by the radial DC collection grid proposed for offshore wind farms in [12], translated to OFPV (Fig. 3, DC 1). Therein a row of OFPV floaters, each with their own DC/DC converter, would be connected in a string, and different strings would be connected to an offshore platform featuring a DC/DC step-up converter to feed an HVDC link.

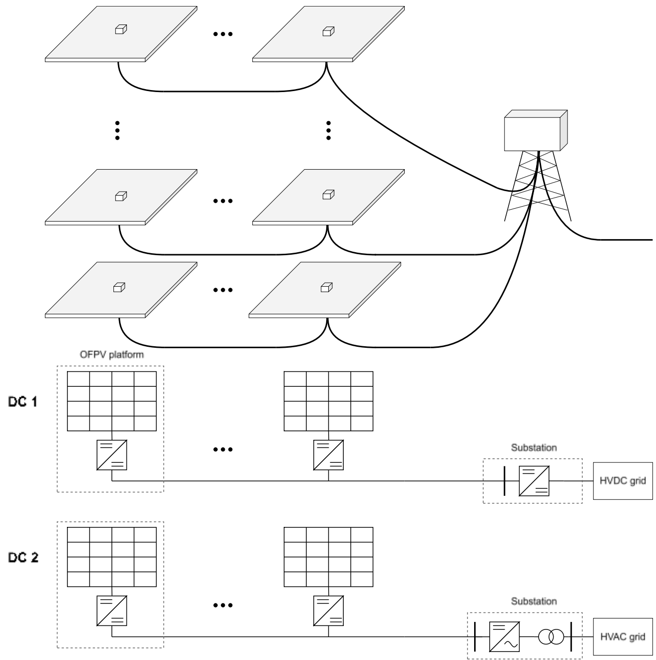

Fig. 3 DC grid options for OFPV farms. Converters can be reduced in size compared to transformers and cables can have thinner cross sections for the same installed power.

The second option consists of several DC/DC step-up converters, one for each floater, connected in parallel strings to a large central inverter and a single transformer stage, located on a substation (Fig. 3, DC 2). The design is inspired by "DC2" in [13]. DC/DC converter circuits that could be considered are dual active bridge and multilevel topologies.

V. ADVANTAGES OF DC GRIDS FOR OFPV

A. Lower transmission and power conversion losses

A fundamental difference between onshore and offshore PV systems is the distance that needs to be covered by the cables. Whereas transmission through both DC and AC power cables results in ohmic losses, AC power cables also lose power due to sheath losses, dielectric losses and armor losses [9], [13]. Transmission capacity is also progressively taken up by reactive power (charging current), increasing with longer distances. As such, DC cables have lower losses than AC cables for the same current density [14], and do not have to reduce capacity for reactive power. The collection of PV power through a DC collection grid already proves to be more efficient for onshore PV systems [13]. Larger transmission distances in OFPV farms further add to the importance of this benefit.

For offshore wind farms, DC power collection was simulated by De Prada Gil et al. [12]. The authors found DC power collection to be more efficient than AC and found losses to be heavily concentrated in the converters (over 90%). As such, the authors point towards converter efficiency improvements as a requirement for economic feasibility of DC collection grids.

It is important to note that since their work was published in 2015, significant progress has been realized in DC/DC converters and their efficiency, mainly due to the emergence of wide bandgap semiconductors (e.g. SiC and GaN) and the demand for better efficiencies and power densities in areas such as electric vehicle charging and aerospace [15].

B. Power density

The superior power density of DC/DC converters is proposed as an argument in favor of DC microgrids in ships [16]. In a parallel to OFPV, structural requirements strongly contribute to the cost of the system, so power density has a larger importance for OFPV than for onshore PV. Moreover, in comparison to offshore wind, where a 10 MW wind turbine can be served by a single transformer, floating platforms or clusters will likely form units of less than 1 MWp per power converter, although larger structures are also being considered. As such, more compact power converters will yield larger benefits for the structural requirements of OFPV than for offshore wind farms. Advancements in the power density of converters will thus contribute considerably to the performance of OFPV systems.

In DC/DC converters, high-frequency switching enables the use of smaller inductors. Combined with the high efficiency of wide bandgap semiconductors, this allows them to function at greater power densities than bulky line frequency transformers, since the converter's power density improves with smaller passive components [15]. For instance, dual active bridge DC/DC boost converters can step up the low voltage from the PV modules to several kV and implement maximum power point tracking (MPPT) through their control. Their capability for high-frequency switching yields a smaller inductor size and thus a better power density [13].

Alhuwaishel and Al-Obaidi [17] further proposed an interleaved modular multilevel converter (IMMC) with SiC switches and high-frequency pulse-width modulation to combine a high efficiency power conversion with compact size and weight, specifically for power collection of large PV systems. The approach already shows promising results for onshore PV, and the corresponding advantages can be even more pronounced offshore.

C. Reliability

Reliability is of critical importance offshore as the system is so remote and maintenance is expensive. The reconfiguration capability of DC (micro)grids greatly contributes to reliability and refers to the ability to alter the network topology or change the operational state to isolate faults and maintain operation in healthy parts of the system [16], [18]. In a bipolar DC voltage topology for instance, survivability is improved if the positive bus can stay operational when a fault occurs on the negative side or vice versa [18].

Further, as opposed to AC systems, the frequency of instabilities is typically limited to the harmonic frequency range of the converter switching frequency [11], which simplifies design-for-reliability. In some cases, DC/DC converters can also provide circuit breaker capabilities by fast isolation of faults and elimination of the associated currents [19].

D. Power quality

DC approaches hold the potential to minimize problems with harmonics, phase unbalances and reactive power (i.e., reactive cable loading), which are characteristic of AC grids [18]. This is a considerable advantage as synchronization problems have complicated the AC grid integration of ocean renewables such as wave power systems before [20].

E. Integration with energy storage

Energy storage technologies such as batteries inherently operate through DC. The connection of these systems with generators can be implemented most efficiently via DC links because the number of power conversion steps can be minimized [21]. Earlier work has also demonstrated that smoothing the power of e.g. wave energy converters with battery energy storage can perfectly be accommodated by a DC grid [20].

F. Integration with HVDC

Similar to the integration with energy storage, the integration of a DC collection grid with HVDC links could be established through fewer conversion steps than through AC, and converters capable of such applications are being developed [19]. Though, direct integration with HVDC also brings about challenges, as the connecting voltage source converters (VSCs) can interact with the passive components of the DC network, leading to instabilities [22].

G. Flexibility in power flow control

The extensive controllability of DC/DC converters allows flexible management of power flows and voltages, even after faults [16], [19]. The elimination of imbalance issues between phases and synchronization problems also simplifies control [18].

VI. CHALLENGES OF DC GRIDS FOR OFPV

A. High capital costs

To consider industrial application of DC collection grids, system cost is of course a critically important factor. De Prada Gil et al. [12] compared DC collection grids with AC collection grids for offshore wind farms and found that whereas the costs associated with energy losses are notably lower for DC collection grids, capital costs are slightly higher, with the difference being driven by the cost of DC/DC converters [12]. This finding is transferable to OFPV, where similar components would be used.

CIGRE working group B4.76 [19] also identified the significant cost difference between transformers and comparable step-up DC/DC converters as an important hurdle for the adoption of DC collection grids. For onshore PV systems it was found as well that increased efficiency of the power collection system does not necessarily imply better economic performance of the system overall [13].

B. System protection

The particular surroundings of OFPV systems create various possibilities for leakage currents and insulation becomes more challenging as the voltages increase. Unfortunately, it is high voltages that are needed to ensure efficient transmission of power (typical voltages for array cables making up the strings are 33 or 66 kV). To protect the system, development of adequate DC circuit breakers is crucial [12]. This is however complicated because of the lack of natural zero crossings of DC fault current and voltage, also complicating the overvoltage protection to deal with e.g. arcs and lightning strikes (which may occur more frequently on offshore platforms). Elaborate overvoltage detection and mitigation strategies are therefore necessary.

Musasa et al. [21] conclude that the unavailability of suitable protection devices is a big hurdle towards DC collection grids in offshore wind. Moreover, the overloading capability of DC/DC converters is lower than that of transformers, which by nature have some inertia to sudden transients [18], [19]. Thus, adequate protection is indispensable.

C. System stability

To manage power flows well, voltage stability should be maintained. The instabilities occurring in DC grids are usually tied to the interaction between converters and dynamics between converters and passive components, driven by the power control [11], [22]. To avoid these, damping methods must be applied. This can be implemented through adding impedances dissipating power and lowering efficiency, or through more complex auxiliary converters. Another more efficient and convenient option is to adapt the load converter control as proposed in [23]. The method consists of adding a control loop in the converter which "changes the negative resistance behavior of a constant power load (i.e., the converter) into a positive resistance only in the region of the potential instability" [23].

D. Reconfigurability requires redundancy

As mentioned in Section V.C, a bipolar voltage bus structure makes sure that half the DC system can stay operational should a fault occur on the other side. This architecture however also requires lots of equipment, leading to higher cable and converter costs. Power architectures that are optimized for reliability invariably increase complexity as well, so this presents an important tradeoff to take into account [18].

E. Technology maturity

The relative novelty of DC collection grids for large solar and wind power plants leaves a lot of technical and economic uncertainties open [12]. This is normal for upcoming technology, but it also complicates technical and economic analyses. As mentioned in Sections III and V.B, transformers benefit from a larger technology maturity than DC/DC converters, and the convenience of their application is still one of the main arguments in favor of AC grids. DC/DC converters, as critical enablers of DC grids, are challenged to reach similar reliability and price levels [19]. Finally, there is also a lack of standards and guidelines for DC power collection, even in the rapidly maturing offshore wind industry [21].

VII. Conclusion

DC collection grids are appealing for OFPV, mostly due to their potential to limit transmission losses and improve power density and reliability. The proposed benefits are shown to yield more significant advantages offshore than for onshore PV systems. However, unlocking this potential also comes with significant challenges, including high capital costs and the development of adequate protection devices, which are the main obstacles to be overcome. Lots of research and development is needed to construct functional converters, standardize voltage levels and establish appropriate equipment specifications. Finally, aside from theoretical analyses, experimental setups are indispensable to assess the true potential of these systems.

References

[1] SolarDuck, “Offshore floating PV system design.” Accessed: Jan. 05, 2024. [Online]. Available: https://solarduck.tech/

[2] IEA, “World Energy Outlook 2023,” Oct. 2023. Accessed: Mar. 12, 2024. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2023

[3] SolarPower Europe, “Floating PV Best Practice Guidelines,” 2023. Accessed: Mar. 25, 2024. [Online]. Available: https://www.solarpowereurope.org/insights/thematic-reports/floating-pv-best-practice-guidelines-version-1-2

[4] “SeaVolt.” Accessed: Mar. 20, 2024. [Online]. Available: https://www.seavolt.be/

[5] “Oceans of Energy.” Accessed: Mar. 25, 2024. [Online]. Available: https://oceansofenergy.blue/

[6] P. Ranjbaran, H. Yousefi, G. B. Gharehpetian, and F. R. Astaraei, “A review on floating photovoltaic (FPV) power generation units,” *Renewable and Sustainable Energy Reviews*, vol. 110. Elsevier Ltd, pp. 332–347, 2019. doi: 10.1016/j.rser.2019.05.015.

[7] M. F. Zia, M. Nasir, E. Elbouchikhi, M. Benbouzid, J. C. Vasquez, and J. M. Guerrero, “Energy management system for a hybrid PV-Wind-Tidal-Battery-based islanded DC microgrid: Modeling and experimental validation,” *Renewable and Sustainable Energy Reviews*, vol. 159, May 2022, doi: 10.1016/j.rser.2022.112093.

[8] S. Z. M. Golroodbari *et al.*, “Pooling the cable: A techno-economic feasibility study of integrating offshore floating photovoltaic solar technology within an offshore wind park,” *Solar Energy*, vol. 219, pp. 65–74, May 2021.

[9] O. Delbeke and J. Driesen, “Harnessing solar-wind complementarity to unlock the full potential of submarine high voltage cables: a case study for the Belgian North Sea,” in *CIGRE Paris Session*, CIGRE, 2024.

[10] MIGRATE, “The MIGRATE project: An EU-funded project under the framework of the European Union’s HORIZON 2020",” 2016. [Online]. Available: https://www.h2020-migrate.eu

[11] G. De Carne *et al.*, “Which Deepness Class Is Suited for Modeling Power Electronics? A Guide for Choosing the Right Model for Grid-Integration Studies,” *IEEE Industrial Electronics Magazine*, vol. 13, no. 2, pp. 41–55, Jun. 2019, doi: 10.1109/MIE.2019.2909799.

[12] M. De Prada Gil, J. L. Domínguez-García, F. Díaz-González, M. Aragüés-Peñalba, and O. Gomis-Bellmunt, “Feasibility analysis of offshore wind power plants with DC collection grid,” *Renew Energy*, vol. 78, pp. 467–477, Jun. 2015, doi: 10.1016/j.renene.2015.01.042.

[13] H. A. B. Siddique and R. W. De Doncker, “Evaluation of DC Collector-Grid Configurations for Large Photovoltaic Parks,” *IEEE Transactions on Power Delivery*, vol. 33, no. 1, pp. 311–320, Feb. 2018, doi: 10.1109/TPWRD.2017.2702018.

[14] P. Monjean and B. Robyns, “DC grid architectures to improve the integration of wind farms into electricity transmission and distribution networks,” in *Eco-friendly Innovation in Electricity Transmission and Distribution Networks*, Elsevier Inc., 2015, pp. 291–311. doi: 10.1016/B978-1-78242-010-1.00014-8.

[15] M. Parvez, A. T. Pereira, N. Ertugrul, N. H. E. Weste, D. Abbott, and S. F. Al-Sarawi, “Wide Bandgap DC-DC Converter Topologies for Power Applications,” *Proceedings of the IEEE*, vol. 109, no. 7, pp. 1253–1275, Jul. 2021, doi: 10.1109/JPROC.2021.3072170.

[16] L. Xu *et al.*, “A Review of DC Shipboard Microgrids - Part II: Control Architectures, Stability Analysis, and Protection Schemes,” *IEEE Trans Power Electron*, vol. 37, no. 4, pp. 4105–4120, Apr. 2022, doi: 10.1109/TPEL.2021.3128409.

[17] F. M. Alhuwaishel and S. A. S. Al-Obaidi, “A Medium-Voltage DC-Collection Grid for Large-Scale PV Power Plants with Interleaved Modular Multilevel Converter,” *IEEE J Emerg Sel Top Power Electron*, vol. 8, no. 4, pp. 3434–3443, Dec. 2020, doi: 10.1109/JESTPE.2019.2934736.

[18] Z. Jin, G. Sulligoi, R. Cuzner, L. Meng, J. C. Vasquez, and J. M. Guerrero, “Next-Generation Shipboard DC Power System: Introduction Smart Grid and dc Microgrid Technologies into Maritime Electrical Networks,” *IEEE Electrification Magazine*, vol. 4, no. 2, pp. 45–57, Jun. 2016, doi: 10.1109/MELE.2016.2544203.

[19] CIGRE WG B4.76, “TB 827: DC-DC converters in HVDC grids and for connections to HVDC systems,” 2021.

[20] M. G. Hussien, A. M. Elkholy, D.-E. A. Mansour, M. M. Akl, M. Numair, and I. A. Soliman, “Performance Enhancement of Wave Energy Converters Integrated with DC Grids Using Energy Storage Systems,” in *22nd International Middle East Power Systems Conference (MEPCON)*, IEEE, 2021, pp. 77–83. doi: 10.1109/MEPCON50283.2021.9686294.

[21] K. Musasa, N. I. Nwulu, M. N. Gitau, and R. C. Bansal, “Review on DC collection grids for offshore wind farms with high-voltage DC transmission system,” *IET Power Electronics*, vol. 10, no. 15, pp. 2104–2115, Dec. 2017, doi: 10.1049/iet-pel.2017.0182.

[22] G. Pinares and M. Bongiorno, “Modeling and Analysis of VSC-Based HVDC Systems for DC Network Stability Studies,” *IEEE Transactions on Power Delivery*, vol. 31, no. 2, pp. 848–856, Apr. 2016, doi: 10.1109/TPWRD.2015.2455236.

[23] F. M. Ibanez, F. Martin, J. Eletu, and J. M. Echeverria, “Input voltage feedforward control technique for DC/DC converters to avoid instability in DC grids,” *IEEE J Emerg Sel Top Power Electron*, vol. 9, no. 5, pp. 6099–6112, Oct. 2021, doi: 10.1109/JESTPE.2021.3058850.