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Hybrid HVAC–HVDC Grids: Review on Techno-economic, Societal, and Regulatory Aspects

Kyriaki-Nefeli D. Malamaki
Georgios A. Barzegkar-Ntovom
Serafeim Panidis
Dept. Res. Technol. & Dev.
Indep. Power Transm. Operator
Athens, Greece
{k.malamaki, g.barzegkar, s.panidis}@admie.gr

Stefania-Vaia P. Gatou
Fotis-Konstantinos Paterakis
Ioannis P. Moraitis
Dept. Res. Technol. & Dev.
Indep. Power Transm. Operator
Athens, Greece
{s.gatou, f.paterakis, imoraitis}@admie.gr

Mustafa Şeker
Dept. of Electr. and Electron. Eng.
Sivas Cumhuriyet University
Sivas, Turkiye
mustafaseker@cumhuriyet.edu.tr

Ahmet Aksöz
Dept. of Electr. and Electron. Eng.
Kayseri University, MMTF
Kayseri, Turkiye
aaksoz@cumhuriyet.edu.tr

Saadin Oyucu
Dept. Comput. Eng.
Gazi University
Ankara, Turkiye
saadinoyucu@gazi.edu.tr

Emre Ünsal
Dept. Softw. Eng.
Sivas Cumhuriyet University
Sivas, Turkiye
eunsal@cumhuriyet.edu.tr

***Abstract*—Nowadays, there is a growing trend towards converting existing transmission infrastructure to hybrid high-voltage alternating current (HVAC) and high-voltage direct current (HVDC) systems, driven primarily by the need for increased power transmission capability and lower operational costs. However, as HVAC grids are becoming more complex with the integration of advanced energy storage systems and power electronics, and as HVDC systems are increasingly deployed to efficiently transmit power from both onshore and offshore renewable sources over long distances or to facilitate interconnections across countries and regions, the implementation of such hybrid grids faces substantial technical, regulatory, and economic challenges. In this context, the primary objective of this work is to review the existing technical and regulatory aspects of HVAC–HVDC systems and to identify gaps that may hinder their effective implementation. Finally, it aims to highlight the benefits of such grids, as well as to examine the key needs and barriers associated with their deployment.**

***Index Terms*—Grid modernization, HVAC–HVDC systems, hybrid grids, regulatory challenges, transmission systems.**

I. INTRODUCTION

The intermittent and inertia-less nature of renewable energy sources (RES) has posed various issues to the traditional alternating current (ac) Electric Power and Energy Systems (EPES) related to their stability, robustness and resilience. Direct current (dc) systems can be more stable and less affected by voltage and frequency fluctuations, which is particularly beneficial for grids with high RES penetration [1]. Hybrid ac/dc grids offer flexibility to accommodate this variability and have various benefits over the traditional ac structure such as improved grid power quality and voltage stability, enhanced resilience during peak demand and contingencies, power transmission over long distances, reduction of losses [2], and increased transmission capacity as well as cost optimization. Hence, hybrid ac/dc grids facilitate the integration of RES in a more efficient manner, accelerate the transition to a fuel-free EPES, and serve the ambitious decarbonization goals set by the European Union (EU). EU promotes the integration of hybrid ac/dc grids at all voltage levels by supporting relevant Research and Innovation Action (RIA) projects [3]–[13], as well as new multi-terminal High Voltage (HV) dc (HVDC) links among European countries [14].

Besides the undoubtful advantages of hybrid ac/dc grids, several barriers still hinder their widespread adoption and there are needs towards several directions: technological [15], [16], e.g., stability [17] and protection [18] problems, resilience issues after natural events [19], as well as interoperability and cybersecurity issues [20]; economic and stakeholder, e.g., coordination among multiple parties; regulatory and standardization. Focusing on the Transmission System (TS) and the hybrid HVAC-HVDC grids, several techno-economic factors should be considered, such as low inertia, fault issues, line length where increased capacitance might appear, as well as investment costs based on the transferred capacity.

In the respective technical literature there exist some recent review papers. For instance, the study [1] provides an overview for control and optimization aspects of hybrid HVAC-HVDC grids, while [15] reviews various HVDC technologies (e.g., converters, cables, circuit breakers, etc.), and analyzes the control methods for weak grid interconnection considering the techno-economic aspects of HVDC links in the Indonesian grid. The paper [16] reviews four Line Commutated Converter (LCC)-Voltage Source Converter (VSC) hybrid HVDC topologies, investigates their PQ operating zone, and compares the dc fault-ride through (FRT) and their power flow reversal capability. Reference [17] focuses on the review of grid modeling in hybrid HVAC-HVDC grids, the control of VSC-HVDC power converters and the impacts of HVDC power converters and

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their control systems on the stability of such grids. The authors of [18] examine protection challenges in multi-terminal HVDC grids, including dc fault current behavior, fault analysis techniques, existing fault current calculation methods, protection requirements, reclosing strategies, and relevant standards. In [19], the hybrid HVAC-HVDC grid aspects are reviewed considering the resilience after natural events, which includes the integration of new converter technologies and grid-forming (GFM) controls, as well as energy storage system (ESS) and demand-response adoption. The study [21] focuses on the reliability and resilience needs for future hybrid ac/dc grids and presents the goals and work conducted within the EU RIA project HVDC-WISE.

This paper focuses on the review and categorization of the main barriers hindering the adoption of hybrid HVAC-HVDC systems in the EU. These barriers are classified into three key groups: technological and operational, economic, as well as political and legal. By systematically identifying and analyzing these categories, the paper contributes to a deeper understanding of the challenges and provides insights to support broader deployment. Moreover, it is within the aim of the paper to discuss national and European regulations designed to support their widespread implementation. Finally, it provides an updated overview on the ongoing activities at EU level from a TS Operator (TSO) perspective, including RIA projects, reports from the European Network of TSOs for Electricity (ENTSO-E) and new planned HVDC links.

The remainder of this paper is organized as follows: Section II reviews European and national regulations, as well as policies related to hybrid HVAC-HVDC grids. Sections III and IV highlight the benefits and challenges of deploying dc technologies and integrating them into hybrid ac/dc TSs, respectively. Finally, Section V concludes the paper with its main findings and directions for future work.

II. REGULATIONS FOR HYBRID HVAC-HVDC GRIDS AND ONGOING ACTIVITIES

To address issues related to synchronous and non-synchronous generation, as well as the integration of HVDC links, many national and European regulations have been established. This Section reviews these regulations in the context of increasing penetration of RES and HVDC links, along with ENTSO-E relevant activities and EU RIA/IA projects.

A. European Regulations

The Commission Regulation (EU) 2016/1447 [22] establishes technical rules for new HVDC links and dc-connected power park modules (PPMs), which are converter-interfaced. It standardizes requirements for offshore connections, mandates synthetic inertia to support frequency stability as RES replace conventional plants, and requires FRT capability so that converters remain operational and inject reactive power during disturbances. It also sets precise active/reactive power control profiles, fast fault-current injection, and oscillation-damping functions to safeguard interconnected ac networks. Commission Regulation (EU) 2016/631 (the "Requirements for Generators" - RfG network code) [23], defines two categories of power generating modules (PGMs): synchronous PGMs and PPMs. Some ancillary services (AS), e.g., true inertia provision is required to perform more complex, advanced functions. The AS differ per PGM type, e.g., type A PGMs do not provide AS and type B PGMs provide only voltage-related services (e.g., reactive power). Types C and D PGMs connected directly to the TS provide almost all the AS necessary for the EPES stability. The four PPM types (A–D) have progressively stricter service obligations—ranging from none (type A) to nearly complete (type D)—with size limits varying by region (e.g., 50 MW in Continental Europe vs. 5 MW in Ireland). This code distinguishes exhaustive requirements, which apply uniformly, from non-exhaustive ones that national regulators must tailor within specified ranges, [24].

More recently, Directive EU 2019/944 [25] establishes common rules for generation, transmission, distribution, storage, and supply, and embeds consumer-protection measures for integrated, flexible markets. It drives smart-meter rollout based on cost-benefit analyses to enable dynamic pricing and interactive data management. For generators, it codifies non-frequency services—steady-state voltage control, rapid reactive-current injection, local inertia support, short-circuit contribution, black-start capability, and island-operation readiness—ensuring that as Europe's grid evolves, both technical consistency and market efficiency keep pace.

As evident, most of the key European regulations related to hybrid ac/dc grids are now over 5 years old with several ongoing R&I activities and projects aiming to advance beyond them. It is noted that the RfG is currently being revised [26], [27] and relevant stakeholders like SolarPower Europe [28] have already provided comments related to:

- the update of the implementation guidance document, in order to better reflect stakeholder input;
- GFM AS. For example, it is proposed that they should be procured via market mechanisms from battery installations, while PV-only systems must prioritize inherently robust, grid-supportive operation; specifically, a transparent roadmap of GFM requirements and industry readiness should be developed with stakeholders;
- manufacturer rules: they should be harmonized by setting both Type A and Type B thresholds at 1 MW and aligning Type A technical criteria, and by prohibiting remote control of behind-the-meter ESS, which can enhance system stability and flexibility;
- the consideration of balancing implementation costs against the tangible security and flexibility benefits.

B. National Regulations and Planned HVDC Links

Hybrid HVAC-HVDC grids are increasingly shaping the evolving European landscape towards decarbonization, even though the pace differs across EU member States (MS). For example, Greece held a public consultation about adopting the RfG NC framework. The main focus was on power thresholds for generator categories (A–D) and their operational rules. These initiatives appear to align with a broader strategy aimed at modernizing the Greek EPES and supporting EU energy targets [29]. Germany has revised its VDE-AR-N 4120 standard related to HV connection rules, so as to align with EU directives. The updates demand faster active power control and improved FRT capabilities [30]. Also, in Germany, TenneT, intends to expand the offshore capacity from 7.1 GW to 22.8 GW by 2031, while in the Netherlands, TenneT is working towards increasing offshore transmission capacity, from 3.5 GW today up to 22.3 GW by 2031.

In the UK, the National grid Electricity System Operator has introduced some voluntary updates to their grid codes [31] regarding the connection of converter-based RES, e.g., recommendations for using GFM technologies. Meanwhile, some cross-border UK projects are moving forward: (a) LionLink (UK–Netherlands) [32], [33]: This subsea HVDC link can handle up to 2 GW of offshore wind power, which helps reduce extra coastal infrastructure; (b) Nautilus & Nemo Link (UK–Belgium) [34]: Nemo Link is already operational at 1 GW. As for Nautilus, the 1.4 GW project is still in development and aims to improve energy exchanges; (c) Viking Link (UK–Denmark), [14]: Covering about 767 km, this HVDC project uses VSC technology to deliver 1.4 GW, improving market integration across Europe.

In the Nordic System, large amounts of power electronic interfaced devices has started causing several stability issues [35] especially with ones related to newest IEEE Task Force definitions of stability [36]. For example, recently, Finland has faced slower converter-related stability issues. In one notable case, nearly 65 wind farms were involved in a reactive power oscillation triggered by a disturbance from a single converter. A 400 kV line failure, followed by the disconnections of many transformers, caused the oscillation occurrence. After stopping the planned disconnection procedure and returning the grid to its prior stable state, the issue was rectified. During the summer of 2023, major transmission outages on Finland's west coast resulted in wind generation being cut by as much as 2000 MW to keep the system stable. A few months earlier, the NordLink HVDC interconnector reversed its power flow unexpectedly—from importing 1375 MW to exporting 300 MW—causing a sudden 1675 MW swing and led system frequency down to 49.4 Hz while the frequency remained below 50Hz for more than 20 minutes.

To deal with these problems, the Nordic TSOs have stepped up their cooperation—sharing what they have learned from past incidents, working towards common standards for modeling and integrating GFMs technologies, and relying more on phasor measurement units for real-time control. On the cross-border front, discussions continue about upgrading or adding new interconnections between Norway, Sweden, Denmark, and Finland. A new HVDC station connecting Finland and Norway is being considered as part of ongoing project to improve grid control and stability, with plans towards possible operation by 2030. Preliminary studies suggest that the most effective option for increasing capacity is a back-to-back HVDC system, which could increase cross-border transfer capacity by 150–200 MW. This solution will provide full control over power flow, enable higher utilization of the existing AC grid, and help dampen electromechanical oscillations.

At the same time, the Nordic countries are working to adjust their AS to keep things running smoothly. In Denmark, Energinet has issued new tenders [37] incorporating AS for fast, primary and secondary frequency regulation. Particular emphasis is placed on accommodating ESS with limited capacity, i.e., approval for 80% of the rated output and operation during specific hours. The ESS needs to pass a prequalification test so as to participate in specific AS [38]. Similarly, Sweden's Svenska Kraftnät has updated its regulatory framework to support improved frequency control and maintain adequate reserve margins when required [39].

C. *ENTSO-E Activities*

As the energy transition progresses, ENTSO-E plays a critical role in supporting TSOs by providing comprehensive factsheets on advanced and state-of-the-art technologies. These factsheets cover a wide range of innovations, including transmission assets, system operations, digital solutions, and flexibility technologies. They aim to improve TSOs' understanding of each technology's characteristics, advantages, and associated Technology Readiness Levels, thus facilitating informed decision-making in the integration of new technologies, like HVDC circuit breakers, large-scale dc overlay grid concepts, LCCs and VSCs, etc., [12], [40]. Furthermore, ENTSO-E focuses on ensuring the safe, reliable, and proper EPES operation, with HVDC technology playing a critical role as the energy transition progresses. Towards this direction, a series of position papers has been published supporting the European Commission's Offshore Strategy, addressing key aspects such as system governance, market challenges, and financial mechanisms [40], [41].

In [42], ENTSO-E has identified TSO concerns, including the low or potentially inadequate supply of total system inertia and fault current infeed described as fault level and also affecting short circuit ratio. For this reason, in [43], ENTSO-E introduced three classes of converter-interfaced RES with different levels of control capabilities [24], i.e., 1) voltage system creation; 2) fault level contribution; 3) acts as sink for harmonics and unbalances; 4) provision of true inertia; 5) supporting system survival to enable the effective operation of low frequency demand disconnection. ENTSO-E highlights the need of several assets to include GFM capabilities. Specifically, it is mentioned that TSOs can advance GFM capabilities by specifying requirements for new assets like HVDC systems, FACTs, and synchronous condensers. This development involves both cost considerations and regulatory engagement at national level. For instance, in France, initial discussions with regulators have begun, highlighting the importance of cost-benefit analyses to balance the requested capabilities with associated costs, which may vary significantly depending on the specifications. In addition, it is emphasized that ESS have significant potential to provide GFM capabilities, due to their technological maturity.

D. Past and Ongoing EU RIA/IA projects

In recent years, several EU RIA projects have showcased technological innovations, simulation capabilities, and demonstration activities, paving the way for wider adoption of HVDC and hybrid HVAC-HVDC networks. For example, PROMOTioN [3] adopted a comprehensive approach to shaping Europe's offshore energy grids, addressing technical, financial, regulatory, managerial, and policy aspects. Also, READY4DC [4] envisioned a future electricity network with a growing role for multi-terminal, multi-vendor HVDC solutions within current ac networks. Moreover, NEWGEN [5] and MISSION [6] demonstrate innovations supporting the broader adoption of HVDC grids. Furthermore, HVDC-WISE [7], [21] focuses on designing and assessing HVDC-based architectures for improved system performance through new reliability and resilience tools. InterOPERA [8] promotes interoperable, multi-terminal HVDC grids, while PROSECCO [9] showcases improved protection methods for multi-vendor MVDC/HVDC systems. DAEDALOS [11] and InterSCADA [10] focus on integrating advanced software tools into Supervisory Control and Data Acquisition (SCADA) systems for hybrid EPES management. Finally, THEUS [12] and HYNET [13] projects aim to demonstrate software tools for planning and managing transnational hybrid systems at all voltage levels, including demonstration of GFM capability at the HV level.

III. BENEFITS OF HYBRID HVAC-HVDC POWER GRIDS

Hybrid HVAC-HVDC grids provide several advantages by combining the distinctive strengths of ac and dc TS technologies [44]. One of the most important advantages is the enhancement in power transfer capability and provision of superior dynamic control. HVDC lines are particularly appropriate for long-distance power transmission because they can utilize the full voltage difference between conductors and they allow for high power transfer with significantly lesser line losses as compared to conventional ac systems [45]. As there is no skin and proximity effect, HVDC lines can carry higher currents with less resistance, typically carrying nearly double the power of HVAC lines at similar voltage levels. In terms of cost, hybrid ac/dc grids reduce transmission loss, infrastructure requirements, and the number of conductors needed. Such efficiencies become critical in integrating geographically dispersed RES like offshore wind farms, mega solar farms in deserts, and mountain hydroelectric plants [46] to the grid. Since dc transmission is not subject to reactive power losses and capacitive charging currents that limit the efficiency and stability of ac lines, it is considered more efficient and reliable for HV TS [47].

Another noteworthy benefit of HVDC technology is its ability to interconnect asynchronous ac grids with different frequencies or distinct stability characteristics, particularly beneficial for international interconnections and the formation of unified energy markets [48]. As a result, better load balancing and system flexibility in large geographical areas can be provided, resulting in optimal use of resources and a more efficient energy market [49].

VSCs integration into HVAC-HVDC hybrid grids is perceived very favorably [50]. The VSCs allow for quick and accurate control of power flows, thereby making their contributions towards improved voltage regulation and stability of the system. Due to their responsiveness, these converters are able to offer AS such as synthetic inertia, frequency support, and transient stability enhancement—services that have traditionally been provided by conventional synchronous generators, which are now gradually being decommissioned. In addition, during fault or disturbance conditions, HVDC links can isolate the grid and limit cascading failure propagation and thus improve overall EPES resilience [51]. The black-start feature of HVDC systems, where power can be restored without relying on an external supply, is also seen as a critical asset in recovery scenarios during emergencies. In environmentally sensitive or high-density locations, hybrid HV systems have the additional advantage of conserving land use by back-fitting the current ac system with dc connections, thereby increasing capacity without requiring additional right-of-way. Power quality is enhanced as well since dc systems do not suffer from typical ac ailments such as harmonics, voltage dips, or high fault currents. Moreover, HVDC converters can also serve as buffers to enclose disturbances and fault block the fault propagation in interconnected ac zones. Via the proper utilization of VDC-based HVDC systems, the amount of dc–ac conversion is reduced resulting in decreased inverter capital and operating expenses [52]. Moreover, as new ESS operate in dc, hybrid networks ensure larger and simpler penetration of the storage, making it easier to utilize RES efficiently and reduce overall electricity production costs.

In a nutshell, hybrid HV grids are poised to play a key role in driving the future to a decarbonized, decentralized, and digital energy economy. By facilitating the integration of variable RES, distributed generation, as well as flexible and adaptive grid operation, these systems enable sustainable and resilient EPES.

IV. NEEDS AND BARRIERS

The aforementioned benefits reveal that hybrid ac/dc grids should be prioritized in determining energy strategies [53]. However, with the integration of RES into grids at HV levels, the existing HVAC system infrastructure reaches and sometimes exceeds the limit values [54]. Therefore, the transition to hybrid EPES structures involves financial investments and several types of challenges related to system integration, which are discussed hereafter.

A. Technological & Operational Barriers

HVDC and hybrid HVAC-HVDC EPES have some differences in terms of operational and technological compatibility. One of the biggest problems encountered in these differences is that protection systems are not sufficiently developed. The direction and dynamics of fault currents in dc systems differ from ac systems. For this reason, existing protection equipment is insufficient [2]. In addition, high-speed switching and isolation problems for HVDC systems also present challenges that need to be improved in terms of compliance and are a current research topic [55]. Furthermore, the algorithms used in the control and dynamic stability analysis of hybrid systems and the integration of these algorithms with the grid as well as monitoring and enhancement of current SCADA platforms present many challenges. Finally, the harmonization of system operators in terms of software, communication and security standards constitutes a significant operational obstacle [20].

B. Economic & Commercialization Uncertainties

European electricity markets in Europe are quite diverse and fragmented, despite the recent efforts made by policy makers and regulators towards a single competitive EU market. In case of widespread adoption of hybrid HVAC-HVDC networks significant amount of investments and respective costs in new equipment (new types of SCADA, energy management systems and TSO-Distribution System Operator (DSO) platforms, GFMs, new protection devices) is required. There are also deficiencies in commercial applications such as integration of hybrid systems, capacity allocation and balancing services, as well as loss calculations [56]. This situation poses financial uncertainties for investors, and consequently, for the development of commercial projects [20].

C. Political & Legal Challenges

Despite the willingness and alignment from the EU MS towards the increase of RES and reduction of GreenHouse Gas (GHG) emissions, there still exist risks related to policy uniformity and potential shifts in political priorities or socioeconomic (e.g., warlike events) factors that could impact the need on EPES infrastructure investments. Therefore, engaging consistently with relevant regulatory bodies will be crucial for navigating these political challenges. In the implementation of hybrid ac/dc grids, effective coordination among TSOs, DSOs, regulators and policy makers is needed to ensure technical and regulatory harmonization. To achieve this, pilot region studies that can serve as paradigm cases should be examined to harmonize the methods and improve standardizations [57]. The ongoing EU projects like THEUS, HVDC-Wise, HYNET could make suggestions for policies, industry standardization and recommendations minimizing legal risks related to the landscape of the European continental EPES.

D. Societal & Environmental Challenges

The adoption of hybrid HVAC-HVDC grids will benefit society by enabling a future EPES with increased security of supply and reduction of energy costs. The environmental benefits that can be gained must be balanced against the environmental footprint associated with the deployment of the necessary technology and infrastructure. Some potential challenges such as community disruptions and cyber vulnerability of the new system implemented based on more digitalized grids might arise. Hence, strategic actions are essential to mitigate these concerns, ensuring that societal benefits are not neglected, so as to build trust between the public and the EPES operators. Moreover, the social landscape presents challenges in terms of public perception and acceptance of new hybrid ac/dc grids due to the lack of knowledge or awareness on the associated topics. In order to overcome potential resistance to technology adoption and achieve social support, clear communication strategies to the general public will be needed to highlight the direct and indirect benefits of hybrid HVAC-HVDC grids.

V. CONCLUSION AND FUTURE DIRECTIONS

This paper provides a comprehensive review of the techno-economic, societal, and regulatory aspects for hybrid HVAC-HVDC grids considering the available technologies and the emerging needs of European TSOs, related to the development of new tools for HVAC-HVDC planning, operation and control. Despite the undeniable advantages of such grids, their commercialization and public adoption encounter techno-economic and regulatory challenges. To unlock and fully exploit the potential of hybrid HVAC-HVDC power grids and facilitate their widespread adoption, a coordinated effort is required from TSOs, equipment manufacturers, and policy-makers. This includes advancing technological innovations, establishing supportive regulatory policies, and developing market frameworks that encourage investment and large-scale deployment. This paper serves as a basis for the research conducted within the EU project THEUS, focusing on GFM control, long-term planning of hybrid HVAC-HVDC systems, and Building Information Modeling for substations. As part of this effort, the Greek TSO, Independent Power Transmission Operator, will also contribute to the dissemination and adoption of THEUS outcomes, aiming to foster collaboration among countries in the EU and the Mediterranean basin.

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