Navigating Grid Challenges: Voltage-Reactive Power Control in the Integration of Power-to-X Facilities

Riofrio, Jonathan ; You, Shi; Weckesser, Tilman

Published in:
Proceedings of 2024 IEEE PES Innovative Smart Grid Technologies Europe (ISGT EUROPE)

Link to article, DOI:
10.1109/ISGTEUROPE62998.2024.10863080

Publication date:
2025

Document Version
Peer reviewed version

Citation (APA):
Riofrio, J., You, S., & Weckesser, T. (2025). Navigating Grid Challenges: Voltage-Reactive Power Control in the Integration of Power-to-X Facilities. In *Proceedings of 2024 IEEE PES Innovative Smart Grid Technologies Europe (ISGT EUROPE)* IEEE. https://doi.org/10.1109/ISGTEUROPE62998.2024.10863080

Navigating Grid Challenges: Voltage-Reactive Power Control in the Integration of Power-to-X Facilities

Jonathan Riofrio
Dep. of Wind and Energy Systems
Technical University of Denmark (DTU)
Kgs. Lyngby, Denmark
aurio@dtu.dk

Shi You
Dep. of Wind and Energy Systems
Technical University of Denmark (DTU)
Kgs. Lyngby, Denmark
shyo@dtu.dk

Tilman Weckesser
Dep. of Wind and Energy Systems
Technical University of Denmark (DTU)
Kgs. Lyngby, Denmark
tweck@dtu.dk

***Abstract*—This paper reviews the technical requirements for inverter-based facilities in modern power systems, focusing on Photovoltaic Power Plants (PVPPs), Wind Power Plants (WPPs), and Energy Storage Facilities (ESFs), with an emphasis on voltage-reactive power (V-Q) control. Case studies from in-force grid codes in Denmark and the United Kingdom are analyzed due to their high share of renewable energy and potential for Power-to-X (PtX) projects. Our findings suggest that existing requirements may apply to electrolysers, key components in PtX facilities, provided that their capability curves are properly defined, considering their electrochemical behavior, the absence of DC-side energy generation, and inverter operation. The paper highlights the need for harmonizing grid codes, particularly for PtX equipment and electrolysers. Transmission System Operators (TSOs) are urged to establish mandatory V-Q control requirements, focusing on connection levels. Moreover, the proposed solutions indicate that electrolysers could mitigate voltage issues in large power systems with appropriate regulation, and future grid codes should define contribution grades for inverters in multi-energy systems to ensure compliance and seamless integration.**

***Index Terms*—electrolyser, inverter-based generation, grid code, power-to-X (PtX), voltage-reactive power (V-Q) control**

I. INTRODUCTION

Power-to-X (PtX) refers to a group of technologies that utilize surplus generation capacity from variable renewable sources (VRS) to produce green hydrogen (GH_2), thereby enhancing the storage and flexibility of energy systems. The core component of PtX is the electrolyser, which could become an active player in electrical grids. Presently, electrolysers are connected to bulk power systems with rated powers (P_n) ranging from kilowatts (kW) to megawatts (MW), and even larger capacities (in the gigawatt (GW) scale) are anticipated soon [1]–[3]. Nevertheless, there are currently few technical guidelines or compliance tests stated for their commissioning and operation in real-time power system operations.

Most current research on integrating PtX and electrolyser in power systems focuses on modeling [5]–[7], market design [8], [9], and the provision of ancillary services [5], [10], [11], using assumptions based on technical requirements outlined in grid codes (GCs) for power generation units due to the lack of specific information. However, treating electrolysers as generators is misleading because they consume power rather than generate it. A more accurate definition would be a flexible load interacting with bulk power systems through inverter equipment which to some degree can fulfill the requirements for inverter-based generators using VRS.

This approach is used in [1], [4] to analyze the requirements for Power-to-Gas and electrolysers, with a focus on active power and frequency (P-f) control and regulation, as well as fault-ride-through (FRT) capability to ensure reliable operation. These requirements began to be included in the latest amendments to the Demand Connection Code issued by the European Network of Transmission System Operators (ENTSO-E) in 2023 [12]. However, voltage and reactive power (V-Q) control is also crucial for reliable operation, especially in modern power systems where all inverter-based equipment is expected to contribute to f and V stability during contingencies before being allowed to disconnect [13]. Therefore, dedicated studies and technical requirements for V-Q control from PtX equipment are still pending for their integration into power systems.

To address this gap, this paper aims to consolidate potential technical requirements for PtX projects concerning V-Q control, using the current grid codes of Denmark and the United Kingdom (UK) as case studies. These countries were selected due to their growing PtX potential, high share of generation from VRS, DC converter stations, ancillary services, and recent updates to their GCs [1]. Following a comprehensive summary, four possible solutions for enhancing system operation are proposed.

The rest of the paper is organized as follows: Section II outlines the technical and operational features of inverter-based equipment in Denmark and the UK. Section III summarizes the functions required for V-Q control, while Section IV details Q control requirements for inverter-based generators in both countries. Section V proposes solutions for PtX facilities to comply with grid codes for V-Q delivery/absorption. Finally, Section VI presents the main findings and insights.

II. INVERTER-BASED EQUIPMENT CLASSIFICATION IN DENMARK AND THE UNITED KINGDOM

This classification relies on current data for inverter-based power plants, such as Photovoltaic Power Plants (PVPPs), Wind Power Plants (WPPs), and Energy Storage Facilities (ESFs) in both countries. The Transmission System Operators (TSOs) define normal and abnormal operations based on acceptable frequency and voltage ranges. In Denmark, normal operating voltage (U_c) should be within -15% $\leq U_c \leq$ 10% [14], while in the UK, nominal connection voltage (U_n) must be within -10% $\leq U_n \leq$ 10% [15]. A more detailed explanation of these conditions is provided in [1].

A. Technical features - Denmark

Table I categorizes inverter-based power plants and ESFs in the Danish bulk power system. Voltage (V) is divided into four groups: extra high (220-400 kV), high (50-150 kV), medium (10-33 kV), and low (0.40-0.69 kV) [14], [16]–[18].

For each group, maximum ($U_{\max}$) and minimum ($U_{\min}$) connection voltages are defined, representing the highest and lowest operating voltages under normal conditions (excluding transient and abnormal conditions) [19]. In EH, $U_{\max}$ ranges from 5-11.36% and $U_{\min}$ is 20%. In HV, $U_{\max}$ ranges from 9.84-20%, and $U_{\min}$ is 10%. In MV, $U_{\max}$ ranges from 9-20%, with $U_{\min}$ at 9-10%. In LV, both $U_{\max}$ and $U_{\min}$ range from 10-10.14% [1], [16]–[18]. These percentages vary by U_n in each group, but U_c is set at each plant's Point of Connection (PoC) and is used as the reference for further analyses.

TABLE I
CATEGORIZATION OF INVERTER-BASED EQUIPMENT IN DENMARK

Cat.	**Technologies**	**Rated power (P_n)**	**Con. Level**
A_{DK}*	ESFs	$P_n \leq 125$ kW	-
$A1_{DK}$	PVPPs-WPPs	RP ≤ 11 kW	-
$A2_{DK}$	PVPPs-WPPs	11 kW $< P_n \leq$ 50 kW	-
B_{DK}*	ESFs	125 kW $< P_n \leq$ 3 MW	-
B_{DK}	PVPPs-WPPs	50 kW $< P_n \leq$ 1.5 MW	-
C_{DK}	ESFs	3 MW $< P_n \leq$ 25 MW	-
C_{DK}	PVPPs-WPPs	1.5 MW $< P_n \leq$ 25 MW	-
D_{DK}	ESFs-PVPPs-WPPs	$P_n > 25$ MW	$U_n > 100$ kV

* Can be recategorized in Cat.SX or T, when temporarily connected or retrofitted with new ESFs.

B. Technical features - United Kingdom

In the UK bulk power system, inverter-based equipment and Power Park modules can operate at 400 kV, 275 kV, and 132 kV. Voltage variation is limited to ± 12% U_n during contingencies and ± 3% U_n in steady-state operation [13], [20]. Table II summarizes the classification of Power Park modules, their P_n, and connection levels in the UK [1], [13], [20].

TABLE II
CATEGORIZATION OF POWER PARK MODULES IN THE UNITED KINGDOM

Type	**Technologies**	**Rated power (P_n)**	**Con. Level**
A_{UK}	PVPPs-WPPs	0.8 kW $\leq P_n \leq$ 1 MW	$U_n < 110$ kV
B_{UK}	PVPPs-WPPs	1 MW $\leq P_n \leq$ 10 MW	$U_n < 110$ kV
C_{UK}	PVPPs-WPPs	10 MW $\leq P_n \leq$ 50 MW	$U_n < 110$ kV
D_{UK}	PVPPs-WPPs	$P_n > 50$ MW	$U_n \geq 110$ kV

III. VOLTAGE AND REACTIVE POWER CONTROL FUNCTIONS

PVPPs, WPPs, and ESFs must have control functions to regulate the Q delivered or absorbed from the bulk power systems to ensure reliable operation [20]. Similarly, V should be controlled at reference points using activation orders with predefined set points. The analyzed grid codes specify three main functions:

A. Q Control

This function independently regulates Q regardless of P at the PoC, shown as a constant horizontal line in the first quadrant of the P-Q plane (red line, Fig. 1). For example, the Danish GC specifies setpoint variations of 0.1 kVAr for PVPPs, 1 kVAr for WPPs, and 1% or more of rated reactive power delivery (Q_{nl}) or absorption (Q_{no}) for ESFs [16]–[18].

B. Power Factor (PF) Control

The regulation of Q is proportional to P at the PoC, shown as a line with constant gradient in the first quadrant of the P-Q plane (blue line Fig.1). Control actions must maintain accuracy within ±2% of the set point or ±5% of the P_n, whichever provides greater tolerance. WPPs should control within 2% deviation of nominal Q in 1 minute, and ESFs within a 1% deviation of the set point for 0.6 seconds [16]–[18], [20].

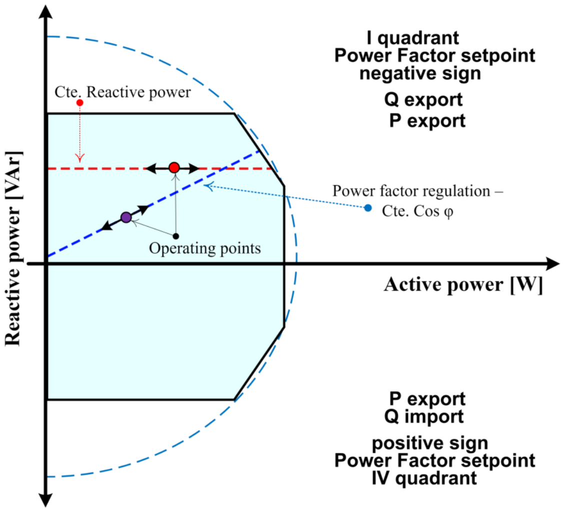

Fig. 1. Reactive power and PF control functions in Denmark and the UK [16]–[18], [20].

C. Voltage Control

This feature controls V at the reference point within specified limits, with at least 0.5% accuracy relative to the nominal value. In Denmark, control must stay within ±2% of set point or ±5% of rated voltage, depending on which provides the highest tolerance. PVPPs and WPPs must maintain control across their operating range with a droop typically set at 4% [16]–[18]. For ESFs, droop settings range from 2% to

12%, with an initial setting of 4%, subject to system operator agreement.

In the UK system, V control features adjustable slopes from points A to H, ranging from 2% to 7%, with a default value of 4% [13], [20]. Fig. 2 illustrates the required droops for each slope in offshore and onshore systems. Here, NS-UK represents the normal slope, while ASOTSDUW-UK and ASOS-UK are the automatic slopes for offshore transmission system development User Works and onshore systems [13]. For both systems, Q_{min} and Q_{max} are set by PF = 0.95 at rated P in leading and lagging modes.

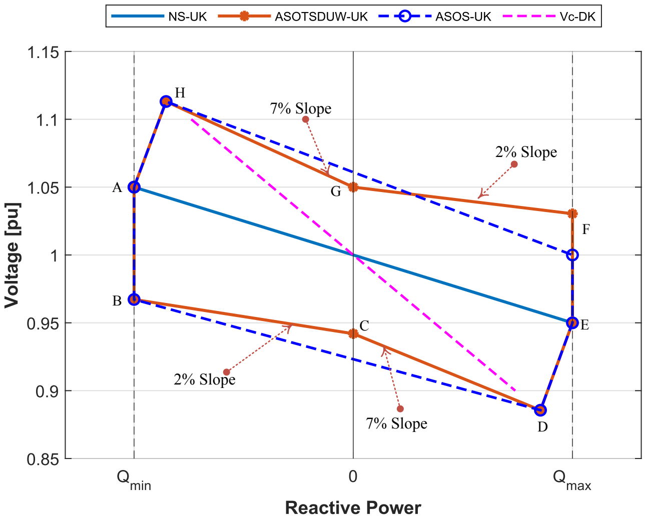

Fig. 2. Voltage control function in Denmark and the UK [13], [16]–[18].

IV. REACTIVE POWER CONTROL REQUIREMENTS

Capability and PF curves are established for inverter-based generators and ESFs, as classified in Tables I and II. A concise summary of each technology, based on the minimum requirements, follows.

A. Photovoltaic Power Plants

The Danish grid code specifies a setpoint of 0 VAr for Q in PVPPs, with operations confined to areas shown in Fig. 3:

- **Cat. A1 and A2:** In area 1 (semi-circle between red and blue dotted lines), PF must be within $0.9 \leq \text{PF} \leq 1$ when P exceeds 20% of rated power, with a default PF of 1
- **Cat.B:** Operates in areas 1 and 2 with a default PF of 1. No Q compensation is required when disconnected.
- **Cat.C:** Operates in areas 1-3 and compensates Q when disconnected or not generating P.
- **Cat.D:** Operates in areas 1-4 with Q compensation similar to Cat. C.

These capability curves are supplemented by Q delivery curves based on PoC voltage (U_{PoC}), using U_c as a reference. Fig. 4 illustrates the requirements for Denmark and the UK, showing narrower operating margins for all Power Park module categories in Table II.

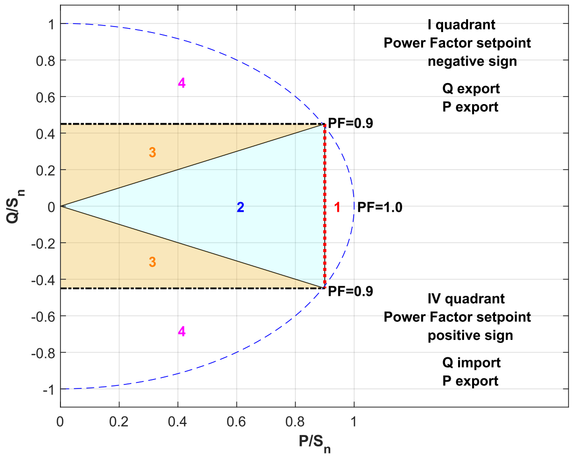

Fig. 3. Denmark: requirements for Q delivery as a function of P/S_n for all PVPP categories, where S_n is the nominal apparent power [13], [15].

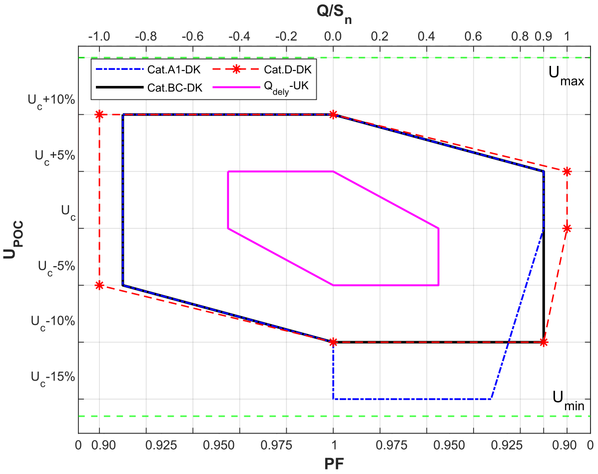

Fig. 4. Requirements for Q delivery as a function of U_{PoC} for PVPPs [14]–[16].

B. Wind Power Plants

Requirements in Denmark for WPPs are vastly developed due to their significant share in the energy mix. Specific requirements for each category are as follows:

- **Cat.A2:** PF must be between 0.95 and 1 when delivered power exceeds 20% of the nominal value.
- **Cat.B:** Operates within the narrow cyan area in Fig. 5, with no Q compensation required when disconnected or P = 0.
- **Cat.C:** Q delivery must fall within the yellow area in Fig. 5, with mandatory Q compensation when disconnected or not generating P.
- **Cat.D:** Operates within the broader grey area in Fig. 5, with Q compensation required as in Cat. B and C.

For WPPs under categories CDK and DDK, Q delivery is specified based on voltage variations at U_{PoC}, as shown in Fig. 6. In the UK, the GC requires Power Park modules to supply their full P_n within a PF range of $-0.95 \leq \text{PF} \leq 0.95$ (leading

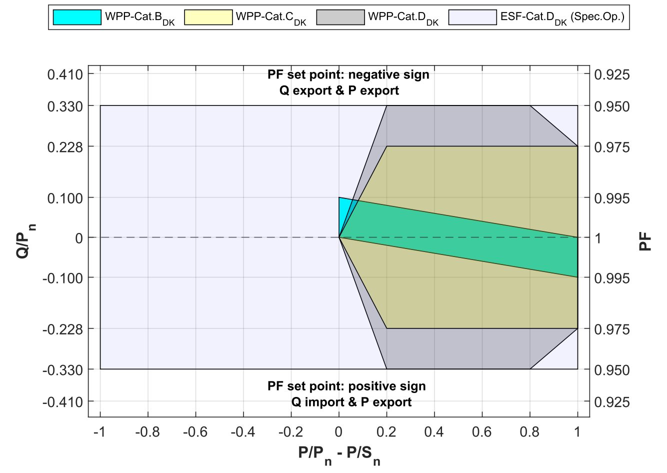

Fig. 5. Denmark: requirements for Q delivery as a function of P for WPPs and ESFs [17], [18].

and lagging). No Q delivery is required for operating points below 20% of P_n [19].

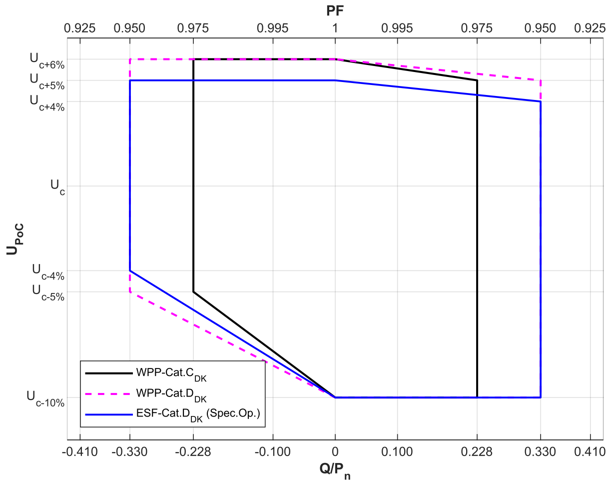

Fig. 6. Denmark: requirements for Q delivery as a function of U_{PoC} for WPPs [15], [20]

C. Energy Storage Facilities

ESFs must operate within specified zones based on P_n and U_{PoC}, maintaining a PF of 1 or as agreed with the electricity provider. Specific operating zones based on the Danish GC for delivering Q are listed below.

- **Cat.A and B (low voltage):** For these categories, precision and accuracy requirements are undefined for powers below 10% of apparent power (S_n). ESFs are not required to compensate Q when not delivering or absorbing P, or when disconnected. Fig. 7 depicts the operational zones: design freedom (green) for $-0.9 \leq$ PF ≤ 1, required capability (blue), and reduced area (black) when for $S_n < 10\%$. Current regulations also define Q provision based on U_{PoC}, as displayed in Fig. 8, with two zones for Q delivery when S_n reduction (S Allow.red-Cat. $A\&B_{\mathrm{lv}}$) is allowed due to technical limits. In the Q export zone, current must be constant at the nominal value (I_n), with the Q/P_n rate calculated by (1). The light purple curve encloses the required capacity.

$$\frac{Q}{P_n} = \sqrt{\left(\frac{U_{\mathrm{PoC}}}{U_c}\right)^2 - 1} \tag{1}$$

- **Cat.B:** ESFs operate within a narrower zone (Fig. 7) with Q/P_n ratio of ± 0.329. There are no accuracy requirements for $S_n < 10\%$, no compensation duties during disconnection, or P delivery/absorption. Fig. 8 outlines the required capability (cyan area) and allowed reduced zones (P Allow.red-Cat. B, C & D) for Q based on the voltage range.
- **Cat.C:** Q delivery overlaps with Cat. B, covering two triangular zones on the left and right sides between 0.10 and 0.20 P/P_n (yellow area, Fig. 7) with smaller reduced zones in grey. This overlap is seen in the olive green area of Fig. 7.ESFs in Cat. C must maintain a PF of 1 during P absorption and compensate Q when disconnected or not delivering/absorbing P. Q delivery must also meet the voltage range shown in Fig. 8 for Cat. B at nominal power (Pnl).
- **Cat.D:** Delivery is defined in two approaches. The first follows Cat. C conditions (Fig. 7) for operating points below P_{nl}. The second applies to special points below P_{nl} and nominal absorbed power (P_{no}), covering a broader area in Fig. 5 [ESF-Cat.D (Spec.Op.)]. Q compensation is required during disconnection, delivery, or absorption of P. Fig. 8 specifies Q provision based on U_{PoC} for this approach (ESF-Cat.D (Req.cap.)).

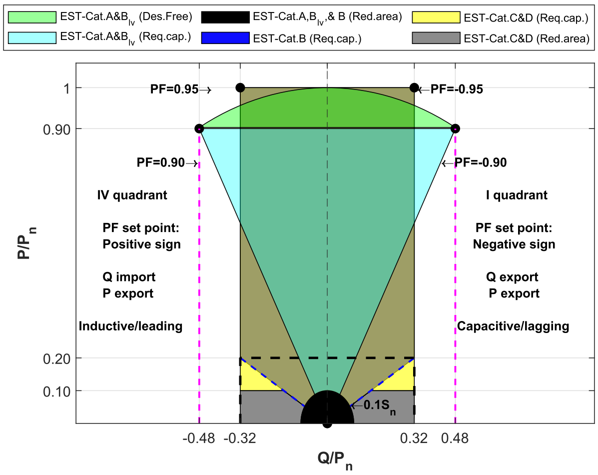

Fig. 7. Denmark: requirements for Q delivery at work points below P_{nl} for ESFs [18].

V. POSSIBLE SOLUTION FOR PTX FACILITIES

The presented curves are typically based on generator designs, power conversion systems, and inverter controls. Nevertheless, for PtX facilities, specifically electrolysers, there is no inherent generation capability since they are loads interfacing with power systems through power conversion systems. This

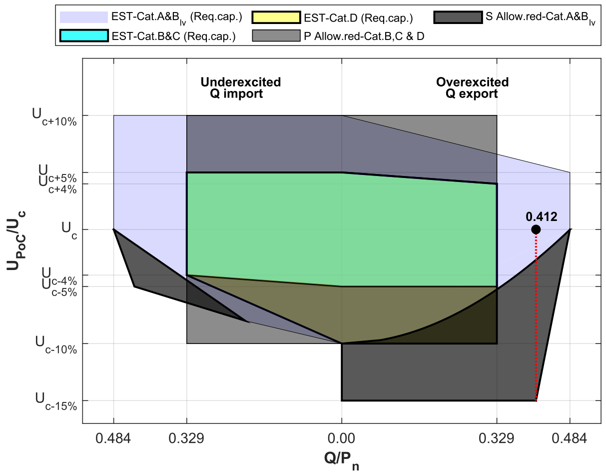

Fig. 8. Denmark: requirements for Q delivery at work points below P_{nl} at function of U_{PoC} for ESFs [18].

suggests that a primary energy source should be added to these facilities to fulfill the $V-Q$ control requirements and ensure the reliable operation of modern power systems. Inverter-based equipment must provide ancillary services to some degree before disconnection is allowed during disturbances. Thus, stakeholders can explore or consider the following solutions for integrating PtX facilities in electrical grids.

- **Oversizing of inverter equipment:** Oversizing inverters allows for Q delivery or absorption without sacrificing P provision. However, this approach may reduce efficiency, increase costs, and complicate the control of PtX facilities.
- **Priorization control strategies:** Incorporating control strategies that prioritize P-f or V-Q control based on grid status and PtX operation goals can help meet the stated requirements. This approach can prevent the need for equipment oversizing and lead to better operational practices for both the grid and PtX equipment.
- **Modifications in topology:** Given that electrolysers lack energy generation capacity, their connection topology to the electrical grid must be reconfigured for stand-alone PtX projects. This reconfiguration may require additional equipment, such as capacitor banks or ESFs, which could increase initial investment costs. However, this setup would enable their participation in ancillary markets. Incorporating capacitor banks into the inverter design could lead to the appearance of specialized inverters for electrolysers, as shown by the green-dotted line in Fig. 9.
- **Multi-energy systems:** Depending on the PoC and available energy sources, integrating other power generators can help meet V-Q requirements in GCs. TSOs should define the proportion of Q delivery or absorption managed by inverters in multi-energy systems, highlighting the need for coordinated V-Q control (CC-VQ). Additionally, these systems can incorporate hydrogen storage combined with fuel cells, enabling PtX projects to generate electricity and comply with grid codes. This approach could even introduce new capabilities, such as black-start functionality, as illustrated on the left side of Fig. 9.

VI. CONCLUSIONS

This paper extensively reviews the technical requirements for inverter-based facilities in modern power systems, with a focus on PVPPs, WPPs, and ESFs, particularly to V-Q control. The study analyzes in-force grid codes in Denmark and the UK due to their high share of renewable generators, GC update periodicity, and potential expansion of PtX projects.

Four solutions are proposed to enable V-Q control for electrolysers connected to bulk power systems. The analysis indicates that existing requirements could still be applicable if capability curves are accurately defined, taking into account the electrochemical behavior, DC-side energy generation, and inverter operation of electrolysers. Proper standardization of the technical features of electrolysers and inverter equipment could facilitate their integration with power grids.

A prompt definition and adjustment of GCs for PtX, aligned with market and technological advancements, are crucial for enhancing the effectiveness of V-Q control in large power systems. Future work should focus on defining the contribution levels of inverters in multi-energy systems to ensure grid compliance and seamless integration.

REFERENCES

[1] J. Riofrio, S. You, and T. Weckesser, ”Power-to-X (PtX) integration in modern power systems: exploring grid code compliance and technical requirements in Denmark and the United Kingdom,” 22nd Wind and Solar Integration Workshop (WIW 2023), Copenhagen, Denmark, 2023, pp. 5-14, doi: 10.1049/icp.2023.2712.
[2] ENTSO-E, “Potential of P2H$_2$ technologies to provide system services,” p. 106, 2020.
[3] ENTSO-E, “Flexibility from Power-to-Hydrogen (P2H$_2$) Webinar,” Tech. Rep. February, 2023.
[4] R. Bogner, J. Weidner, V. Schulz, C. Schöll, S. Janković and H. Popella, ”Requirements for power-to-gas units,” 22nd Wind and Solar Integration Workshop (WIW 2023), Copenhagen, Denmark, 2023, pp. 1-4, doi: 10.1049/icp.2023.2711.
[5] C. Huang, Y. Zong, S. You and C. Træholt, ”Analytical Modeling and Control of Grid-Scale Alkaline Electrolyzer Plant for Frequency Support in Wind-Dominated Electricity-Hydrogen Systems,” 2023 IEEE Power & Energy Society General Meeting (PESGM), Orlando, FL, USA, 2023, pp. 1-1, doi: 10.1109/PESGM52003.2023.10253345
[6] X.Jin, S. You, M. Petersen, J. Riofrio, S. Thakur, C. Træholt, ”Exploring commercial water electrolyser systems: a data-based analysis of product characteristics”, Clean Energy, 2024, pp. 126-133, doi: /10.1093/ce/zkad072
[7] A. M. De Corato, M. Ghazavi Dozein, S. Riaz and P. Mancarella, ”Hydrogen Electrolyzer Load Modelling for Steady-State Power System Studies,” in IEEE Transactions on Power Delivery, vol. 38, no. 6, pp. 4312-4323, Dec. 2023, doi: 10.1109/TPWRD.2023.3315749
[8] Y. Zheng, C. Huang, S. You, Y. Zong, ”Economic evaluation of a power-to-hydrogen system providing frequency regulation reserves: a case study of Denmark”, International Journal of Hydrogen Energy, Volume 48, Issue 67, 2023, pp. 26046-26057, ISSN 0360-3199, doi:10.1016/j.ijhydene.2023.03.253.
[9] E. Raheli, Y. Werner, J. Kazempour, ”A conic model for electrolyzer scheduling”, Computers & Chemical Engineering, Volume 179, 2023, 108450, ISSN 0098-1354, doi:10.1016/j.compchemeng.2023.108450.
[10] M. Saretta, E. Raheli and J. Kazempour, ”Electrolyzer Scheduling for Nordic FCR Services,” 2023 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm), Glasgow, United Kingdom, 2023, pp. 1-6, doi: 10.1109/SmartGridComm57358.2023.10333890.

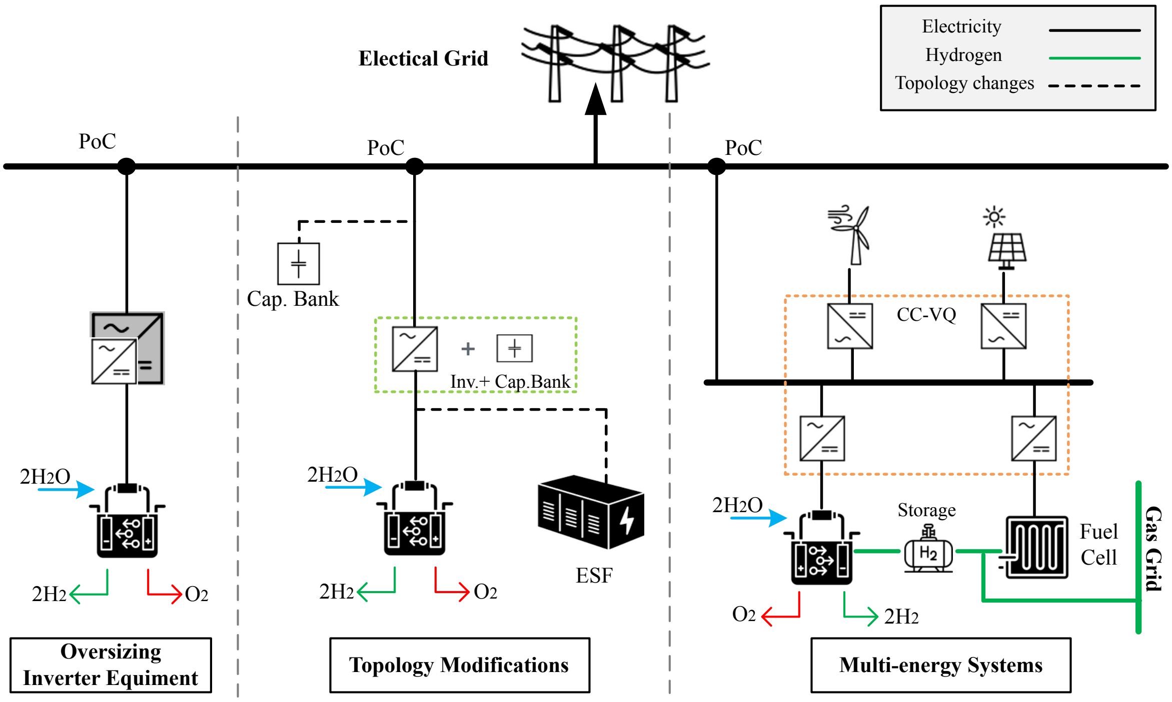

Fig. 9. Proposed solutions for Q delivery in PtX facilities

[11] A. Buttler and H. Spliethoff, ”Current status of water electrolysis for energy storage grid balancing and sector coupling via power-to-gas and power-to-liquids: A review”, Renewable Sustain. Energy Rev., vol. 82, pp. 2440-2454, 2018.

[12] European Union, “Network code on Demand Connection - Amendment 2023,” Official Journal of the European Union, vol. 2023.

[13] ENTSO-E, “System dynamic and operational challenges,” Tech. Rep. May, 2023.

[14] Energinet, “Technical Regulation 3.2.1 for power plants up to and including 11 kW (Type A1 only),” pp. 1–51, 2016.

[15] National Grid Electricity System Operator - ESO, “The Grid Code,” Tech. Rep. 5, National Grid Electricity System Operator - ESO, 2023.

[16] Energinet, “Technical regulation 3.2.2 for PV power plants above 11 kW,” pp. 1–108, 2016.

[17] Energinet, “Technical regulation 3.2.5 for wind power plants above 11 kW,” pp. 1–108, 2016.

[18] Energinet, “Technical Regulation 3.3.1 for Electrical Energy Storage Facilities,” no. September, pp. 1–8, 2019.

[19] European Committee for Electrotechnical Standardization - CENELEC, “DS/EN 60038: Standard voltages,” no. 1, 2011.

[20] National Grid Electricity System Operator - ESO, “Guidance Notes - Power Park Modules,” no. 2, 2012.