

Review

A Systematic Review of Key Challenges in Hybrid HVAC–HVDC Grids

Umar Javed ^{1,†}, Neelam Mughees ^{1,†}, Muhammad Jawad ¹, Omar Azeem ², Ghulam Abbas ², Nasim Ullah ³, Md. Shahariar Chowdhury ⁴, Kuaanan Techato ^{4,5,*}, Khurram Shabih Zaidi ¹ and Umair Tahir ²

- ¹ Department of Electrical and Computer Engineering, COMSATS University Islamabad, Lahore Campus, Lahore 54000, Pakistan; umarjaved636@gmail.com (U.J.); engrneelam.m@gmail.com (N.M.); mjawad@cuilahore.edu.pk (M.J.); kzaidi@cuilahore.edu.pk (K.S.Z.)
- ² Department of Electrical Engineering, The University of Lahore, Lahore 54000, Pakistan; omar.azeem@ee.uol.edu.pk (O.A.); ghulam.abbas@ee.uol.edu.pk (G.A.); umair.tahir@ee.uol.edu.pk (U.T.)
- ³ Department of Electrical Engineering, College of Engineering, Taif University, Taif 21944, Saudi Arabia; nasimullah@tu.edu.sa
- ⁴ Faculty of Environmental Management, Prince of Songkla University, Hat Yai 90112, Thailand; mdshahariar.c@psu.ac.th
- ⁵ Environmental Assessment and Technology for Hazardous Waste Management Research Center, Faculty of Environmental Management, Prince of Songkla University, Hat Yai 90112, Thailand
- * Correspondence: kuaanan.t@psu.ac.th
- † Co-first author: U. Javed and N. Mughees contributed equally to this paper.



Citation: Javed, U.; Mughees, N.; Jawad, M.; Azeem, O.; Abbas, G.; Ullah, N.; Chowdhury, M.S.; Techato, K.; Zaidi, K.S.; Tahir, U. A Systematic Review of Key Challenges in Hybrid HVAC–HVDC Grids. *Energies* **2021**, *14*, 5451. <https://doi.org/10.3390/en14175451>

Academic Editor: Mario Marchesoni

Received: 24 July 2021

Accepted: 27 August 2021

Published: 1 September 2021

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Abstract: The concept of hybrid high-voltage alternating current (HVAC) and high-voltage direct current (HVDC) grid systems brings a massive advantage to reduce AC line loading, increased utilization of network infrastructure, and lower operational costs. However, it comes with issues, such as integration challenges, control strategies, optimization control, and security. The combined objectives in hybrid HVAC–HVDC grids are to achieve the fast regulation of DC voltage and frequency, optimal power flow, and stable operation during normal and abnormal conditions. The rise in hybrid HVAC–HVDC grids and associated issues are reviewed in this study along with state-of-the-art literature and developments that focus on modeling robust droop control, load frequency control, and DC voltage regulation techniques. The definitions, characteristics, and classifications of key issues are introduced. The paper summarizes the key insights of hybrid HVAC–HVDC grids, current developments, and future research directions and prospects, which have led to the evolution of this field. Therefore, the motivation, novelty, and the main contribution of the survey is to comprehensively analyze the integration challenges, implemented control algorithms, employed optimization algorithms, and major security challenges of hybrid HVAC–HVDC systems. Moreover, future research prospects are identified, such as security algorithms' constraints, dynamic contingency modeling, and cost-effective and reliable operation.

Keywords: hybrid grids; frequency deviations; active and reactive power flow; supervisory control; contingency analysis

1. Introduction

The power grids are growing both in terms of complexity and size. The added complexity is due to the regulations that aim to integrate renewable energy systems to make sustainable power systems and due to the increase in efficiency. The advanced energy storage techniques and power electronics technology is also contributing towards making the current high-voltage alternating current (HVAC) grids more complex. The high-voltage direct current (HVDC) systems are becoming equally important due to the involvement of onshore and offshore renewable energy sources, such as solar and wind power, since the output from their AC asynchronous grid system has to be transformed into HVDC for long-distance power transmission. This is because of fewer expenses,

increased power transfer capability, and fewer dielectric losses. Therefore, the advanced research is focused on hybrid HVAC–HVDC grids that led to developing improved power transmission capability, introducing back-to-back systems for interconnected regions with different frequencies, and making power transmission systems more efficient for long distances [1].

The complete shift of HVAC grids into HVDC grids is more unlikely due to technical issues, such as power reversal and communication network for coordination between grids, as these problems are not found in HVAC systems [2–4]. Therefore, it is more likely that the existing power grids will transform into hybrid HVAC–HVDC systems. The hybrid grids will receive the benefits of both the HVAC and the HVDC systems. It is worth mentioning that these hybrid grids are also facing some major integration challenges related to reliable and adequate modeling of high-speed power converters and protection from large fault currents that have been identified and discussed in this paper [5]. This survey has highlighted the control strategies and optimization algorithms for fast, accurate, and robust control of generation, power-flow, supervisory, and contingency of hybrid HVAC–HVDC grids for their normal and abnormal operation. The security of the hybrid power system relevant to physical malfunctioning of power system equipment, line-outage, and contingencies, and various other physical reasons that sources variations and uncertainties in the MTDC networks causing a security breach has also been analyzed in detail for the stable and cost-effective operation of hybrid grids.

Power flow control (PFC) is considered one of the major issues in hybrid systems, which has not been comprehensively addressed earlier. The integration of asynchronous AC systems in multi-terminal direct current (MTDC) networks has also provoked numerous and critical challenges related to DC voltage control, power-sharing, and power flow that restrains the establishment of independent and self-sustaining regulation of active and reactive power conservation and flow [6–9]. Therefore, appropriate control strategies should be modeled considering the converter (voltage source converter (VSC) or line-commutated converter (LCC)) losses and DC transmission line losses for a fast, accurate, and robust DC voltage regulation [10–12]. Moreover, reactive power support is essential for the dispersal and dispatch of a stable, optimal, and instantaneous balanced power in HVDC grids under normal and fault circumstances [13,14].

The distribution of hybrid fields, formed through the combination of HVDC and HVAC electric fields originating from HVDC–HVAC overhead transmission lines, offers comprehensive and extensive research in the field of electromagnetic environment of transmission line engineering based on the analysis of ion-flow field characteristics. Therefore, appropriate control measures incorporating reasonable corridors arrangement must be analyzed explicitly to lower ion current density for a safer environment [15].

The operational strategy of the MTDC networks becomes quite troublesome in contingency conditions when the system is prone to a sudden outage of converters and various transmission equipment [16–18]. Therefore, a stable bi-directional power flow regulation and reactive power support in post-contingency conditions should be necessarily addressed. This review article addresses operational contingency control topologies, such as dynamic electrothermal effects of the conductor and grounding configurations of the MTDC grid for an accurate and robust real-time contingency analysis [19–21].

Generation and supervisory control of hybrid HVAC–HVDC grids are quite essential for a fast and robust frequency regulation with optimal power flow [22]. This review paper also presents a comprehensive review of generation and supervisory control topologies that have not been addressed inclusively in other review articles. The voltage-based load control, frequency support, and modular multilevel converters (MMC) are the most profound control schemes used in generation control [23–26]. Several droop control and persistent DC voltage control schemes are used for supervisory control [27–31].

Optimization algorithms are quite necessary for the effective integration of asynchronous grids into the MTDC network [31]. Therefore, a comprehensive review of optimization algorithms is presented that ensures the successful and optimal inclusion

of renewable energy resources having asynchronous grids in MTDC networks. These optimal solutions ensure a cost-effective economic dispatch in hybrid HVAC–HVDC networks. Several state-of-the-art algorithms have been analyzed in detail for a cost-effective optimal economic dispatch inclusive of optimal fuel cost and reduction in transmission line losses [32–34]. Moreover, algorithms proposing optimal solutions for optimal power flow (OPF) and voltage stability in multi-area objective dynamic economic dispatch (MAMODED) systems have been analyzed in detail [35].

Optimal generation control is a basic requirement for the deviation-less frequency of the hybrid grids. The load flow control (LFC) in a deregulated environment consisting of multi-source generating units power systems should be implemented optimally to maintain an adequate balance between generation and demand. Therefore, optimal control of automatic generation control (AGC) of a multi-source system is quite essential in this regard, when frequency fluctuation occurs due to sudden contingencies of AC asynchronous grids in an MTDC grid [36,37]. Therefore, a comprehensive review of modified hybrid optimization algorithms is presented that is more proficient than other traditional algorithms for the tuning of existing controllers [38–41]. Moreover, an overview of hybrid algorithms is presented for calculating the optimal pricing capital cost of integrating offshore and onshore renewable energy sources into an MTDC network. This optimal solution ensures the essential security level of the power system at the expected operation cost [42–45].

Robust optimization algorithms are quite necessary for establishing reactive power support in hybrid HVDC grids that ensures DC voltage stability and power loss reduction. This paper presents an overview of state-of-the-art algorithms useful in providing transient voltage stability and reactive power support to hybrid HVAC–HVDC grids [46–49]. The cost-effective integration of distributed generations (DGs) into a hybrid HVAC–HVDC network requires optimal approaches. The advancements in renewable DGs, electric vehicles (EVs), and photovoltaic energy (PVs) have made the integration of renewable energy sources into the system complex and have also forecasted the need for integration of battery storage devices with DGs, and future distributed systems (DSs). This paper presents a review of algorithms that produces OPF in DGs and DSs [50–57].

The security of hybrid HVAC–HVDC networks is quite important for their stable cost-effective operation under normal, abnormal, and contingency conditions. The paper has emphasized two major control techniques, i.e., corrective and preventive control. In the corrective control security-constrained optimal power flow (CSCOPF) scheme, a control action is required for each set of possible contingencies [58,59]. Whereas in the preventive control security-constrained optimal power flow (PSCOPF) scheme, all possible sets of contingencies are considered, and it satisfies all security requirements without any extra control action. The maximum-security of the hybrid HVDC grids system can be achieved through these control schemes [60–62].

The main objective of this survey is to give the reader a key insight into the past work, current developments, and future research directions and prospects that led to the evolution of this field. To the best of the authors' knowledge, this survey is the first attempt to summarize the issues related to integration challenges, control strategies, the implemented control algorithms, employed optimization algorithms, and major challenges of the combined security of hybrid HVAC–HVDC system under one umbrella. Table 1 shows abbreviations of acronyms used in the paper. Whereas Table 2 provides a comparative analysis of our survey literature with other relevant state-of-the-art surveys. Table 2 clearly reveals the predominance of our survey paper over other surveys since it discusses the current research areas of hybrid HVAC–HVDC grids from every possible aspect.

Summarizing in a nutshell, the main contributions of our review paper are:

- **Integration Challenges:** Based on the literature, six main categories of integration challenges in hybrid HVAC–HVDC grid systems have been identified and discussed in detail. These categories include technical, protection, modeling, social and economic, climate, and generation-source-based challenges. Modeling and protection are more

considerable among them since they provide overall grid voltage and frequency stability and provides appropriate control actions at all possible contingencies.

- **Control Strategies:** DC voltage regulation, frequency support, and droop control strategies ensure stable and optimal power flow control in MTDC grids. Moreover, the distribution of hybrid electric ion-flow fields is analyzed through the finite element method (FEM) and finite volume method (FVM) to lower the ion current density for a safer and secure environment. Furthermore, several grounding methods in MTDC networks and PPFC renders a stable bi-directional power flow and reactive power support during HVDC line blockage or AC transmission system tripping.
- **Optimization Techniques:** The state-of-the-art hybrid optimization algorithms are discussed and compared that ensure optimal generation, economic dispatch, security, and power flow control. Optimal solutions for AGC and LFC are examined to ensure stable frequency and voltage operation in a MAMODED power system. Moreover, algorithms rendering optimal solutions for integration of battery storage devices with DGs, and for future DSs, are discussed.
- **Security Challenges:** The classical security-constrained optimal power flow (SCOPF) problem and its shortcomings are examined and discussed. Therefore, a modified SCOPF utilizing the corrective and preventive control schemes is discussed, satisfying all security requirements by taking control actions at all possible contingencies.

The rest of the paper is organized as follows: Section 2 identifies the integration challenges; Section 3 introduces and compares the different control strategies being used in literature; Section 4 discusses the optimization algorithms; Section 5 provides the security analysis; Section 6 is the concluding section, which concludes the paper with future directions.

Table 1. Abbreviations of acronyms used in the paper.

Acronym	Abbreviation	Acronym	Abbreviation	Acronym	Abbreviation
PF	Power Flow	MMC	Modular Multilevel Converter	NSGA	Non-Dominated Sorting Genetic Algorithm
HEF	Hybrid Electric Field	POD	Power Oscillation Damping	FOA	Fruit Fly Optimization Algorithm
DC	Direct Current	LQR	Linear Quadratic Control	SOCP	Second-Order Cone Programming
PLL	Phase-Locked Loop	CC	Coordinated Control	OIO	Optics-Inspired Optimization
TL	Transmission Lines	PRB	Pseudo-Random Binary	BDE	Binary Differential Evaluation
PFC	Power Flow Control	MINP	Mixed-Integer Nonlinear Programming	MTDC	Multi-Terminal Direct Current
FRT	Fault Ride Through	NR	Newton Raphson	VSC	Voltage Source Converter
MRAC	MRAC: Model Reference Adaptive Control	GA	Genetic Algorithm	DEGW	Differential Evaluation Grey Wolf
MMC	Modular Multilevel Converter	SPEA	Strength Pareto Evaluation Algorithm	DL	Defense Line

Table 2. Comparison of this paper's review with reviews of other literature.

Ref.		[63]	[64]	[65]	[5]	[66]	[67]	[68]	[69]	[70]	[71]	Our Survey
Integration Challenges	Technical Challenges	✓	✓	✓	✓	✗	✗	✓	✓	✓	✗	✓
	Grid Codes	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓
	Protection Challenges	✗	✓	✗	✗	✗	✓	✗	✗	✓	✗	✓
	Modeling Challenges	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓
	Socio-Economic Challenges	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓
	Climate Challenges	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓
	Generation Source-Based Challenges	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✓

2. Integration Challenges of Hybrid HVAC–HVDC Systems

The HVDC grid is needed to transmit the huge power being produced by remote power plants, such as wind farms, in addition to balancing the sporadic characteristics of renewable power sources. Currently, the deployment of HVDC systems with existing HVAC systems is a major challenge. This section discusses the major integration challenges of hybrid HVAC–HVDC super grids.

2.1. Technical Challenges

The HVDC circuit breakers that are required for isolating the faulty sections in super grids are not easily accessible. AC circuit breakers are being used to isolate the whole HVDC grid even if the fault is occurring in only one section, which is not an acceptable option. HVDC circuit breakers with an operating time of 5 ms or less are needed to overcome this challenge [2]. Dealing with the constraints of overhead and underground cable systems for HVDC is also a problem. Traditionally, HVDC grids were used to be realized as LCC that is also known as a current source converter (CSC), but was practically infeasible due to the following reasons [3,4]:

- Difficult power reversal;
- Dependency on HVAC system strength for whole system recovery;
- Consumption of reactive power when supplying shunt capacitor bank;
- Need for DC and AC filters because of harmonics;
- The special design of LCC-based HVDC systems;
- More prone to commutation failures;
- Inverter and rectifier needed data communication systems;
- Only works when the inverter is in an active state.

With the advent of insulated gate bipolar transistors (IGBTs), VSC for HVDC systems was introduced to deal with these drawbacks. However, VSC technology posed the following new technical challenges that need to be addressed [3]:

- Protection coordination and secondary protection system;
- Fast removal of faulty locations without affecting the whole;
- Sophisticated DC voltage control approach and power flow;
- Functioning during communication failure and its requirements;
- Load supply after isolating a section of the HVDC grid.

There are also some technical codes that need to be fulfilled when integrating HVDC transmission systems into the AC grid. The operating frequency and voltage range and the operation duration in these ranges need to be defined. Researchers need to take care of the frequency deviations and the resulting required control of active power. In case of faults, the required reactive current should be taken care of as described in [5]. The P/Q capabilities of the grid state are permitted by the exchange of reactive power [71].

2.2. Protection Challenges

Another big integration challenge of hybrid HVAC–HVDC systems is protection. The HVDC protection systems should have a response time of a few milliseconds, as the DC lines have very small impedance [3]. The whole power system can experience a major voltage drop if a short circuit occurs. The DC current does not have zero crossings; therefore, it is complicated to break it. The HVDC converters cannot bear large fault currents; so, they need more protection than HVAC. Every HVAC system can supply DC fault [3].

2.3. Modeling Challenges

The simulation of a real VSC–HVDC system needs to be reliable and adequate. Their model should consider the details of their operation [72]. It should take into account the usage of fully controlled power converters operating at high speed and working of VSC when operating in phase–phase mode.

In addition, the continuous working of VSC devices at high speed in emergency, post-emergency, and normal working conditions of the power system should be examined. However, these difficulties can be solved if the simulation models can meet the subsequent conditions [73–75]:

- The simulation software should be flexible enough to model any size of the power system.
- The HVDC power system model must be of minimum three-phase networks to consider the effect of any unbalanced conditions.
- The implemented model should ignore the disintegration of processes and the constraints associated with their time period.
- The simulation can be in real-time and have the capability to connect with external systems and devices.

2.4. Social and Economic Challenges

Globally, a precise economic valuation of HVDC super grids is a big challenge. An exact evaluation is not obtainable as it highly depends upon how HVDC systems will be integrated with the current HVAC systems. In Europe, politicians have estimated that EUR 600 billion are needed for distribution system operators (DSOs) and TSOs in 10 years [76]. Potential investors will be utilities, TSOs, DSOs, and manufacturers. Public funds can also accelerate the development [77–79].

For deployment projects, regulatory and national funding agencies are already investing [80]. Another concern is that several states are reluctant to alter their energy policies or to welcome the new hybrid HVDC and HVAC grids. For example, France spent huge money on the development of a nuclear power plant that is providing about 75% of its electrical power. Therefore, France might not accept the new green hybrid HVAC–HVDC super grids. Table 3 shows the main HVDC projects in the world from 1990 to 2018 and the minimum number of deployments that have been planned up to 2030 [77–79].

Table 3. Worldwide acceptance of HVDC projects from 1990–2018 [79].

Area	Deployed	Minimum Expected Number of Installations Up to 2030
Asia	41	29
Europe	42	38
North America	18	22
Oceania and Australia	5	3
South America	4	6
Africa	3	2

2.5. Climate Challenges

New cable routes for hybrid HVAC–HVDC systems should take care of lakes, natural parks, environment-sensitive areas, archaeological sites, and agricultural lands [76]. Likewise, offshore HVDC grid systems should not hamper navigating regions and fishing during their manufacturing process. The natural ecosystems must be sheltered and shall not be interrupted by any acoustic noises. For example, it is still not exactly known how marine fauna perceives sound emissions.

The HVDC cables also have the problem of seepage of filling materials that could pollute grounds. In the long run, this could hugely cause contamination of aquifer living underneath. Moreover, the generated electromagnetic fields may influence the migratory behavior and the orientation of marine mammals and fish [81]. In a nutshell, exact climate assessments are not available, and more research is required to develop them.

2.6. Generation Source-Based Challenges

The different renewable energy generation sources affect the HVDC systems integration with the traditional HVAC transmission systems. The sporadic power generation from a hydraulic power plant will differ from the power generated using a wind turbine [82].

Furthermore, different times of the day and seasons also affect the power generation profiles and predictions of operation and design. The HVDC system must provide balance among the various generation sources and respond to the generation.

The HVDC integration technologies communicate with the present HVAC transmission network technologies, affecting their operation and design. The HVDC system must provide a balance among the various generation sources and respond to predominance and diversity. For offshore wind farms, HVDC transmission systems are preferred for integration with the onshore grid because of their capabilities and long distances [83]. Hence, reducing the cost and improving the efficiency of DC–DC converters is a big integration challenge for wind farms. Moreover, wind turbines integration into the traditional grid also need to be in check with protection scheme requirements [84]. The HVDC advanced protection devices provide research opportunities.

Similarly, the integration of solar energy also faces challenges as the solar generation system with more penetration has higher congestion levels when compared with wind generation. Therefore, energy policies and transmission planning valuations should be formulated by the available energy mix [85]. Table 4 summarizes the main areas of all the above-discussed integration challenges identified from the literature, i.e., technical challenges, protection challenges, modeling challenges, social and economic challenges, climate challenges, and generation source challenges.

Table 4. Integration challenges of hybrid HVAC–HVDC grids.

Technical	Protection	Modeling	Social and Economic	Climate	Generation-Source
Power Reversal [3,4] HVDC Circuit Breaker [2] Commutation Failures [3,4] Communication Systems [3,4] HVDC Voltage Protection Control Strategies [4] Coordination [3] Hybrid Grid Codes [71] High Transmission Voltages [5]	Fast HVDC Protection Schemes [3] Short-Circuits [3] No Zero-Crossings in DC Current [3] HVDC Converters' Fault Bearing Capacity [3] DC Faults Coming from HVAC Systems [3]	Reliability and Accuracy [72] Real-time Simulation [73–75] Flexible Simulation Software [73–75] Simulate Unbalanced Conditions [73–75] Connection with External Equipment [73–75]	Precise Economic Valuation [76] Integration Cost [76] Government and Public Consent [76] Global Acceptance [77–79] New Hybrid HVDC–HVAC Energy Policies [80] Funding Study [80]	New Cable Construction [76] Marine and Nature Life [76] Acoustic Noises [82] Seepage of Filling Materials [76] EMT Emission [82] HVDC Sea Cables Accurate Climate Assessments	Sporadic Power Generation Profiles [81] Communication between Integration Technologies Time of Day and Seasons [81] Alignment with Existing Protection Schemes [84] Energy Mix Consideration [85] Transmission Planning Assessments [85]

2.7. Real Implementation Analysis

Converting the current multi-circuit HVAC transmission system to pure HVDC or hybrid HVAC–HVDC overhead cables is increasingly being used to expedite power grid upgrades. Due to the aesthetic similarity, acceptance of such hybrid systems is expected to be greater than with new construction. For instance, the authors in [86] analyze the operational benefits of a potential hybrid HVAC–HVDC transmission line in a Swiss transmission network. It was found out that the transmission system efficiency is compromised due to higher converter losses. However, it was also proved that hybrid conversion is advantageous since it can result in reduced lower operating costs, AC line loading, and increased network infrastructure usage. Similarly, the researchers in [87] handle the power frequency coupling effect in MMC because of a 400-kilometer-long hybrid HVAC–HVDC transmission line. The results showed no stability issues or adverse effects. Another research work has also analyzed the ion-flow conditions in hybrid HVAC–HVDC transmission grid systems due to the corona effect [88]. They have verified that a net DC ion current results from AC conductors in hybrid HVAC–HVDC grid systems.

2.8. Conclusion of Integration Challenges

In a nutshell, these are the six main categories of integration challenges that hybrid HVAC–HVDC systems are currently facing. All the challenges open up new research

questions that should be answered at the latest. Researchers should research to find solutions to challenges such as:

- How HVDC faulty areas could be removed quickly without affecting the whole hybrid HVAC–HVDC grid?
- Which HVDC protection schemes would respond quickly and remove any faults introduced by HVAC systems?
- What simulation requirements should be fulfilled and which ones could be ignored for the real-time case?
- What is the best way to obtain funds for HVDC systems' deployment?
- How can marine life be saved from getting extinct because of the installation of new HVDC systems?
- Which generation source would prove to be more beneficial in terms of cost and transmission capacity for hybrid HVAC–HVDC grid systems?

The impending hybrid HVAC–HVDC grid should have the capability to surpass the present HVAC grid system. It should provide higher power levels, increased transmission capacity, better grid models, and cost-effective configurations among other benefits. There is no doubt that big investments would be required to realize the hybrid HVAC–HVDC grid systems but finding the right investors is the main issue. Developed nations and big energy firms can collaboratively work out with each other for efficient and cost-effective integration of hybrid grid systems.

3. Control Strategies of Hybrid HVAC–HVDC Systems

The section of “Control Strategies” has been explored from various aspects, such as power flow control, contingency analysis, fault ride control, and generation control. The integration of asynchronous AC systems in MTDC networks has also instigated numerous critical challenges related to DC voltage control and power-sharing in hybrid grids that restrains the establishment of self-sustaining regulation of active and reactive power flow in hybrid grids. The “Power Flow Control (PFC)” sub-section explains the aforementioned problems from every possible critical aspect. Moreover, the MTDC networks become unstable when the power systems are prone to sudden outages of the transmission line equipment and bi-directional power flow convertors. The “Contingency Analysis” sub-section addresses some real-time analysis of operational contingency control topologies been proposed. Furthermore, the generation and supervisory control of MTDC grids are quite essential for fast frequency regulation with optimal power flow during normal and fault scenarios. The “Generation Control” and “Supervisory Control” sub-section presents a comprehensive overview of proposed generation and supervisory control topologies for hybrid HVDC grids.

3.1. Power Flow Control

The OPF in a hybrid grid is necessary for establishing an independent regulation of active and reactive power conservation between both sides of VSC–HVDC through rectifiers at both ends, i.e., offshore and onshore. Sequential and unified approaches are the two widely used strategies for this purpose. Still, the unified approach is mostly preferred for OPF tools because it solves all the equations together leading to less complex computation that requires a much smaller number of iterative loops [6]. Using the same unified method, VSCs are significantly preferred over CSCs in MTDC systems, since they offer an AC side voltage control by regulating reactive power demand. They are capable of handling converter control modes and converter loss modeling irrespective of the extension or expansion of the system and the number of VSCs been installed [7,8].

Moreover, for optimal power flow calculations in a combined AC and MTDC system, a steady-state model has also been designed, which develops full power flow equations and nonlinear mathematical optimization by considering DC line losses and VSC terminal losses [9,10]. LCC is still considered a dominant technology over VSC since it offers an economical solution for transmitting bulk power. The two widely used control method-

ologies for the stability of LCC–MTDC networks are: (a) inverter topology with constant extinction angle (CEA) control, (b) rectifier topology with constant ignition angle (CIA) control. LCC–MTDC networks with the CIA control method offer well stable and faster control response in initialization and DC power transfer conditions [11].

DC voltage droop control is a widely used strategy in DC voltage regulation in achieving stability and the dynamic response of an MTDC Figure 1. The steady-state analysis chooses droop parameters by incorporating maximum current limits and desired voltage errors of wind farm side converters (WFCs) and grid side converters (GSCs). Droop control in AC GSCs regulates voltage deviations due to the wind’s stochastic nature. In contrast, WFCs regulate DC voltage by tackling AC Grid faults when the currents are injected by WFCs and extracted by the GSCs. So, the distribution of power among various terminals of MTDC terminals without communication channels during normal and fault conditions is possible using this scheme [12,89].

Different control modes can be employed for power dispatch in an MTDC network. Either a single GSVSC or a combination of two or more GSVSC, with different droop characteristics, has been modeled to regulate DC voltage and with an appropriate power-sharing ratio between all, ensuring a balanced generation and power transition of active-power during fault scenarios. Offshore wind farm frequency modulation and DC damping resistors strategies are used to ensure uninterrupted output power of WFVSC even during AC grids faults in GSVSCs [13]. An adaptive droop control (ADC) scheme in MTDC networks improves power-sharing between AC and DC grids and frequency support [90]. A frequency-based consensus method with an optimization technique incorporated using the coupling gain solution method is used to tune droop coefficients. It not only reduces VSC station losses and generation cost, but also improves power-sharing between AC and DC grids and guarantees smoother transitions during contingency scenarios [90,91]. A hybrid adaptive control scheme has also been proposed for WF–VSCs with a coordinated strategy between the adaptive controllers for improving power-sharing in an MTDC network [92].

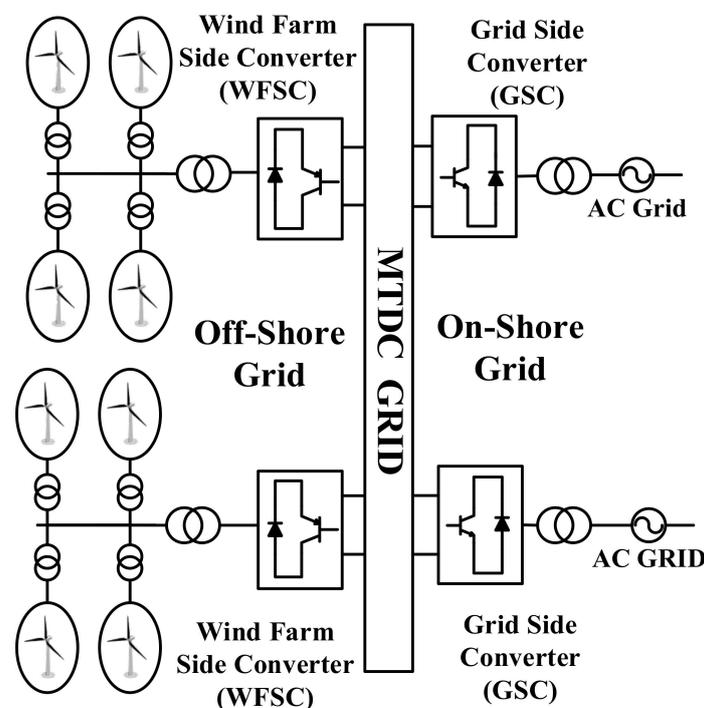


Figure 1. Typical multi-terminal HVDC (MTDC) network [12].

The conventional droop control leads to DC voltage deviations and instability in an MTDC network. Therefore, a secondary controller added as a supplementary controller

to the primary droop control with a distributed architecture has been proposed. This secondary droop control level only acquires local information from neighboring convertor stations instead of taking global information and observes the voltages and output powers of local convertor stations through a communication protocol, thus greatly reducing the communication cost and complexity. It not only compensates the DC voltage deviations due to conventional droop control, but also performs well for converter outages, power imbalances, and communication link failure in radially connected and meshed grids [93].

DC line resistances source unequal fluctuations of DC bus voltages and create complications in instantaneous balancing power dispersal in DC grids in the DC voltage droop control scheme. HVDC terminals in a network with shorter transmission lines effectively respond to power balancing demands due to fewer dc line resistances [14]. The parallel formation of HVAC and HVDC transmission lines produces a hybrid electric field. The finite element method (FEM) and finite volume method (FVM) are the two widely used methods to analyze the characteristics of ion flow fields. The hybrid-electric fields become more corridor-centric as the separation distance is reduced because of an increased coupling effect between the DC and AC electric fields. The HVAC line's shielding effect on the electric field of the HVDC line reduces the DC component of the ground electric field and ion field density [94,95]. Nodal discontinuous Galerkin time-domain analysis can be used to analyze the distribution of this hybrid electric field and ion-flow field, and corona interlinkages of HVAC and HVDC. The analysis reveals that the AC conductor sizing and AC voltage level impacts the electric field's distribution since the density of ion current and electric field decreases remarkably with the increment of corona strength [96].

3.2. Contingency Analysis

LCC convertors alone are incapable of handling the bi-directional flow of active and reactive power support during an outage of a transmission line or overload condition. It results in the worst transient response, reduction in usage of remaining lines, and system blackout. Therefore, for attaining the system's reliability during contingency conditions, the flexibility of the existing LCC-MTDC system can be modified to a hybrid MTDC system by incorporating an extended VSC terminal between generation and load areas Figure 2a. The extended VSC terminal functions as an inverter during generation side contingency and contrarily as a rectifier during load side contingency. The MTDC controller and CRPS controller are responsible for regulating active and reactive power, respectively (Figure 2b) [15].

The influence of negative sequence components gives excellent contingency analysis. Therefore, a decoupled double synchronous reference frame (D2SRF) PLL has been designed, which proficiently detects the vector of voltage at a faster degree comparatively and extracts the negative and positive sequence components. Low-pass filtering and decoupling are then applied on negative sequence components for contingency analysis [16]. The contingency analysis of a meshed network of HVDC power grids can be performed by linearized AC-DC grid modeling framework under various operational control strategies of VSC units (VSC-slack converter, VSC-power scheduled convertor, VSC-passive circuit converter). Sensitivity and conversion factors analyze the overloaded/contingency scenarios during system disturbances for helping network operatives in maintaining the reliability of the AC-DC network [17]. A post-contingency power flow control (PPFC) methodology of hybrid grids has been formulated, which incorporates the effects of electrothermal consequences of the conductor under load fluctuations and different weather conditions. Sensitivity and optimization control methods are the two widely used methods for PPFC. The analysis reveals that the maximum tolerable currents of transmission lines favor high wind speed and low ambient temperature. The downward load fluctuation gives reduced generation cost without load shedding, whereas the upward load fluctuation trend not only increases the control cost but is also prone to load-shedding [18].

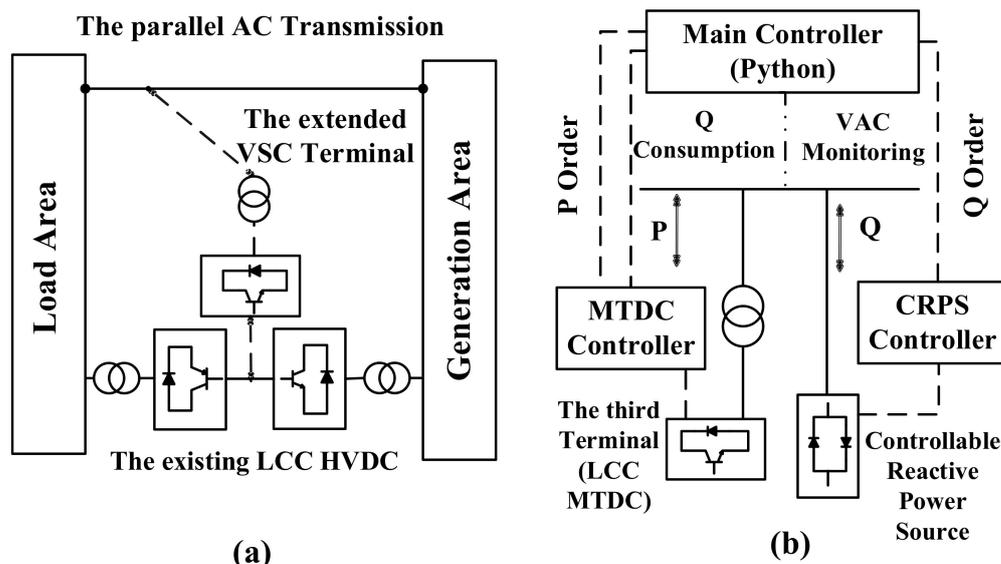


Figure 2. Extended MTDC architecture in power system. (a) Extended VSC terminal structure between generation and load. (b) Control architecture for MTDC system [15].

The grounding conformations in an MTDC network ensure safety and protection during contingency conditions. A critical analysis of grounding resistors values in different conformations of (a) monopole/bipolar ideal earth return ($R_{\text{gnd}} = 0$), (b) monopole/bipolar earth return ($R_{\text{gnd}} = 1\Omega, 2\Omega, 3\Omega$), (c) monopole/bipolar no-ground return is performed, and results reveal that grounding resistance’s increment has a significant influence on highest post-contingency DC voltages (Figure 3a,b). Therefore, the grounding conformations nearer to ideal-earth return should be opted for to achieve the stable operation of MTDC networks [19].

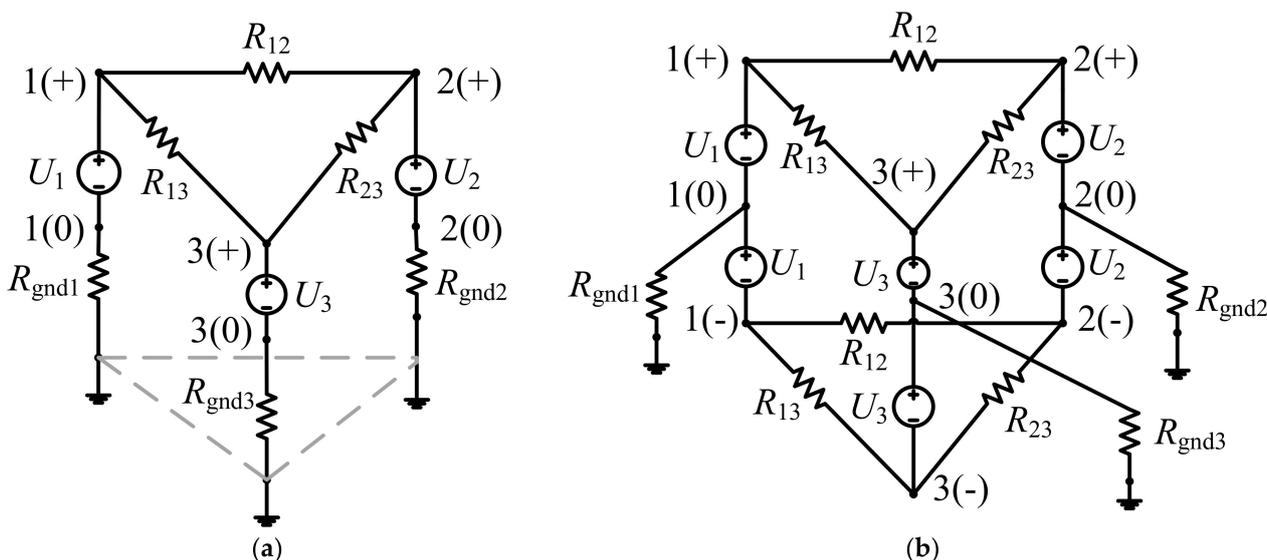


Figure 3. Ground return schemes in MTDC network (a) monopole and (b) bipolar [19].

3.3. Fault Ride through Control

The MTDC network should be responsive with fault ride through, e.g., (FRT) capacity in onshore AC grid faults. Communication-free control strategies (a) wind-turbine power set-point alteration, (b) offshore grid frequency alteration, (c) offshore AC grid voltage-controlled reduction, have been formulated, which provides FRT capability during AC faults and contingencies. They deliver a fast regulation of the turbine’s power output

without the use of conventional chopper resistors, which is considered a conventional solution for providing FRT capabilities during contingencies [20,21,97].

3.4. Generation Control

The incorporation of wind, renewable energy resources, and remote grids have produced numerous frequency stability challenges. Therefore, stabilizing the MTDC grid frequency swings during abnormal conditions is necessary, as it impacts power flow regulation. Voltage-based load control provides a controlled voltage amplitude variation and regulating active power flow consumption as per demand by frequency support service at each HVDC terminal. This control scheme manages the active power requirement for frequency deviation reduction and DC voltage regulation from both generator and load [22], since there is a risk of backflow of excessive power flow consumption as per demand by frequency support service at each HVDC terminal. This control scheme manages the active power requirement for frequency deviation reduction and DC voltage regulation from both generator and load [22]. Since there is a risk of backflow of excessive power to grids in isolated working grid networks, a control strategy is needed to optimize power share-out between AC and DC transmission lines. The modular multilevel converter (MMC) uses a power feedback loop control scheme that not only follows AC power flow value but also minimizes constraints and losses [23].

The latest research is pondering frequency support for AC asynchronous grids, since both VSC–MTDC and LCC–MTDC possess the desired capability. A weighted average frequency control (WAF) has been proposed, which provides frequency support in the VSC–MTDC network through the exchange of primary frequency reserves between AC asynchronous grids. WAF not only reduces the impact of frequency deviations on DC voltage profile, but also gives reliable control with different DC voltage droop controls and is prone to convertor contingencies [98]. Moreover, a coordinated control strategy has been proposed, which provides mutual frequency support to affected AC asynchronous grids, which is based upon pre-defined frequency deviation ratios between the disturbed AC grids and other areas. These ratios are pre-defined by network operators and allocate mutual frequency support and, thus, the active power reserves sharing for affected grids from healthy systems during imbalances and contingencies [99]. Furthermore, a two-level combined control (TLCC) scheme of VSC–MTDC with OWFs integrated has been proposed for providing onshore AC asynchronous grids with frequency support. In the first level, an adaptive inertial and droop control is applied at WTs side with WTs working at MPPT mode. Whereas, a communication-free frequency control support scheme has been applied on the second level, which formulates an effective coordinated scheme between OWF and VSC–MTDC for frequency regulation power [100].

The model reference adaptive control scheme, a hybrid frequency controller, incorporates linear quadratic regulator (LQR) control and pole placement methods for LFC during sudden load variations. Here, optimal coefficients are calculated using the genetic algorithm [24]. Frequency synchronization between HVAC and HVDC grids is necessary for the smooth working of hybrid grids during bulk power transfer, which can be provided using droop characteristics-based control strategies. Voltage droop responds to changes and balances in power flow detected by the frequency droop in AC grids [25].

Power oscillation damping (POD) designed through pole placement helps in maintaining system stability and in reducing its stress during power fluctuations in HVDC grids. Devising POD strategy through active power provides more effective results than reactive power modulation in response to deviations of the voltage's network regulation capacities [26]. Supplementary controllers for VSC–MTDC using coordinated-design methodology and the concept of eigenvalue sensitivity can also damp POD [101].

3.5. Supervisory Control

Weak AC grids or isolated working grids in the hybrid HVDC system require a control strategy for stable operation during normal and fault conditions. A coordinating control

scheme known as Vernier has been proposed, which comprises a series combination of the two VSC–HVDC and a capacitor-commutated converter, and is capable of sharing control burden and keeping constant margin and firing angle at inverter and rectifier [27]. HVDC and HVAC systems are used separately for bulk power transfer, but we need to model their frequency at some specified level for their parallel operation using the transmission network having two systems, one with 110 kV and 380 kV HVAC and converted to the other with 400 km hybrid HVAC–VDC current line, with bipolar MMC HVDC line link. Here, DBC gives more profound results over CCC in terms of control capabilities [28,87]. A supervisory control strategy based on LQR control theory assists in a stable, synchronous, and parallel operation of a coordinated network of HVDC link and FACT devices. The proposed model integrates VSC HVDC link, static VAR compensator (SVC), and thyristor-controlled series capacitor (TCSC) devices. TCSC produces desired values of line reactance and power flow, and SVC helps out in reactive power injection for a stable operation of the power system. The proposed supervisory methodology proficiently mitigates power system blackouts [102].

System inertia is mitigated when a large number of wind farms are integrated into the VSC–MTDC network. An adaptive control strategy for the fast frequency response of VSC–MTDC has been proposed to counter that issue. The proposed model drives an optimum DC-link capacitance value and HVSC (virtual inertia time constant). These small capacitors produce large DC voltage deviations when the frequency and inertia of the system are altered during its integration with weak AC grids, therefore producing a fast frequency response [30]. A detached HVDC produces improved transient stability than a hybrid HVAC–HVDC system when disturbances occur in the rotor angle of the generator [103]. A coordinating control scheme of the real power reference is proposed for balancing undesirable voltage variations at OWFs [29].

4. Optimization Algorithms for Hybrid HVAC–HVDC Systems Control

The section of “Optimization Algorithms” has been explored from various aspects, such as economic dispatch, generation control, onshore and offshore power systems, and reactive power control and power loss reduction. The use of various optimization algorithms is quite essential for the effective and successful integration of asynchronous grids into the MTDC network by ensuring overall stability and an adequate balance between generation and demand in the power system. The “Economic Dispatch” sub-section discusses the optimal solutions that ensure a cost-effective economic dispatch in hybrid HVAC–HVDC networks. Moreover, the “Generation Control” sub-section discusses several proposed hybrid optimization algorithms implemented in different hybrid PID controllers for the load frequency control (LFC) of generation sources in hybrid grids. Resultantly, an improved dynamic response of hybrid PID controllers is achieved, which improves the overall stability and control of individual and multi-power generation sources. Furthermore, the “Onshore and Offshore Power Systems” sub-section presents an overview of proposed optimal solutions for calculating the optimal pricing capital cost of integrating onshore and offshore renewable energy sources into an MTDC network. Lastly, the “Reactive Power Control and Power Loss Reduction” sub-section elaborates the proposed optimal solutions that establish reactive power support in hybrid HVDC grids by ensuring power loss reduction and DC voltage stability. The aforementioned section also discusses the proposed optimal solutions for the cost-effective integration of renewable energy resources, such as distributed generations (DGs), electric vehicles (EVs), and photovoltaic energy (PVs) and into a hybrid HVAC–HVDC network.

4.1. Economic Dispatch

Several economical, technological, and environmental factors and challenges such as improper load sizing, design complexities, and imbalanced power-sharing have disrupted cost-effective successful integration of the latest renewable portfolio system comprising of hybrid HVAC–HVDC grids [31]. An improved strength Pareto evolution algorithm

(SPEA2) gives an optimized solution for several economic dispatch problems. This multi-area objective dynamic economic dispatch (MAMODED) algorithm studies both HVDC and HVAC transmission systems by considering power losses and fuel cost of hybrid HVDC–AC systems with renewable energy and line losses incorporated [32]. An improved genetic algorithm (IGA) produces more optimal solutions than a rudimentary genetic algorithm and improves PFC and ED challenges such as voltage stability and reduced transmission line losses [33]. Novel bat algorithm (NBA) interprets several economic dispatch challenges by giving an optimized fuel cost for achieving consistency and a sustainable power system. It attains the fuel cost of HVDC systems 39.19% smaller than the HVAC transmission link [34]. Improved wheeling method with modified firefly algorithm with levy flights and derived mutation (MFA-LF-DM) implemented has also been proposed for a MAMODED system to ensure optimized solutions [35]. Moreover, an improved genetic algorithm (IGA) has been proposed for a better PFC, DC voltage stability, and transmission losses reduction in MAMODED systems [104].

4.2. Generation Control

Hybrid differential evolution grey wolf (DE-GWO) optimization technique implemented on a fuzzy proportional integral derivative (PID) controller for a two-area multi-source interconnected system has been used to improve the dynamic performance of the MTDC grid. This optimization technique proves the control system's adaptability in AGC, which controls the frequency fluctuations and monitor the tie-line power interchange in a multi-source interconnected system. The proposed methodology gives comparatively more optimal and efficient results over local unimodal sampling teaching–learning-based optimization (LUS-TLBO), optimized fuzzy PID controller (OF-PID), and differential evolution optimized PID controller (DEO-PID) regarding the dynamic performance of MTDC system such as undershoot, overshoot, and settling time [36]. Sudden outages of AC asynchronous grids cause abnormality and frequency fluctuation. This abnormality can be regulated by using the LFC method by using the proposed fuzzy logic controller. A fuzzy logic controller gives more profound results in robust performance than other conventional controllers by ensuring the reliability of the system [37].

Multiple power generating sources such as hydro, gas, or thermal inter-connected through AC–DC parallel links having optimal regulators designed using optimal control theory are shown in Figure 4. Differential evolution (DE) algorithm produces more profound stability and dynamic performance in HVAC–HVDC parallel links, as compared to hybrid bacterial foraging optimization algorithm particle swarm optimization (HBFOA-PSO) and craziness-based particle swarm optimization (CRAZYPSO) [38]. Similarly, the LFC of a power system with multi-sources of generation can effectively be implemented by fine-tuning the parameters of P, PI, and PID regulators using the differential evolution (DE) algorithm. An improved dynamic response than that of the feedback controller is observed [39].

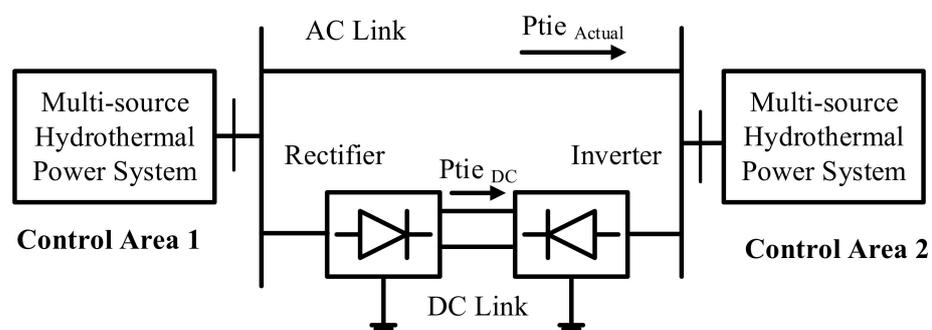


Figure 4. Two Area multi-source power system interconnected via AC/DC parallel line [38].

A deregulated environment consisting of multi-source generating including several conventional controllers I, PI, PID, IID, PIID, and AC–DC link parameters tuned using

a fruit fly optimization algorithm (FOA) has been presented in [40]. FOA is an innovative version of the particle swarm optimization algorithm (PSO). The dynamic response shows that PID controller produces much better performance and robustness than other controllers [40]. Similarly, a novel fuzzy PID controller has also been proposed with its parameters optimized by the teaching–learning-based optimization algorithm (TLBO) for optimal regulation of AGC. The dynamic performance and transient response of TLBO are much better than the genetic algorithm [41].

4.3. Offshore and Onshore Power Systems

An optimization technique based on mixed-integer nonlinear programming (MINLP) has been proven proficient in optimizing the variable frequency produced from the stochastic nature of wind speeds and in attenuating the overall operational price. The proposed approach gives more dynamic performance than the OWPP approach [42]. Moreover, a unified Newton Raphson (NR)-based algorithm can also model several control parameters of large-scale hybrid AC–DC systems with VSCs employed for an accurate load-flow analysis with or without the incorporation of OWF [43]. For the transmission expansion problem (TEP), a fuzzy optimization technique based on a new binary differential evaluation (BDE) algorithm considering active power losses and total investment cost as the objective function has also been proposed. The point estimation method (PEM) is employed to study the stochastic nature of wind/solar farms and loads. The proposed algorithm reduces power losses and investment costs in HVDC systems [44,105]. The specified objective of security and economic constraints, such as disturbances and contingencies in hybrid HVAC–HVDC grids, can be modeled using a security-constrained optimal power flow SCOPF tool (in MATPOWER). Moreover, transmission system operators (TSOs) for facing disturbances and contingencies, spinning reserves of the power system, and the wind variability are modeled using the proposed CSCOPF tool [45].

4.4. Reactive Power Control and Power Losses Reduction

The integration of OWF in MTDC grids is quite challenging from the control perspective, specifically in terms of reactive power support and DC voltage regulation. A hybrid topology for MTDC systems has been proposed in which the model comprises a pulse width modulation current source converter (PWM-CSC) and LCC placed at offshore and onshore sites, respectively (Figure 1). The PWM-CSC is not only self-starting but also possesses the capability of feeding island mode grids with reactive power support without an exterior commutation and can overcome AC/DC faults and contingencies [46]. In a parallel HVAC–HVDC, the DC voltage instability occurred due to onshore and offshore faults, and it depends on the reactive power support and losses. A methodology has been proposed that can introduce innovative advancements in power semiconductors modeling such as an insulated gate bipolar transistors (IGBT) commutation process and spectral analysis-based hybrid modeling of VSC–HVDC [72].

A catastrophic genetic algorithm-based model for improving reactive power support in a VSC–HVDC system has also been proposed. Voltage quality improvements, loss reduction, and cost-effective voltage and power regulation are the key features of this approach [47]. For providing optimal interconnections of land-to-land and distributed generation power systems in a VSC–MTDC network, an optimal power flow algorithm has also been proposed, which uses primal–dual interior-point Newton-type optimal power flow (PD-IP-N-OPF). The point-to-point (PTP) method is implemented for offshore or overseas windfarms interconnections, whereas the back-to-back (BTB) method has been proposed for land-to-land or wide-area interconnections [48,106]. A numerical energy model, including a detailed dynamic model of HVDC, generators, and an induction motor, has also been designed for calculating the system's stability. The transient stability analysis in terms of controlling unstable equilibrium point (CUEP) of an HVDC interconnected power system has been explored using the heuristic method. The combination of CUEP

and the proposed numerical energy function gives a critical clearing time for maintaining transient voltage stability in a network [49].

4.5. Optimal Power Flow for Distributed Generators

The need for the integration of battery storage devices and elements with renewable DGs for future DSs has been increasing [107]. For that purpose, a planning model has been proposed, which is hybrid in nature and projects dual-nested optimization challenges: (1) genetic algorithm (GA) for searching the best AC–DC design and (2) an OPF solution for each generated AC–DC configuration. The proposed algorithm optimizes the cost of DS installation and operations with the Monte Carlo simulation technique implemented. This optimization methodology not only improves the reliability of DSs, but also assists DS planners in organizing an optimal configuration of hybrid AC–DC power systems for forthcoming DSs [50]. For increasing the controllability of hybrid HVDC systems, an iterative chance-controlled AC–OPF algorithm has been proposed, which not only integrates all the AC power-flow equations and point-to-point HVDC line modeling but also models the stochastic nature of wind power by optimizing variability in renewable energy production. The proposed algorithm optimizes the generation as well as the HVDC participation factors through Monte Carlo simulation [51].

For scheduling the output of generation and voltage regulation of offshore wind farms, a non-convex programming model has been presented. The second-order cone programming (SOCP) relaxation approach models the power flow equation required for a non-convex programming model. This model delivers optimal scheduling and a safe working environment by assuring limited DC voltage variation [52]. MMCs in a wide-area MTDC network improve the security, DC voltage stability, and increased transmission capacity of distributed generation asynchronous offshore grids by providing black-start capability and reactive power support. A hybrid MMC modulation technique has been proposed, which combines the sub-modules (SMs) of both full-bridge (FB) and half-bridge (HB) throughout over modulation. The proposed model is implemented on the HVDC–DC auto transformer (HVDC–AT). HVDC–AT acquires DC FRT capability and active DC fault current repression and also reduces semiconductor losses by designing a DC fault adaptable HVDC–DC converter [53]. Fault diagnosis and anomaly detection in HVDC networks can be performed optimally using modern-day artificial intelligence-based deep-learning methodologies [108,109].

Recent research on solid-state transformer (SST) convertors has publicized it as an advanced solution to controllability and power-quality performance of the MTDC network. A coordinated operation scheme of multiple SST convertors working in different modes of operation with an OPF model embedded has been presented, which not only optimizes the voltage outline of the SSTs link by fast voltage regulation of its ports, but also formulates a hybrid optimal power flow scheme through efficient coordination between transformers, generators, and SSTs. This scheme adjusts fast fluctuating DGs output and provides control flexibility in the power flow direction at SST ports to avoid congestion in transmission network when they over-reach its capacity [54]. The DGs' energy from offshore sites can also be optimized using a power electronics transformer (PET). A steady-state model of a PET steady-state model has been proposed, which designs an optimized AC–DC hybrid network system. Through the scheduled model, the proposed PET-based hybrid AC–DC network minimizes the load reduction in manageable DC and AC load sites such as at EV charging stations at peak timings. Resultantly, the reliability and protection of the whole DGs hybrid system are improved [55,110]. Furthermore, a hybrid AC–DC nanogrid based distributed power generation and power consumption model design for plug-in electric vehicle charging at the workplace has also been proposed to reduce multiple conversion losses within the organizations [111].

Another methodology has been proposed, which transforms the VSC–HVDC system into an equivalent AC system and developing conventional power-flow equations. It utilizes the commercially available AC–OPF tool for the system's comprehensive analysis since

the conventional open-source OPF tools available are based on the AC grid system. System losses and generation costs can be decreased by optimally controlling the operating point of the VSC-based MTDC system embedded in a meshed HVAC grid [56]. For a deviation-less frequency operation of a system, an optics-inspired optimization (OIO) method is capable of absorbing frequency oscillations of hybrid HVAC–HVDC parallel systems operated with or without using PLLs. The impact of this methodology is quite promising in those areas where load fluctuating is quite frequent, since it limits and improves the frequency deviations, maximal surge distortion, and settlement time, so advancing the stability of the system [57]. Table 5 presents a thorough comparison between the most profound hybrid optimization algorithms implemented for the effective integration of asynchronous grids into the MTDC network. The table discusses the proposed objective function of discussed optimization algorithms in literature to achieve minimum cost in obtaining optimal solutions. Moreover, the parameters required for the tuning process of discussed algorithms and the constraints experienced in their implementation are also tabulated in Table 5.

Table 5. Comparison of optimization constraints and algorithms.

Reference	Objective Function	Parameters	Constraints	Technique
[33]	Min = thermal cost, renewable cost, losses	Power generation, wind power generation, hydro plant output, PV power generation, AC/DC line losses	Combined renewable HVAC HVDC	SPEA-II
[35]	Min = thermal cost, transmission line cost, conversion loss cost	Power generation	Power balance, HVDC, generation capacity, converter ignition angle, extinction angle, voltage, current	NBA
[36]	Min = thermal cost, wind cost, solar cost, tie line losses emissions	Power generation, wind power, PV power, real power transmission, pollutant emission	System combined HVDC	MFA-LF-DM
[101]	Min = thermal cost, renewable cost, emission cost, max = transmission cost	Power generation, wind power, PV power	Combined renewable VAC HVDC	IGA
[37]	Min = ITAE	Δf_1 , Δf_2 , $\Delta PTie$	(CRCs)	HDE-GWO
[41]	Min = J	Δf_1 , Δf_2 , ΔTie	KP, KD, KI	FOA
[49]	Min = cost function	Power generation	Active power, reactive power, bus voltage, AC power line capacity, DC bus voltage, DC transmission line	NSGA-II
[51]	Min = total present cost value Min = AC/DC generation cost	Power generation of AC, power generation of DC	Integer, bus connectivity, generation connectivity, power balance, network security, converter connectivity	GA
[53]	Min = total generation cost	Power generation	Voltage magnitude, current magnitude, dispatch thermal generation, total renewable generation	SOCP
[56]	Min = total operating cost	Power generation of microturbines, storage energy, load reduction, number of electric vehicles charging	Power generation, energy storage, load reduction	PE T/F
[57]	Min = generation cost	Power generation	Real power, reactive power, voltage, current	A simplified algo.

Abbreviations: SPEA-II: strength Pareto evaluation algorithm-2, NBA: novel bat algorithm, MFA-LF-DM: modified firefly algorithm with levy flights and derived mutation, HDE-GWO: hybrid differential evaluation grey wolf optimization, NSGA-II: non-dominated sorting genetic algorithm-2, GA: genetic algorithm, SOCP: second-order cone programming, PE T/F: power electronics transformer, ACE: error signal, OIO: optics-inspired optimization, ITEA: integral time error algorithm, FOA: fruit fly optimization algorithm, Δf : change in frequency, ΔTie : change in tie line, GRCs: generation rate constraints, J = (ISE): integral of square root error, KP: proportional gain, KD: derivative gain, KI: integral gain, Pg: generation.

5. Security of Hybrid HVAC–HVDC Systems

Due to the complexity of hybrid HVDC and HVAC smart grids, a large set of contingencies are raised, which can cause large variations and uncertainties in the power system. These aspects endanger power system security. This section will discuss the

security challenges and multiple schemes to overcome these challenges for secure hybrid smart grids.

5.1. Classical Security-Constrained Optimal Power Flow Problem

The classical SCOPF system makes a decision on the basic two stages, i.e., preventive and corrective control. The preventive control decisions are applied when the operating state is known and on real-time problems, whereas the corrective control decisions are applied when there is an occurrence of assured contingencies. The former faces challenges in a large and complex problem due to the influx of large renewable and other energy resources into the power system. Resultantly, the number of contingencies increases, and the security criterion goes above the classical $N-1$ criteria. Therefore, a security criterion is needed, which can take into account all the possible sets of contingencies and can be framed as a multi-stage decision-making problem under uncertainty [112].

5.2. SCOPF Problem Incorporating Corrective Hybrid HVAC–HVDC Control

To improve the SCOPF problem, linear current distribution factors are introduced in the formulation of SCOPF in reducing complexity and making the computation problem of SCOPF faster. The effect of line and generation contingencies are evaluated to calculate the corresponding corrective control action of HVDC lines [113]. The probabilistic SCOPF framework works best for post-contingencies corrective control action with higher operating cost as compared to deterministic SCOPF in contingencies other than generation and lines. Power injection and HVDC terminal power are the control variables [114]. A modified corrective SCOPF can handle outdated rescheduling control mechanisms for a long time period of the AC system, contingencies on both AC and DC systems, and short-term post-contingencies of HVDC system in a hybrid system at a lower cost than traditional corrective control methods, evaluating the security constraints of the $N-1$ criterion [58].

MMC-based corrective SCOPF is also used, which can adjust generators and MMCs accordingly by minimizing the network losses by considering the security constraints on $N-1$ and corrective control for post-contingency. It can handle static security constraints and reduces computation time and complexity by avoiding the usage of a greater number of security constraints [59]. A meshed AC–HVDC grid with a preventive control method accounts for all potential blackouts even the one in an HVDC terminal. A corrective control is a complex one and makes use of all the functions of the HVDC terminal and can make leads to a lower cost of operation as compared to preventive control. However, the set point adjustment of the terminals is necessary in case of any contingency scenarios. Although corrective control methodology is more complex, it is also more economical [115]. Figure 5a shows the implementation of corrective SCOPF.

5.3. Security-Constrained OPF Incorporating Preventive Control

PSCOPF is challenging to be implemented on a large-scale power. Therefore, a compensation method with higher computation speed is introduced, which is used in both static security-constrained analysis (SSSA) and PSCOPF and has a tendency to avoid branches overload and outage contingencies [60]. A PSCOPF method based on differential evolution with a faster computational time has also been proposed, which acclimates VSCs set points and reduces the critical contingencies for enhancing the security of the power system. DC voltage set points and the active power of each VSC are used as controlled variables. Therefore, the hybrid power system can be made secure by applying preventive control for the setpoints of VSCs [61]. Active and reactive power of all the VSCs and their DC voltages in the solution of optimization use the PSCOPF algorithm. A trade-off between overall security and optimization of the system has been observed [116]. An improved PSCOPF optimizing the VSCs set points to set up the $N-1$ security criterion has been proposed to overcome the security challenges in hybrid AC–HVDC grids, but it could not eliminate all the critical contingencies. Therefore, a new preventive approach based on VSC outages was used, which could predict the behavior of DC voltage control and increase

the security by keeping the operational security limits in control. This approach focused on the effects, such as slow stability, that occur as a result of the AC contingencies [117,118]. The implementation procedure of PSCOPF has been shown in Figure 5b.

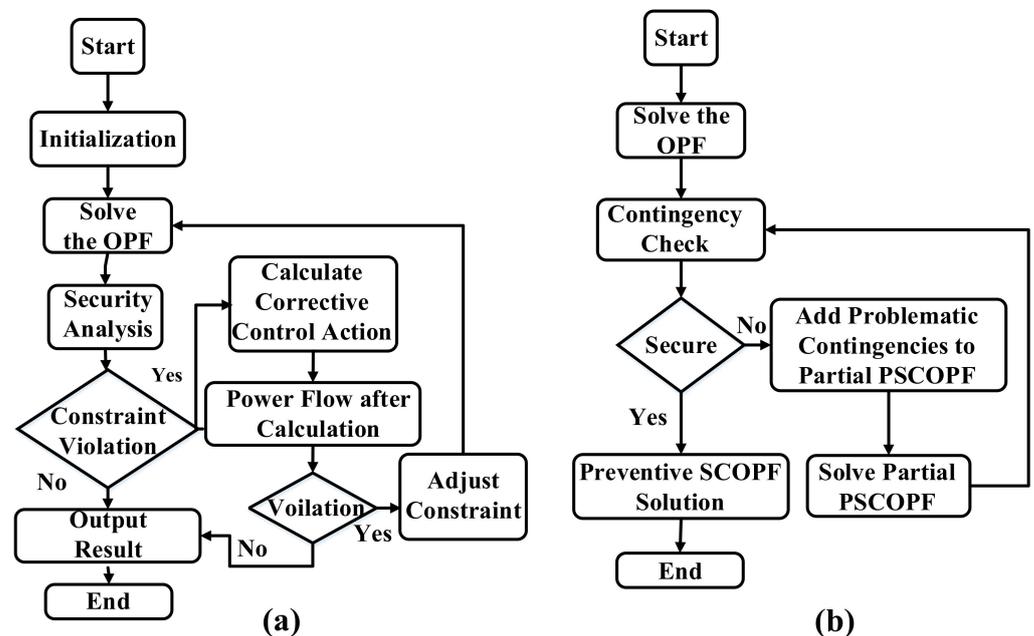


Figure 5. The SCOPF procedures. (a) Implementation corrective SCOPF procedure and (b) implementation of preventive SCOPF procedure.

5.4. Other Techniques for Security Constraint Optimal Power Flow

Monte Carlo methodology considering the transient security constraints for the reliability of the hybrid AC–HVDC system has been investigated, which reveals the importance of transient stability for system reliability and impacts of AC system faults. The proposed methodology can be applied for calculating the risk assessment of energy systems on large-scale power systems by reducing the system’s complications [119]. A passive defense system here for an active type of power grid system has been proposed in [120]. The power system defense has been divided into parts, with the first one being the network planning and operation, equipment monitoring, and the second one being the relay protection scheme for the fault recovery of the EHV AC–DC bulk power grid system [120]. CIGR’E HVDC Test System estimated the reliability of the HVDC grid after the outages of different components of the system. Here, both the corrective and preventive control methods could be used to ensure the security of TSO with an optimal operational cost [45]. A relevant test system is required for the operational strategies that can cope with all the static and dynamic stability aspects. A new mixed AC–DC benchmark technique has been proposed that compares the general requirement of the test system with already existing test systems and also overcomes all the AC and HVDC contingencies and security challenges of complexity and planning [121]. Table 6 gives a comprehensive summary and comparison among the various security-constrained optimal power flow (SCOPF) and preventive security-constrained optimal power flow (PSCOPF) techniques discussed in the literature. The comparison is presented in terms of the technique’s distinguished proficiency and objective function and on the standardized power system/network on which the test is performed.

Table 6. Summary of the techniques used to overcome the security challenges of hybrid HVAC–HVDC grids.

Ref	Objective Function	Technique/Method	Technique's Proficiency	Test System
[110]	Relieve the line overloading	Corrective control of HVDC using linear current factors	Fast computation	10 bus system
[111]	Minimize the production cost	SCOPF with multi-terminal HVDC	Accurate line limits	IEEE RTS96 test system
[59]	Overcome all long- and short-term contingencies	CSCOPF with VSC–MTDC	Lower cost of operation	IEEE 14 bus system IEEE 18 bus system
[60]	Minimize the total network loss	SCOPF with MMC–HVDC	Reducing complexity	IEEE 39 bus system
[112]	Cover the HVDC terminal outages	CSCOPF PSCOPF	Fast operation Lower cost	IEEE 14 bus system RTS96 test system
[61]	Overcome the branches overload	PSCOPF with compensation method	Fast calculation of post-contingencies	IEEE 30 bus system
[62]	Minimize the transmission line outages	PSCOPF including DE algorithm	Fast computation	AC–HVDC test system
[113]	Minimize the deviation between pre and post SCOPF set points	PSCOPF with VSC set points	Power system operational planning	AC–HVDC test system
[114]	Minimize all component outages	Preventive coordination of VSC set points and DC voltage	Feasible results	AC–HVDC test system
[116]	Sampling of AC and DC components	Reliability evaluation	Accuracy and speed	IEEE RTS96 test system

6. Conclusions and Recommendations

This paper provides a comprehensive and inclusive review of integration challenges, control methodologies, optimization techniques, and security of hybrid HVAC–HVDC grids. In the coming years, everyone will witness the evolution of the current HVAC power grids because of increasing expectations from the power systems. The whole world will embrace the new concept of hybridization of power grids along with their changed operation and composition. This acceptance means addressing the technical, protection, modeling, social and economic, climate, and generation-source-based integration challenges that have been discussed in this paper.

Moreover, the satisfactory operation and control flexibility of MTDC networks requires stable, optimal, and balanced power in HVDC grids. Therefore, a comprehensive overview of various PFC strategies of MTDC networks has been technically explored. OPF, HMIDC, droop control, adaptive droop control, LCC–CIA, and LCC–CEA control are distinguished methodologies that address solutions for the establishment of independent and self-sustaining control of active and reactive power flow and power-sharing in an MTDC grid. The ion-flow field characteristics analysis contributes to the reasonable corridor arrangement of parallel HVAC–HVDC transmission lines.

The contingency and post-contingency control methodologies and analyses such as D2SRF PLL and grounding schemes and HMIDC have also been explored in real-time to ensure a stable, fluctuation-less, and bi-directional PFC and reactive power support during sudden outages or AC contingencies. Moreover, some of the fault-ride-through control configurations and capabilities have also been highlighted. The paper has also reviewed the various hybrid HVAC and HVDC systems' control schemes such as voltage source converter and current coupled converter for reducing the power and frequency deviations. Generation and supervisory control of hybrid HVAC–HVDC grids are quite necessary for fast and robust frequency regulation for optimal power flow. Voltage-based load control, frequency support, MMC, model reference adaptive control designed using a hybrid approach, and power oscillation damping (POD) designed using pole placement and supplementary controllers are the control strategies proposed for generation control. Whereas, Vernier, CCC, DBC, VSCs integrating TCSC and SVC devices, and several droop control schemes and persistent DC voltage control schemes are proposed for supervisory control of hybrid HVAC–HVDC systems.

There is also a complete assessment of the different types of optimization techniques that are being used in hybrid HVAC–HVDC power systems. A brief explanation is provided to demonstrate how optimization influences the OPF, economic dispatch, LFC, and generation control of the hybrid HVDC–HVAC grid. Furthermore, the optimization approaches in the field of offshore and onshore power systems are also elaborated in detail.

A review of algorithms that produces OPF in DGs and DSs has also been discussed in detail. After analyzing the various research articles, it is clear that by using the modern state-of-the-art optimization algorithms, the cost function can be minimized to achieve the objective function of economic dispatch and AGC.

For security challenges, this paper has examined papers based on the SCOPF of hybrid AC–HVDC smart grids. Classical security-constrained optimal power flow shows some disadvantages, i.e., the complexity and inability to handle large power systems. An insight of new techniques incorporating PSCOPF and CSCOPF as a control method for meshed systems security considering all types of contingencies of the system is also elaborated.

For expediting the upgradation of current power grids, the current HVAC transmission systems are popularly being converted to hybrid HVAC–HVDC power transmission systems. Apart from the integration and security problems noted previously, the acceptability of such hybrid systems is expected to be stronger since there is no need for developing completely new construction. The visual appearance is similar to that of existing HVAC systems.

For future works, manufacturers, utilities, stakeholders, and third parties need to find a balance between the performance and cost of installation of the hybrid HVAC–HVDC systems. The researchers should look for solutions for technical challenges, reliable and fast HVDC protection schemes, the best models for real-time simulation, agencies to get funding for the installation costs, ways to save the environment, and beneficial generation sources.

The impending hybrid HVAC–HVDC grid should be able to surpass the present HVAC grid system. A security algorithm can be formulated by using both the preventive and corrective control methods, which can fulfill all the security constraints of line, generator, and equipment outages. It can also allow the hybrid grid to exchange power with minimum losses. This dynamic model can encounter all contingencies instead of a static security model.

Author Contributions: Conceptualization, U.J., N.M., M.J. and K.S.Z.; methodology, U.J., N.M., M.J. and K.S.Z.; validation, U.J., N.M., M.J., K.S.Z., O.A., G.A. and N.U.; formal analysis, U.J., N.M., M.J., K.S.Z., G.A., N.U. and M.S.C.; investigation, G.A., N.M., M.J. and N.U.; resources, U.J., N.M., M.J., K.S.Z., G.A., K.T. and U.T.; data curation, U.J., N.M., M.J., O.A. and U.T.; writing—original draft preparation, U.J., N.M. and M.J.; writing—review and editing, M.J., G.A., K.T. and K.S.Z.; visualization, U.J., N.M. and M.J.; supervision, M.J., G.A. and K.T.; project administration M.J., G.A., M.S.C. and K.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by Grant 235 Number ENV6402012N from Prince of Songkla University.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research was supported by Grant 235 Number ENV6402012N from Prince of Songkla University. The authors are also thankful to the Department of Electrical Engineering, The University of Lahore, Pakistan, for providing facilities to conduct this research.

Conflicts of Interest: The authors declare no conflict of interest.

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