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Published in:
Proceedings of 14th IEEE PES Asia-Pacific Power and Energy Engineering Conference 2022 (APPEEC)

Link to article, DOI:
10.1109/APPEEC53445.2022.10072035

Publication date:
2023

Document Version
Peer reviewed version

Identifying Opportunities for Medium Voltage DC Systems in Australia

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***Abstract*—Transmission and distribution networks based on medium voltage direct current (MVDC) solutions have the potential to provide higher power quality, greater power transmission/conversion efficiency, enhanced power supply reliability/stability, improved power supply capacity, and more efficient corridor utilisation compared to an equivalent ac system. Moreover, MVDC networks can facilitate the integration of renewable energy sources (RESs), energy storage systems (ESSs), and the increasing number of dc loads. However, these systems are still in early development stages; their advantages in need of clear demonstration before large-scale commercial adoption. This paper explores general MVDC network structures and different application scenarios focusing on cases of particular interest to Australian power systems and to Australia in general. Areas of interest are identified and equipment requirement, protection schemes and related challenges are also discussed, highlighting both technical barriers and possible development directions.**

***Index Terms*—Medium Voltage Direct Current (MVDC), Renewable Energy Sources (RESs), ac/dc converters, dc/dc converters, MVDC protection.**

I. Introduction

Direct current (DC) power systems have experienced substantial growth in the last two decades due to their technological advances and suitability to certain applications, such as high-voltage dc (HVDC) transmission [1] and low-voltage dc (LVDC) microgrids [2]. A future power system will see the co-existence of alternating current (AC) distribution and transmission networks in parallel with dc systems at different voltage levels. Medium-voltage dc (MVDC) (i.e., systems with dc voltage typically between $\pm$0.75 kV to $\pm$50 kV [3]) has the potential to play a significant role in sub-transmission, distribution and collection grids, supporting the integration of large-scale renewable energy sources (RESs) and different energy storage systems (ESSs) [4]–[7] and the transition to power electronics dominated power systems. Moreover, decoupling of different MVAC grids can be achieved by using voltage source converter (VSC)-based back-to-back (BTB) configurations at MV voltage level, which can provide voltage support and independent power control for adjacent ac grids. The VSCs of an MVDC system can also be used as static synchronous compensators (STATCOMs) to enhance the reliability of ac grids at MV level [8]. Besides the above mentioned grid-connected systems, the use of MVDC solutions in shipboard drives and traction power supply system (TPSS) has also attracted broad attention in both academia and industry [9], [10].

Compared to conventional MVAC systems, MVDC networks offer a number of additional benefits. They are mainly manifested in the following aspects: *i*) improved power supply reliability and stability, *ii*) enhanced power supply capacity, *iii*) greater power transmission/conversion efficiency, *iv*) higher power quality, and *v*) more efficient utilisation of available power supply corridors [3], [11]. The substantial growth of dc loads combined with integration of distributed RESs and ESSs also drive the need for further development of MVDC systems. Of particular note is that the MVDC systems are different from the conventional dc microgrids, since the latter is mainly used in LV scenarios based on simpler network structures (i.e. typically using one dc bus with a single interface to an ac network) [12].

MVDC is still in its infancy with regards to commercial applications; relevant demonstration projects have just started been carried out over the last decade. Initial studies towards MVDC systems are conducted from the concept of flexible dc distribution network projects. An example is the 12 kV "Future Renewable Electric Energy Delivery and Management (FREEDM)" MVDC distribution system architecture that explored the integration of distributed RESs and ESSs. This study also provides technology requirements from dc-to-dc conversion, fault isolation to grid intelligence in an MVDC system [13]. In a similar fashion, the 10 kV campus MVDC distribution system at Aachen University [14], among other trial MVDC projects, demonstrates the potential of MVDC solutions in future power grids. The Angle-DC in the UK is the first MVDC sub-transmission project (dc-link) that converts existing double-circuit lines from 33 kV ac to $\pm$27 kV dc [15]. The Shenzhen Baolong [16], Zhuhai Tangjia Bay [17], and Suzhou industrial park pilot [18] MVDC project are three representative MVDC distribution projects that demonstrate integration of photovoltaics (PVs), battery ESSs (BESSs), electric vehicle (EV) chargers, and power delivery to different ac and dc loads at a single location using MV network topologies and solutions.

The case for MVDC solutions in a future power system needs to consider both the requirements of a specific application and the unique characteristics of certain distribution and transmission networks. To this extent, and with the current conditions in Australia in mind, this paper aims to be the first exploration of possible applications of MVDC systems in Australia, identifying a number of use cases where MVDC solutions have the potential to enhance current practice. The second aim of the article is to draw a possible and plausible future Australian MVDC "grid map" accounting for the structure of MVDC networks in different applications and hardware requirements for future project developments in a way that potential Australian MVDC systems can be developed to adapt to existing ac and dc networks and manage the interactions between generation and consumption at all levels and stages. Protection schemes related to system and converter layers are discussed as well. The challenges of MVDC networks in Australia are further explored identifying potential development bottlenecks that need to be addressed for successful application.

Australia is also one of the world's solar resource-rich countries and has the highest average solar radiation per square metre in the world. The total installed PV capacity is above 26 GW [19], and it could reach to 80 GW in 2030 [20]. In addition to the PVs, approximately 35% RESs of Australia is provided by wind farms (WFs) in 2020, which also accounts for 9.9% (more than 7 GW) of annual electricity generation in Australia [21]. ESSs are also finding wider adoption in Australia including large-scale commercial and residential ESS installations. The installed capacity of residential ESSs is 238 MWh with 23,796 batteries in 2020 [21] .The elimination of dc to ac conversion stages through MVDC networks would facilitate the integration of abundant RESs and ESSs in Australia, thereby enhancing conversion efficiency. At the same time, most electricity is consumed in major load centers. Major cities, such as Sydney and Melbourne, are also the power load centers of Australia. MVDC can provide higher power in these dense regions with limited line corridors, such as large-scale commercial zones, hospitals and schools, compared to the current MVAC grids [8]. In addition, long distance power supply in Australia is necessary for satisfying the power demand in non-commercial and remote areas. Due to the lower voltage drop in dc transmission lines, the power supply distance of MVDC systems would be longer than equivalent MVAC when delivering the same power [11].

The rest of the paper is structured in the following manner. Section II describes potential MVDC networks in Australia. Section III provides equipment requirements and protection schemes, while the current and ongoing challenges are discussed in Section IV. Section V draws the conclusions of this article.

II. Potential MVDC Networks in Australia

A. General MVDC Network Structures

An MVDC network can act as an intermediate link in large power systems that allows coordination between ac and dc systems at different voltage levels. Four potential MVDC network structures, corresponding to different development options can be identified. The first option considers interconnection between two or more ac nodes via an MVDC link, while no loads are connected into dc bus (Fig. 1(a)). Fig. 1(b) (second development stage) demonstrates a similar structure to Fig. 1(a) including integration of PV, wind, ESS and different ac/dc loads as part of the MVDC grid. In addition, HVDC systems can also directly deliver power to MVDC grids by dc/dc converters; the third development option (Fig. 1(c)) [22]. Dc/dc converters for HVDC or MVDC applications are not commercially available at current stage, hence there are opportunities to explore effective dc-to-dc conversion solutions linking the dc voltage at HV and MV levels.

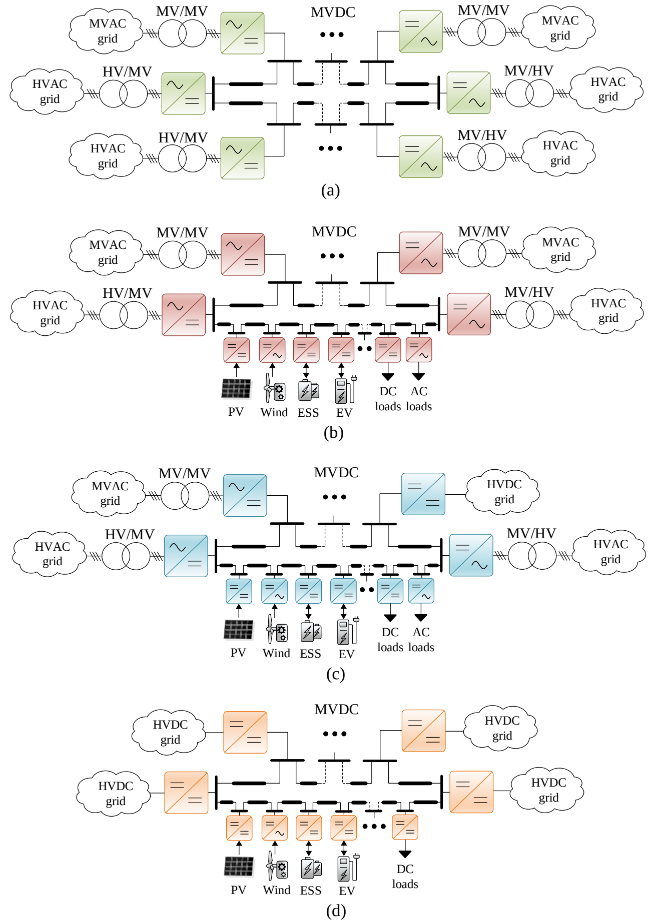

Fig. 1. Future MVDC network structures: (a) structure with no loads connected into dc bus, (b) structure with loads connected into dc bus, (c) structure with HVDC grid connection, and (d) structure with ac systems replaced by dc systems.

Other options that can be considered as the dc systems replacing ac systems from transmission to distribution networks and ac loads replaced with dc loads as shown in Fig. 1(d). However, HVAC will remain the main power delivery mode over a long period considering the limited number of current HVDC projects in Australia. Hence, based on current and future trends, the first two general structures are identified as more suitable to Australian applications for development of MVDC networks; at least in the current point in time.

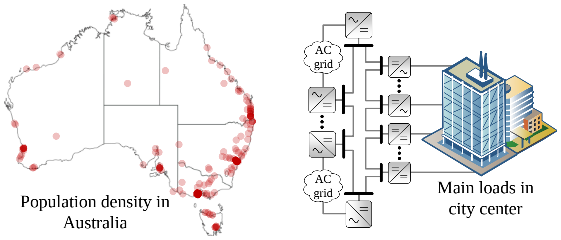

Fig. 2. MVDC in city centers.

B. *Specific Australia-oriented MVDC Application Scenarios*

1) Metropolitan Zones and Load Centers: Conventional MVAC networks in growing metropolitan areas need to address, among other power supply limitations and constraints, issues with limited line corridors, which hinders or delays any further increase of power transfer capacity. The power supply radius of an MVDC system is greater compared to an equivalent MVAC system due to the higher acceptable line current and dc voltage level. Moreover, the required corridor for the MVDC is smaller than the MVAC when transferring the same power [3]. Therefore, it can be beneficial to consider the development of MVDC networks to augment or gradually replace the current MVAC networks in city load centers to accomodate the increase of power supply requirements. Fig. 2 shows an example of such an MVDC network, serving the main loads in city centers.

Partial modification of current ac distribution networks is another potential solution towards accommodating the increasing power demands in load centers of metropolitan regions. The MVDC voltage level would be selected according to the current ac distribution voltage level (e.g., $\pm$10 kV dc would be recommended to match the 11 kV ac).

2) Industrial Parks and University Campuses: Highly-centralized power supply is required in industrial parks or university campuses. An MVDC network can offer power supply reliability and stability of critical loads within these areas, due to no regulation requirements of phase angle and frequency in conventional ac systems [8].

Industrial parks or university campuses could also act as MVDC demonstration projects (see Fig. 3) for verifying the integration feasibility of RESs, ESSs, EV chargers, data centers and other ac/dc loads, because of the location independence and load concentration. MVDC with $\pm$10 kV and $\pm$20 kV can be used to match the typical 11 kV and 22 kV ac distribution networks, while a power rating of a few MW is usually required in industrial parks or university campus with a certain scale.

3) Remote Communities: The main power supply characteristics of remote communities in Australia, such as those found in Western Australia, Northern Territory etc, are long distances and load decentralization. Moreover, 2% of Australia's population, living in off-grid regions, relies on electricity generated by diesel or natural gas generators, leading to high energy costs [23]. RE integration together with ESS can lower energy costs and reduce carbon emissions for isolated communities, and a typical case is King Island hybrid energy solution [24]. A possible MVDC network for remote communities is shown in Fig. 4.

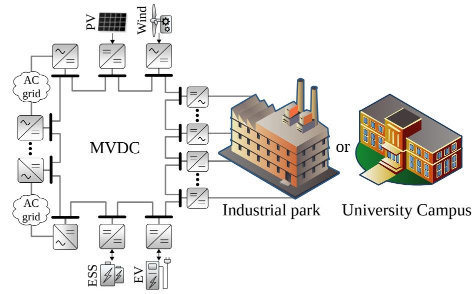

Fig. 3. MVDC in industrial parks and university campus.

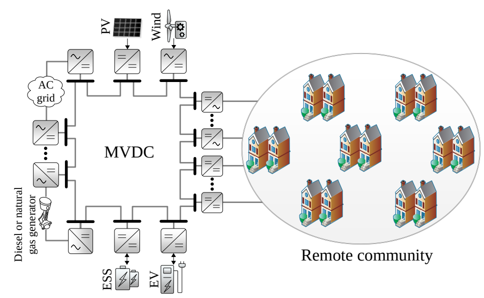

Fig. 4. MVDC in remote communities.

In many cases, the load is not sufficient to justify expansion of an LVDC microgrid to an MVDC system, however, when sufficient generation and load can be identified, the adoption of an MVDC system in these communities will allow the easier and more direct integration of REs and ESSs, and power losses caused by long transmission line in conventional MVAC systems can be reduced as well.

4) Mining Sector: Australia is rich in mineral resources with more than 400 operating mines, which consume roughly 10% of Australia's total energy. The current trend is to integrate RESs for reducing the reliance of fossil fuels, especially the diesel and natural gas, in mining districts of Australia [25]. Compared to ac systems, fewer stages of power conversion are required if MVDC is used for integrating wind and solar PV. In addition, MVDC networks in mining sector would facilitate the integration of ESSs storing the excess power generated by RESs. An MVDC network structure similar to that of remote communities (Fig. 4) can also be used to support power supply in remote mining sites.

5) Renewable Energy Collection Grids: MVDC presents many benefits in power collection for large-scale solar PV plants and offshore wind farms compared to MVAC systems [8]. These include elimination of dc-to-ac converters and bulky step-up transformers. With the development of large and further growing ratings of PV plants in Australia, MVDC collection grids (Fig. 5(a)) offer a major opportunity. In such applications, common solutions would, most likely, operate at a higher voltage level for reducing losses and improving

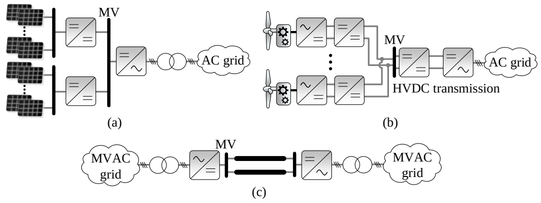

Fig. 5. MVDC networks for RE collection and ac network augmentation: (a) collection network for PV plants, (b) collection network for offshore wind farms, and (c) ac network augmentation.

efficiency [3].

Although no offshore wind farm projects are currently operating in Australia there are proposals for development of multi-GW projects, in which case MVDC would be a potential candidate for power collection of future offshore projects. The collection bus voltage is typically in the range of ±25 kV to ±50 kV based on [26]. A possible MVDC collection scheme for offshore wind farms is shown in Fig. 5(b). It is noteworthy that the renewable energy zones established in different states of Australia also have opportunities to be linked by MVDC grids [27].

6) AC Network Augmentation: MVDC can be used to link distant nodes for improving power capacity, enhancing different voltage profile, and optimizing network losses (Fig. 5(c)) [28]. It can be specifically used in the modification of the end-of-lines and in regional ac grid interconnection below sub-transmission voltage levels (e.g. 33 kV) to improve power capacity and quality. The recently commissioned Angle-DC project (±27 kV, 30.5 MW) in the UK shows the feasibility of such modifications. The dc voltage can be ±27 kV to ±30 kV to match the also used 33 kV ac in Australia.

III. Equipment Requirements and Protection Schemes

A. Converter Requirements

1) AC/DC Converters: Ac/dc converters used in the MVDC can be generally classified into: *i*) conventional and modular multilevel VSCs [16], [17], [29], *ii*) two-level (2L) and three-level (3L) VSCs [15], and *iii*) 6-pulse and 12-pulse LCCs [7]. VSC-based converters, especially the modular VSCs such as the modular multilevel converter (MMC) [30] and the alternate arm converter (AAC) [31], would be the dominant converters in future Australia's multi-terminal MVDC systems and MVDC grids, owing to the flexible power reversal capability. Fig. 6 shows the schematics of several typical VSCs including the 2L-VSC, 3L-VSC, MMC and the AAC [8].

MMCs with different submodules (SMs) has been widely used in HVDC projects, due to their salient features such as modularity, scalability and excellent harmonic performance [32]. Recently commissioned MVDC demonstration projects in China also adopt MMCs as ac/dc converters [16], [17], [29]. Since a smaller number of semiconductor devices are required in ac/dc converters with MV level, it is also possible to compare the performance of different VSCs and the modular VSCs with various SM configurations [32].

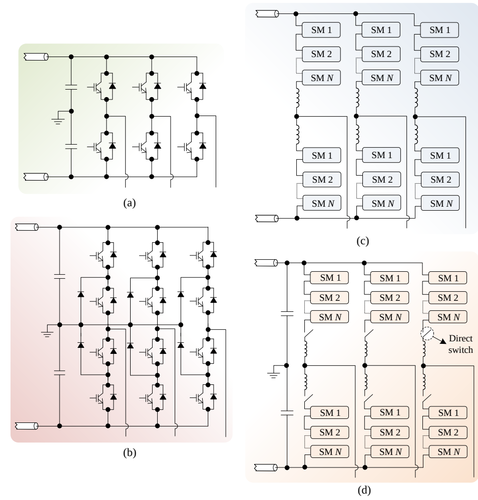

Fig. 6. The schematics of different VSCs: (a) 2L-VSC, (b) 3L-VSC, (c) MMC and (d) AAC.

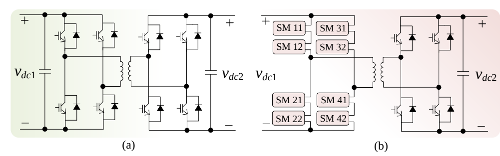

Fig. 7. Topologies of dc/dc converters: (a) DAB and (b) MDAB.

2) DC/DC Converters: Dc-to-dc conversion is also likely to have a major role in MVDC grids, since it can realize the change of voltage levels in different dc buses. Isolated dc-dc converters can provide galvanic separation, facilitating high voltage-ratio applications and allowing different grounding schemes between the MVDC grids and the dc loads. Non-isolated dc-dc converters, while not been used in the current MVDC projects, have smaller size and simpler structure than the isolated dc-dc converters [33].

The requirements of high power density, high efficiency, low filtering effort and galvanic isolation drive the rapid development of isolated dc-dc converters [33]. Dual active bridge (DAB)-based dc-dc converters and extended modular multilevel structures have been studied extensively in the current literature; some have been successfully applied in currently commissioned MVDC projects, such as the DAB converter (Fig. 7(a)) in Aachen campus MVDC [14] and Shenzhou Baolong Industrial Park project [16], and the modular DAB (MDAB) (Fig. 7(b)) converter in the Zhuhai Tangjia Bay project [17]. It is noted that dc-dc converters require further development, since there are limited and mostly ad-hoc solutions, especially in MV and HV applications.

B. Protection and Relevant Equipments

1) System Protection: Protection of an MVDC system can be divided into *i)* ac system protection and *ii)* dc system protection. In order to interrupt fault current during ac and dc faults, a direct approach is to install ac or dc circuit breakers (ACCBs and DCCBs) in the ac side and the dc link, respectively [15], [34]. The dc fault can also be cleared by tripping any ACCBs and later opening dc isolators without installing DCCB. In addition to CBs and isolators, surge arrestors and fuses are also important protection components in MVDC systems for providing overvoltage and short-circuit protection [8]. It should be mentioned that MVDC systems have shorter line fault detection, location, isolation and system restoration time compared to MVAC systems, although dc fault currents should be reduced by proper schemes [35].

2) Converter Protection: Protection of converters is also critical in MVDC systems, necessitating protection schemes adopted for ac/dc and dc/dc converters. The protection of ac/dc converters during dc faults is significant for avoiding switch damage. The current study mainly focuses on the protection of the MMC in the MVDC application. Bipolar SMs used in the MMC can self-interrupt dc fault current with reduced investment of DCCBs or without configuring DCCBs. An integrated control and protection scheme is studied in [36] and MMC with full-bridge SMs is adopted for reducing the number of DCCBs. MMC based on clamp double SMs (CDSMs) is reported in [37] with a current correlation protection algorithm, while different hybrid SM schemes are proposed in [38], [39].

The protection of dc-dc converters can be classified into protection against short-circuit faults (SCFs) and open-circuit faults (OCFs). SCF has to be isolated immediately, while the power transfer can still be accomplished during OCF in a short time [40], [41].

IV. Current and Ongoing Challenges

A. Grid Structure and Converter Availability

Examples of possible grid structures that can be applied in future MVDC grids of Australia have been described in Section II. Although many grid structures can be employed, there are, at least at this stage, no standards or MVDC grid codes to adopt for any structure selections. Different VSCs, especially modular VSCs, are suitable ac/dc converters for MVDC. However, limited experience can be offered by only a few VSC-based MVDC projects, and the current literature mainly focuses on VSCs in high power and HV applications. Although plenty of dc/dc converters have been proposed for MVDC applications in the current literature, such as resonant dc/dc converter [42] and current source-based dc/dc converter [43], they are still under development and their reliability should be further guaranteed.

B. Interaction between MVDC and MVAC

Researching how to coordinate the operation of MVDC and MVAC networks is of great significance to further development of MVDC systems. The coordinated operation of MVDC and MVAC systems, particularly the transient fault processes, will have inevitable effects (such as overcurrent and stability issues) to each other. Transient capacitor discharging currents in VSCs during dc faults will lead to current increase in the ac system. In addition, ac voltage sags and unbalance will occur during ac faults, which further influence the normal operation of converters [3]. Thus, coordinated protection schemes should be explored and developed, to isolate faults effectively considering the interactions between MVDC and MVAC grids.

C. DC Fault Handling Capability

DC fault handling capability is one of the significant challenges of future MVDC grids. Although MV-DCCBs can be used to clear dc faults, they are still under early development. Modular VSCs with bipolar SMs have dc fault self-clearing capability at the cost of high investment and power losses. For instance, ACCBs and dc isolators are used in Angle-DC project for handling dc faults [28], but such a scheme may not be suitable for future large and complex MVDC grids, mostly due to the low response speed of ACCBs. In addition, the detailed system performance under dc faults with BESS integration should also be considered in an MVDC system.

D. Investment Costs

In an MVDC project, the lines, VSCs, dc/dc converters, secondary equipment and lightning protection equipment typically account for around 40%, 25%, 15%, 15% and 5% of the total costs, respectively [3]. The additional introduction of VSCs and dc/dc converters will result in higher investment costs for MVDC networks than that of MVAC networks; advantages offered by an MVDC system need to justify such additional costs. Moreover, DCCBs have to be installed in MVDC projects without dc fault self-clearing capability. The structure of DCCB is complex and DCCB at MV level is still in the initial development stage. Hybrid DCCBs present characteristics of rapid current interruption and low voltage withstand by combining mechanical switches and power semiconductors, while the structural complexity brings about considerable investment costs [34].

V. Conclusion

MVDC systems have the potential to offer promising solutions that can augment or replace current ac systems at MV level due to their salient benefits. These include the optimisation in the use of power supply corridors, the improvement of power transmission/conversion efficiencies, and the enhancement of power supply capacity, quality, reliability and stability. This paper explores options and potential applications of MVDC systems focusing on the equipment requirements and applications that relate directly or indirectly to use cases and conditions in Australia and the Australian networks. Current grid layouts in the metropolitan areas, industrial zones, remote communities/mining districts can be optimised via constructing MVDC networks. Collecting power generated by large-scale PV plants and offshore wind farms via dc buses at MV level would eliminate multiple dc-to-ac conversion stages and bulky transformers. MVDC collection grids can facilitate the integration of current PV plants in Australia and future offshore wind farms. In addition, remote ac nodes can be connected via MVDC networks, which can achieve power capacity improvement, voltage profile enhancement, and network loss optimisation.

Additional protection schemes have to be adopted either in system or converter layer, and bottlenecks for the development of MVDC networks, including the grid structure selection, converter availability, interaction between MVDC & MVAC, dc fault handling capability, and investment costs need to be further researched.

ACKNOWLEDGMENT

The work is supported by Australian Research Council's Discovery Project (DP210102294).

REFERENCES

[1] P. Sun, F. Arrano-Vargas, H. R. Wickramasinghe, and G. Konstantinou, "Benchmark models for HVDC systems and DC-grid studies," in *ICPES 2019, Perth, WA*, Dec. 2019.

[2] S. Negri, E. Tironi, G. Superti-Furga, and M. Carminati, "VSC-based LVDC distribution network with DERs: Equivalent circuits for leakage and ground fault currents evaluation," *Renewable Energy*, vol. 177, pp. 1133–1146, Nov. 2021.

[3] CIGRE WG C6.31, "Medium voltage direct current (MVDC) grid feasibility study," CIGRE, Tech. Brochure 793, Feb. 2020.

[4] CIRED WG 2019-1, "DC networks on the distribution level–new trend or vision?" CIRED, Tech. Brochure, Jul. 2019.

[5] J. K. S. et al., "MVDC applications and technology," in *PCIM Europe 2019*, May 2019, pp. 1–8.

[6] A. Giannakis and D. Peftitsis, "MVDC distribution grids and potential applications: Future trends and protection challenges," in *EPE'18 ECCE Europe*, Sep. 2018, pp. P.1–P.9.

[7] C. Harrison and L. Brand, "MVDC power transmission with a twist," CIGRE Australia, Tech. Rep., 2017.

[8] S. Coffey, V. Timmers, R. Li, G. Wu, and A. Egea-Àlvarez, "Review of MVDC applications, technologies, and future prospects," *Energies*, vol. 14, no. 24, p. 8294, Dec. 2021.

[9] U. Javaid, F. D. Freijedo, W. van der Merwe, and D. Dujic, "Stability analysis of multi-port MVDC distribution networks for all-electric ships," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 2, pp. 1164–1177, Jun. 2020.

[10] P. Simiyu and I. E. Davidson, "MVDC railway traction power systems; state-of-the art, opportunities, and challenges," *Energies*, vol. 14, no. 14, p. 4156, Jul. 2021.

[11] G. Bathurst, G. Hwang, and L. Tejwani, "MVDC - the new technology for distribution networks," in *11th IET In.l Conf. on AC and DC Power Transmission*. Institution of Engineering and Technology, Feb. 2015.

[12] F. S. Al-Ismail, "DC microgrid planning, operation, and control: A comprehensive review," *IEEE Access*, vol. 9, pp. 36 154–36 172, Mar. 2021.

[13] A. Q. Huang, M. L. Crow, G. T. Heydt, J. P. Zheng, and S. J. Dale, "The future renewable electric energy delivery and management (FREEDM) system: The energy internet," *Proc. of the IEEE*, vol. 99, no. 1, pp. 133–148, Jan. 2011.

[14] F. Mura and R. W. D. Doncker, "Design aspects of a medium-voltage direct current (MVDC) grid for a university campus," in *8th Int. Conf. on Power Electron. - ECCE Asia*. IEEE, May 2011.

[15] Liu et al., "Analysis and protection of converter-side AC faults in a cascaded converter-based MVDC link: ANGLE-DC project," *IEEE Trans Smart Grid*, pp. 1–1, 2021.

[16] B. Zhao, R. Zeng, Q. Song, Z. Yu, and L. Qu, "Medium-voltage DC power distribution technology," in *The Energy Internet*. Elsevier, 2019, pp. 123–152.

[17] Qu et al., "Planning and analysis of the demonstration project of the MVDC distribution network in Zhuhai," *Frontiers in Energy*, vol. 13, no. 1, pp. 120–130, Nov. 2018.

[18] Y. Fan, Y. Chi, Y. Li, Z. Wang, H. Liu, W. Liu, and X. Li, "Key technologies for medium and low voltage DC distribution system," *Global Energy Interconnection*, vol. 4, no. 1, pp. 91–103, Feb. 2021.

[19] Australia PV Institute (APVI), "Solar PV maps and tools," https://pv-map.apvi.org.au/, accessed May 31, 2022.

[20] B. Matich, "New report forecasts Australia's solar capacity to reach 80 GW by 2030," https://www.pv-magazine-australia.com/2021/05/11/new-report-forecasts-australias-solar-capacity-to-reach-80-gw-by-2030/, accessed May 11, 2021.

[21] CLEAN ENERGY COUNCIL, "Clean energy in Australia," 2021.

[22] R. Mo, H. Li, and Y. Shi, "A phase-shifted square wave modulation (PS-SWM) for modular multilevel converter (MMC) and DC transformer for medium voltage applications," *IEEE Trans. Power Electron.*, vol. 34, no. 7, pp. 6004–6008, Jul. 2019.

[23] Australia Renewable Energy Agency (ARENA), "Off grid," https://arena.gov.au/renewable-energy/off-grid/, accessed Mar. 30, 2022.

[24] Tasmania Hydro, "King Island renewable energy integration project," 2015.

[25] Australia Renewable Energy Agency (ARENA), "Renewable energy in the Australia mining sector," 2017.

[26] G. Abeynayake, G. Li, J. Liang, and N. A. Cutululis, "A review on MVdc collection systems for high-power offshore wind farms," in *2019 14th Conf. on Ind. and Inf. Syst. (ICIIS)*, Dec. 2019, pp. 407–412.

[27] AEMO, "Appendix 3. renewable energy zones," Dec. 2021.

[28] J. Yu, A. Moon, K. Smith, and N. MacLeod, "Developments in the angle-DC project; conversion of a medium voltage ac cable and overhead line circuit to DC," *CIGRE Paris Session*, 2018.

[29] L. Su, P. Zhu, A. Yan, Y. Ma, M. He, J. Meng, B. Wang, and G. Fan, "Design scheme and simulation verification of Suzhou medium voltage DC distribution project," *Electr. Power*, vol. 54, no. 1, pp. 78–88, 2021.

[30] A. Lesnicar and R. Marquardt, "An innovative modular multilevel converter topology suitable for a wide power range," in *2003 IEEE Bologna Power Tech. Conf. Proc.,*, vol. 3, Jun. 2003, pp. 6 pp. Vol.3–.

[31] M. M. C. Merlin, T. C. Green, P. D. Mitcheson, D. R. Trainer, R. Critchley, W. Crookes, and F. Hassan, "The alternate arm converter: A new hybrid multilevel converter with DC-fault blocking capability," *IEEE Trans. Power Del.*, vol. 29, no. 1, pp. 310–317, Feb. 2014.

[32] P. Sun, Y. Tian, J. Pou, and G. Konstantinou, "Beyond the MMC: Extended modular multilevel converter topologies and applications," *IEEE Open J. Power Electron.*, vol. 3, pp. 317–333, May 2022.

[33] I. Alhurayyis, A. Elkhateb, and J. Morrow, "Isolated and nonisolated DC-to-DC converters for medium-voltage DC networks: A review," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 9, no. 6, pp. 7486–7500, Dec. 2021.

[34] G. Li, J. Liang, S. Balasubramaniam, T. Joseph, C. E. Ugalde-Loo, and K. F. Jose, "Frontiers of DC circuit breakers in HVDC and MVDC systems," in *2017 IEEE Conf. Energy Internet and Energy Syst. Integr. (EI2)*. IEEE, Nov. 2017.

[35] G. Li, L. Zhang, T. Joseph, J. Liang, and G. Yan, "Comparisons of MVAC and MVDC systems in dynamic operation, fault protection and post-fault restoration," in *IECON 2019 - 45th Annu. Conf. of the IEEE Ind. Electron. Soc.*, vol. 1, Oct. 2019, pp. 5657–5662.

[36] T. Zheng, W. Lv, Q. Wu, R. Li, X. Liu, C. Zhang, and L. Xu, "An integrated control and protection scheme based on FBSM-MMC active current limiting strategy for DC distribution network," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 9, no. 3, pp. 2632–2642, Jun. 2021.

[37] K. Jia, C. Wang, T. Bi, T. Feng, and R. Zhu, "Transient current correlation based protection for DC distribution system," *IEEE Trans. Ind. Electron.*, vol. 67, no. 11, pp. 9927–9936, Nov. 2020.

[38] Y. Wang, Q. Li, B. Li, T. Wei, Z. Zhu, W. Li, W. Wen, and C. Wang, "A practical DC fault ride-through method for MMC based MVDC distribution systems," *IEEE Trans. Power Del.*, vol. 36, no. 4, pp. 2510–2519, Aug. 2021.

[39] X. Huang, L. Qi, and J. Pan, "A new protection scheme for MMC-based MVdc distribution systems with complete converter fault current handling capability," *IEEE Trans. Ind. Appl.*, vol. 55, no. 5, pp. 4515–4523, 2019.

[40] L. Ferreira Costa and M. Liserre, "Failure analysis of the dc-dc converter: A comprehensive survey of faults and solutions for improving reliability," *IEEE Power Electron. Mag.*, vol. 5, no. 4, pp. 42–51, Dec. 2018.

[41] G. K. Kumar and D. Elangovan, "Review on fault-diagnosis and fault-tolerance for DC-DC converters," *IET Power Electron.*, vol. 13, no. 1, pp. 1–13, Jan. 2020.

[42] Xiang et al., "Resonant modular multilevel DC–DC converters for both high and low step-ratio connections in MVDC distribution systems," *IEEE Trans. Power Electron.*, vol. 36, no. 7, pp. 7625–7640, Jul. 2021.

[43] L. Zheng, R. P. Kandula, and D. Divan, "Current-source solid-state DC transformer integrating LVDC microgrid, energy storage, and renewable energy into MVDC grid," *IEEE Trans. Power Electron.*, vol. 37, no. 1, pp. 1044–1058, Jan. 2022.