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TOPICAL COLLECTION: LOW-ENERGY DIGITAL DEVICES AND COMPUTING 2023

A Review on Topological Advancement and Performance of Low Voltage DC Distribution System

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Abstract

Globally, grid systems are facing substantial challenges due to the rapid growth in power demand. New technologies equipped by means of smart energy resources are one promising solution to cope with this challenge, leading to microgrid systems. The growing demand to develop the power sector by utilizing alternative energy resources plays an influential role in the advancement of low-voltage DC (LVDC) systems. With the prompt development of LVDC distribution grids, bipolar LVDC distribution topology is becoming a leading and promising solution. Therefore, this review paper represents a comprehensive overview as well as a comparative and critical analysis for the development of novel methods on LVDC grid analysis, control strategy, and protection schemes to solve energy management problems that lead to a futuristic novel solution in the green revolution.

Keywords Converter · distribution systems · energy storage system (ESS) · fault detection · hybrid circuit breaker · low-voltage direct current (LVDC) · LVAC · microgrid · renewable energy sources (RES) · standards

Introduction

Human creations and living standards have achieved remarkable growth in modern times. The enhancement in living standards produces high electricity consumption leading to massive energy demand in every utility sector.

The prime concept of current electricity was invented in the eighteenth century by the renowned scientist, Michael Faraday. In 1879, Thomas Edison focused on inventing static electricity which in turn became the inspiration for developing an electrical system to utilize electrical power. In the nineteenth century, direct current (DC) power distribution was the primitive standard electrical distribution system. The turning point of the electric era came when Croatian scientist, Nikola Tesla, developed alternating current (AC) power systems. Since then, AC power has been the fundamental aspect of modern power systems in terms of electricity generation, transmission, and distribution.[1] In every aspect of modern electrical technology, an obvious use of AC power had been incremented in the late twentieth and early twenty-first centuries.[2] The invention of transformers eased long-distance power transmission where AC power is transmitted over high-voltage AC transmission (HVAC) lines. Electrical energy conversion has been easily accustomed with the aid of transformers in AC systems by means of high-voltage (HV) and low-voltage (LV) supplies. However, in recent years, due to high power density, stability, and controllability, high-voltage DC (HVDC) has become a widespread technology in modern long transmission (800 km in overhead lines and 450 km in cable lines) grid systems.[3] Also, the pioneering invention of semiconductor technology widened the use of HVDC in long transmission grid systems. Again, in comparison to HVAC transmission systems, to connect dissimilar frequency AC grids and enhance efficiency and control capability, HVDC transmission is the most effective.[4] Moreover, capacitance

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issues of underground cables in HVAC lines can be overcome by HVDC systems, and therefore HV power can be transferred over very long transmission lines. Alternatively, in distribution systems of less than 11 kV, the utilization of LV AC is more economical and safe, particularly in terms of transmission and distribution losses that affect their efficiency.[3] Nowadays, modern electrical grid systems are highly dependent on AC–DC hybrid topology, which suffers from additional power loss due to several stages of conversion and poor power quality. To enhance the power quality as well as the efficiency, the switchover concept to low voltage direct current (LVDC) systems has been implemented.[5]

LVDC systems have recently been gaining popularity due to their potential for energy efficiency by reducing conversion steps and by cost savings in various applications, such as data centers, lighting, and renewable energy systems. LVDC systems are also well suited for use with renewable energy sources (RES), such as solar and wind power, as they facilitate more efficient energy storage and distribution.

The emerging energy demand is a prime factor in the reckless depletion of established energy sources, combined with detrimental atmospheric emissions from the combustion of fuel causing the climate crisis as well as increasing energy costs. As a result, the rapid penetration of renewable resource-oriented fresh technologies are being adopted to accord with the increasing power demand in conventional power systems. Therefore, renewable energy generation-based power plants are considered as an effective way towards energy advancement. To generate energy from renewable resources, solar PV is becoming the most economical option for new generation systems. However, in modern electricity networks, the dimensions of generation, distribution, and transmission are being changed by solar PV-based DC. In a conventional power management system, DC power output generated from renewable resources needs to be converted to AC for delivering conventional loads, which increases the complexity and also produces power quality problems.[6,7] To overcome these, scientists are starting to evolve a DC power supply grid through a DC bus in order to relieve power quality and to fully capitalize the electric energy.[5] In the recent era, drastic growth in energy transition has been developed for LVDC grids as a substitute for traditional LVAC grids.

Remarkable work had been carried out by several researchers[6,8–10] on energy-savings analysis of DC power distribution systems. Moreover, gap analysis and updating have been carried out to optimize the systems. An energy management system was proposed by Lee et al. to design a control strategy with the operation procedure in an LVDC system.[11] Vishal and Nath highlighted the prospects and deficiencies of LVDC-based power distribution systems where the load is dominated by a renewable energy-based power supply.[12] Singh et al. modeled a rural microgrid system based on renewable energy interconnected through an LVDC network. According to their study, the controller of the microgrid system can control the generation as per system requirements to remain in a steady state.[13] Little modification was caried out by Li et al. who proposed a DC–DC converter having an integrated voltage balance capability for a bipolar LVDC system which had been experimentally proved through a prototype model.[14] Chen et al. designed a combinational DC–DC converter for a bipolar LVDC system having a full active bridge on the input side and semi-active bridge on the output side. The proposed system could operate in dual mode using zero voltage switching, maintaining steady output power.[15] Ashitha and Thomas had an independent approach by designing a buck–boost converter for an LVDC system. This non-isolated SEPIC-based DC–DC converter regulated the overall voltage level of the system which was further analyzed by a MATLAB model.[16] Almasri et al. discussed the contribution of a PV source for the realization of a DC nano-grid. As per their discussion, this nano-grid PV system was utilized for the maximization of the grid efficiency, further realized by MATLAB simulation.[17] Similar approaches have been made by quite a few researchers (Arun et al., Mohapatra and Mohapatro). They intended a bidirectional non-isolated three-port converter for a PV-based LVDC microgrid network to harvest energy from solar irradiance to meet the additional load requirements. To ensure an uninterruptible power supply, a reformed power flow management control with different algorithm techniques was introduced to regulate the control strategy of the converter operated in various modes.[18–20] An alternative design was by Zhang et al. of a multiport DC–DC converter for bidirectional power flow in a DC grid. The proposed scheme reduced switching loss through ZVS-based soft switching validated through simulation.[21] On the other hand, Purgat et al. developed a control converter to maintain a power flow suitable for LVDC grids. With the help of state–space representation and simple algorithms, the optimization and stability analysis of the converter was validated.[22] Hou et al. proposed a smart energy converter for an LVDC distribution grid having distribution and storage integration. With the help of an intelligent control strategy of the above converter, the stability of the overall grid could be maintained uninterruptedly.[23] For cost reduction in construction and protection, dual-active bridge converters (DABs) have been suggested in recent years. Cui et al. designed a DAB converter for LVDC distribution systems with integral bipolar operation capability. By implementing a DAB converter, overall bipolar operation can be carried out without using any additional active or passive elements.[24] Similarly, Yao et al. designed a hybrid DC transformer that interrelated MVDC and LVDC distribution networks combined with multiple series resonant converters and a DAB converter.[25] Mohammed and Jamil adapted the voltage of a DC power network by using a capacitive DC transformer. Based on their mathematical analysis, power can be transformed from LVDC to HVDC and vice-versa up to 600 MW and 500 kV within a DC power system network.[26] Zengin created a hybrid current-modulated DAB DC/DC converter with partial shading to assimilate PV modules.[27] One more design approach was proposed by Li et al. regarding power electronic transformers based on PSFB/DAB-MMC topology to afford ample dependability under severe disruption in the LVDC system.[28] To interconnect LVDC and MVDC grids, Zhao et al. designed a novel bidirectional scheme using a multilevel DC–DC converter. According to their study, the proposed scheme can be bidirectionally regulated with dual mode of operation to optimize the transformer current to its fullest range, as well as eliminating circulating power.[29] Similar topology was designed by Kanathipan et al. They developed an LVDC to medium-voltage AC (MVAC) inverter having grid side control and a voltage balancing approach whose effectiveness was validated using PSCAD.[30] Wang et al. designed and developed an innovative structure of a hybrid coupled interlinking converter (HCIC) for hybrid AC and LVDC microgrids. The power flow and harmonic control operation of the converter was controlled by a different control strategy which was verified by simulation and achieved the requirements of power flow for the proposed hybrid AC–DC microgrid system.[31] However, by means of this traditional design method, due to the huge conduction loss, productivity became lowered under heavy load conditions. To expand the power conversion efficiency, Choi et al. contributed a design methodology of magnetic components used in 3-ph DAB converter, which could diminish the drawbacks of conventional design by means of specific control techniques.[32] Saha et al. instigated a control scheme to balance the power for a DAB MVAC–LVDC Converter. Their prime objective was to solve the power-routing imbalance issue throughout steady-state operations.[33]

By the rapid growth and development of LVDC distribution systems, the risk caused by appliance malfunction and electric shock increases. In addition, more DC–DC conversion stages of multilevel bus LVDC systems may increase power losses as well as complications in wiring topology. Lee et al. introduced a voltage-matching device for LVDC distribution systems having high frequency isolation. The suggested voltage balancer could control the voltage level completely under unbalanced load and no load conditions through switching modulation.[34]

In comparison with AC systems, LVDC systems are also liable to numerous types of electrical faults that can cause equipment damage and diminish system flexibility. DC fault location and protection selectivity are very challenging. Whenever a fault occurs in a DC microgrid, a fault current rises rapidly. Subsequently, the arc behavior as well as changes in line parameters that occur in the circuit are inimitable to the fault area. To overcome these particular conditions, numerous techniques have been established depending on the observation and analysis of the nature of the faults. Several fast and reliable protection schemes were introduced by Sharma et al. to detect faults in LVDC grids. The ability of the suggested schemes can be to inspect both grid-connected and standalone operative modes.[35,36]

Due to deficiencies in commonly accepted protection methods and standards, the transition from AC-based systems to AC–DC hybridized systems is quite problematic. For dependability and reliability of a DC system, the protection plans of an LVDC microgrid are crucial where accurate selectivity of the protection scheme is imperative. On that basis, Bhargav et al. discussed an algorithm to detect and localize faults in LVDC microgrid networks. Their comparative analysis with other methods proved its superiority in fault detection.[37]

Over the last few decades, the stimulating demand in the development and utilization of LVDC systems has led to numerous research projects aiming at power quality improvement and economic benefit. The perception of microgrid systems to overcome the environmental exhaustion as a part of green energy management systems has been introduced by renewable energy harvesting processes, mainly using PV and wind energy. Meanwhile, developments in recent technology make DC power an alluring prospect. Numerous adaptation stages with their respective losses can be eliminated by implementing the concept of hybrid AC–DC grids or LVDC. Energy produced from renewable resources by implementing LVDC micro- and nanogrids can efficiently reach the energy demand while decreasing the losses at the time of AC/DC and DC/AC energy conversion. Several comparative analyses and feasibility studies have been made in different microgrid architecture for optimum planning and designing of LVDC systems and their impact on social development.[10,38–40]

A comprehensive summary has been furnished to highlight different LVDC architecture and their key features or limitations and is given in Table I.

To the best of the knowledge of the authors, various approaches have been made to assess the potential and drawbacks of LVDC distribution systems. Most of the research work has mainly focused on different design aspects of LVDC microgrid distribution topology. Focus has also been on the development of fresh ways and means and tools for LVDC grid analysis, control strategy, and protection schemes to solve energy management problems. However, very few approaches have been observed in the literature to focus on developing efficient and reliable LVDC systems which can deliver loss-free power. This has motivated the authors to make an attempt to provide a comprehensive overview on different design essentials of interlinking DC–DC

Table I Key features and limitations of different LVDC structures

References	Key features	Major limitations
14–16	Bipolar DC–DC converter topology ZVS-based soft switching Built-in voltage balance capability	Switching loss is high Loss due to leakage inductance is high Little expensive
18–20	Non-isolated multiport converter topology Smooth power flow by inclusion of SISO mode of operation. Can used in both grid-connected and standalone load	Integrating with AC circuit is not possible High switching loss Higher size and cost due to battery as energy storage device.
21, 24, 27, 28	Bridge converter topology Bipolar operation capability Can interconnect LVDC and MVDC grids Low switching loss due to ZVS switching	AC link transformer for dual stage operation Complex design aspect Critically capable in asymmetrical DC-linked pole power control
29, 30	Bidirectional Interconnect LVDC and MVDC grids Offer high reliability	Effect of high-frequency harmonics Medium cost.
32–34	DAB converter topology Offers voltage and power balancer control Interconnect LVDC and MVDC grids	Filtering required for harmonics elimination Numerous switching operation High switching loss
38–40	LVDC grid topology to retrofit existing AC circuit Low energy consumption High efficiency No harmonics elimination	High initial establishment cost

converters and relevant control strategies and protection schemes for smooth operation of the systems.

The rest of the paper has been organized as follows. Section "Existing Topology for Design of LVDC Network" describes the existing design topology of an LVDC grid network. Section "Converter Design-Based Isolated Topology" and Sect. "Converter Design-Based Non-isolated Topology" describe different design topologies of converter circuits. Various performance analyses are illustrated in Sect. "LVDC Performance Analysis". Discussion on different design approaches and performance as well as the direction of future works is explained in Sect. "Discussion and Direction for Future Research". Finally, the summary and conclusions with future scope are furnished in Sect. "Conclusions".

Existing Topology for Design of LVDC Network

The rising demand to develop and utilize renewable energy resources has a great influence in the growth of LVDC systems. In this context, LVDC distribution topology is becoming a leading promising solution. LVDC distribution systems offer the facility of sustainable, affordable, and reliable energy to the distribution grids. Moreover, prospects of connecting DC-based microgrids will be easier due to less complexity in terms of frequency and phase synchronization than for AC systems. Several schemes designed by researchers have been discussed earlier. This section highlights suitable design criteria for specific applications to provide higher efficiency, reliability, and stability.

To design a stable and economic LVDC distribution grid system, many researchers have focused on power electronics-based DC–DC converter design topology, as it delivers power in both unidirectional and bidirectional ways (AC to DC and vice versa). The conversion process has been carried out with the help of assembled elements in the converter module. In the modern LVDC architecture, two types of converter configuration have usually been employed: (1) isolated topology, and (2) non-isolated topologies that provide higher operation flexibility. Several design structures have been introduced by the researchers with different performance characteristics and switching techniques.[16,18,25,29] This section describes and estimates the feasibility of all the design schemes reputable in DC microgrid systems.

Converter Design-Based Isolated Topology

Conventional design technique for the bipolar LVDC distribution system composite with voltage balancers comprises numerous power phases which deteriorate their power density and cost-effectiveness. To reduce the construction cost and enhance efficiency, several approaches of bridge converters based on isolated topology have been taken in recent years. In this section, the operating principles with the topology of such proposed isolated converters are introduced. The isolated DC–DC converters are comprised of a DC–AC bridge, a transformer, and an AC–DC bridge[41] as shown in Fig. 1.

To assimilate the individual voltage levels, several modular MMC-based design approaches have been represented.

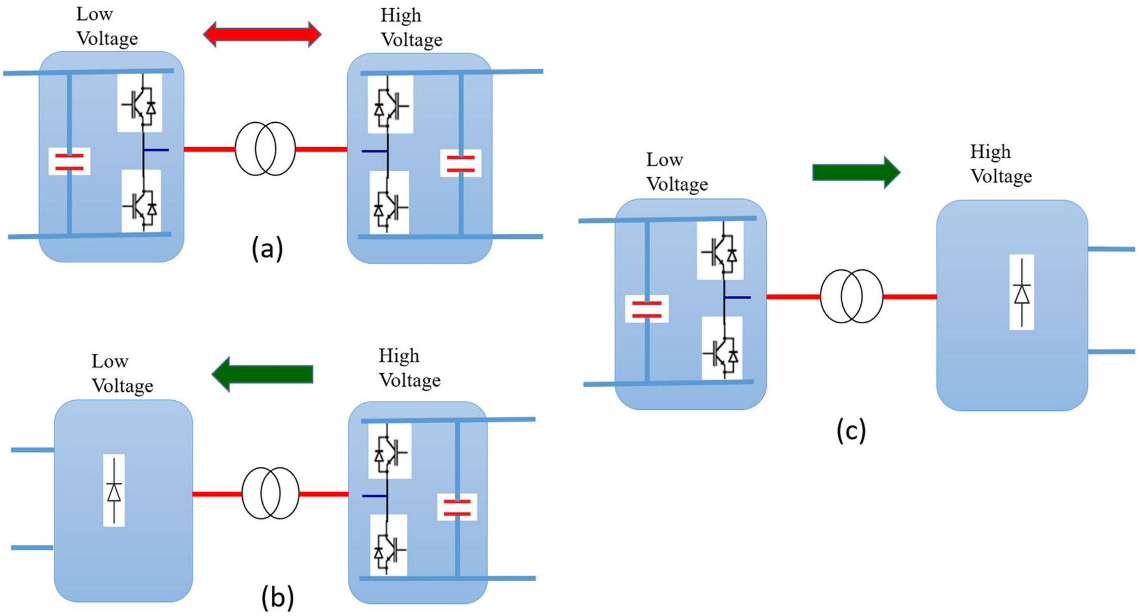

Fig. 1 Isolated DC–DC converters for LVDC network: (a) bidirectional, (b) unidirectional step down, (c) unidirectional step up.

The most common types are DAB converters and phase shift full bridge converters. A one-stage voltage balancer circuit based on 3-level DAB converter was introduced to enhance the switching modulation as well as control the power output of the converter.[34] Similar methods using two-stage partially rated power flow control converters were autonomously proposed for LVDC microgrid systems which consist of a full bridge converter coupled with a DAB converter.[22] Another novel PSFB/DAB-MMC topology was proposed with IGBT switching to minimize the power stages. In comparison with isolated MMCs, this PSFB/DAB-MMC is more reliable under severe disturbances in the LVDC system.[28] Furthermore, to interrelate an LVDC system with a MVDC grid system, a neutral-point clamped converter-based MPC was introduced which consists of two full H-bridge converters.[21] To neutralize the power imbalance problem, a power balance control scheme in conjunction with the existing LVDC bus voltage controller was developed.[33] For the advancement of power conversion efficiency, an approach of a three-phase DAB converter has been presented[24,32] , where efficiency has been improved by reducing the switching and conduction loss, i.e., the overall power loss. A comparison of the key parameters among different isolated converter designs proposed by several researchers in recent years is set out in Table II.

Converter Design-Based Non-isolated Topology

Voltage regulation is the fundamental aspect of a DC–DC converter used in LVDC distribution systems where overall system voltage is to be regulated by increasing or decreasing the output voltage. The simplest mechanism of a DC–DC converter used in an LVDC grid system for power regulation is a buck–boost-type converter, shown in Fig. 2, that can operate as a bidirectional isolated DC–DC converter.

For better performance characteristics, various modifications have been proposed in the design of bidirectional DC/DC converters by different researchers. To shrink the power loss of the converter, the following have been discussed in various publications: non-isolated SEPIC-based buck–boost converter,[16] modular multilevel converter (MMC),[29] multi-port DC–DC converter with neutral point clamp (NPC),[42] Modified CLLC converter with voltage balancing mechanism,[14] three-phase LLC resonant converter with built-in pole voltage balancing mechanism,[25] non-isolated three-port converter (TPC),[18] non-isolated multiport converter with continuous conduction[19]

Table II Parametric comparisons of different isolated converters

References	Converter configuration	Basic model	Input voltage	Output voltage	Output connected with	Switching technique	Switching elements	Switching frequency (fsw)
21	Neutral-point clamped MPC	Full H-bridge converter	4 kV	400 V	Grid connected	ZVS-based soft switching	MOSFET	40 KHz
22	Power flow control converter	Unfolded full bridge converter	350 V	50 V	Grid connected	ZVS-based soft switching	MOSFET	83 kHz
24	DAB converter with inherent bipolar operation	3-phase DAB (DAB3) with zig-zag/delta winding AC-link transformer	60 V	20 V	Load connected	ZVS-based soft switching	MOSFET	16.7 kHz
28	Three-port PSFB/DAB-MMC	Combination of DAB MMC and I MMC	6 kV	750 V	Load connected	Phase shift control	IGBT	10 kHz
32	Three-phase dual-active-bridge (3P-DAB)	3P-DAB with active bridges on HV and LV sides	550 V	278 V	Load connected	ZVS-based soft switching	IGBT	8 kHz
33	Cascaded matrix-based DAB (CMB-DAB)	Matrix-based DAB with sub-module	2.9 kV	800 V	Grid connected	Phase shift control	MOSFET	20 kHz
34	Single-stage voltage balancer	Three-level DAB converter	600 V	300 V	Load connected	Phase shift control	MOSFET	50 kHz

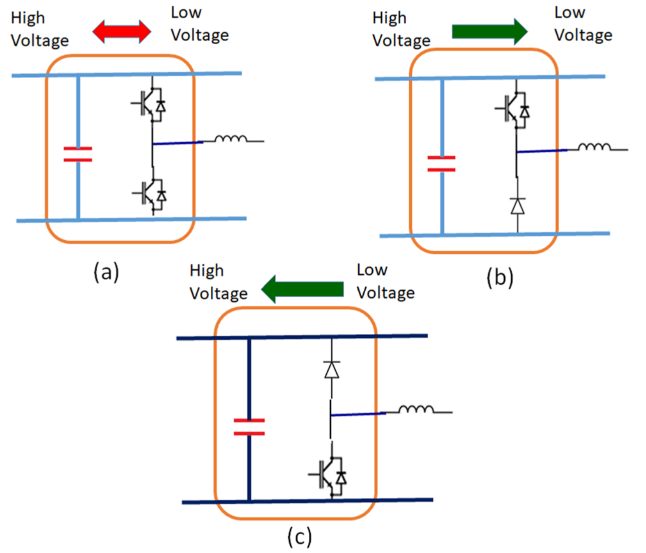

Fig. 2 Non-isolated DC–DC converter for LVDC network: (a) bidirectional, (b) unidirectional step down, (c) unidirectional step up.

single-stage, single-channel non-isolated buck converter,[41] Non-inverting SEPIC-based single-switch buck–boost DC–DC converter,[43,44] triple-port DC–DC buck–boost converter,[45] with high voltage gain suitable for RE application and dual-input–dual-output converter with a dynamic energy management system.[46]

The overall power loss of these non-isolated DC–DC converter technique has been analyzed as shown in Fig. 3.

Due to different voltage balancing mechanisms, the quality of the output voltage as well as the efficiency of the proposed DC/DC converters can be significantly improved.

LVDC Performance Analysis

Compared to conventional AC systems, the LVDC system provides many advantages covering easier incorporation of modern energy resources with high energy efficiency. Multiple factors permit the utilization of DC systems instead of AC which affects the reliability performance and power quality of the supply system. The performance of an LVDC network can be evaluated under (1) normal load flow operating conditions and (2) under different fault conditions by using various performance indices. On the other hand, in a DC electrical system, commonly, two electrical faults (i.e., line-to-line and line-to-ground) can occur. In this study, the author emphasizes the performance analysis under (1) normal load flow operating conditions and (2) under different fault conditions by using various performance indices.

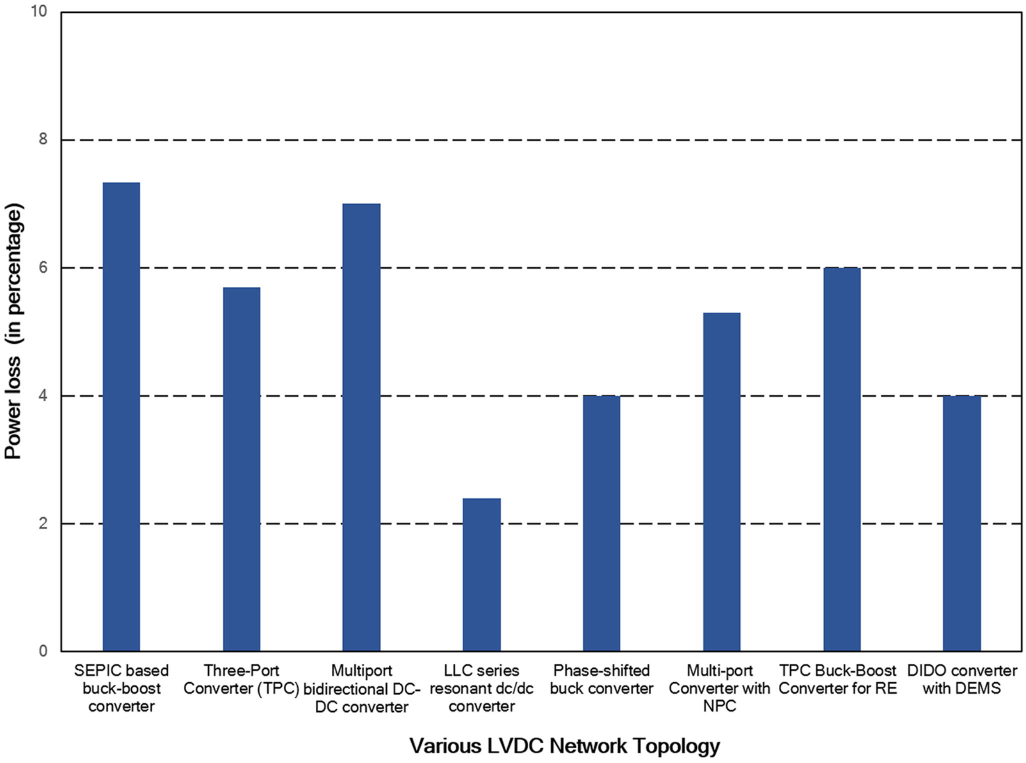

Fig. 3 Percentage Power loss in non-isolated DC–DC converter used in LVDC network.

It is obvious that during normal operating conditions the performance of an LVDC system affects the power quality of the network which relies on various indices like voltage deviation, power loss, voltage regulation, and efficiency, as shown in Table III.

Discussion and Direction for Future Research

This study clearly depicts the advancement scenario of LVDC distribution systems. Different design approaches and their performance have been revealed and analyzed, as summarized in Table IV.

The operation of LVDCs still has a few challenges that can be improved. Various enhancements may involve exploring new converter topologies or improving existing topologies to improve performance, reduce footprints, or meet specific requirements. Research can also focus on optimizing parameters such as voltage and current, switching frequency, and control mechanisms. It is critical to look for ways to reduce power losses and switching losses in converters to improve the overall system performance. This can be achieved through the development of new semiconductor materials, improved thermal management, and the development of new circuit topologies. Research may also include the development of filters, modulation strategies, or control algorithms that effectively reduce or eliminate harmonic distortions to maintain power quality in electrical systems. The use of advanced control algorithms, feedback mechanisms, or intelligent control strategies through improved voltage, power, and gain control techniques can lead to more adaptive and responsive power electronics systems. Reliability issues arising from energy imbalance can be addressed by exploring methods to balance energy distribution through advanced control techniques, energy storage integration, or other innovative solutions. The development of dynamic energy management systems is necessary to optimize the use of available energy sources. This can include the integration of RES, advanced energy storage solutions, and intelligent real-time energy management algorithms.

Conclusions

The worldwide energy alteration towards carbon-free green energy solutions with different RES and mostly non-synchronous energy sources entails the imposition of new topologies in electrical networks. The enormous perception of DC-based distributed RES generation combined with innovative EV and various residential and industrial appliances stimulates the progress of LVDC networks. The implementation of innovative strategies for the development of

Table III Performances under different faulty condition

References	Name of fault	Fault detection method	Response time	Reliability	Remarks
35	PP and PG fault in grid-connected as well as standalone mode	Variational mode decomposition (VMD)-based iteration method	2 ms	High	The VMD-based relaying scheme offers a reliable and fast fault detection scheme to detect all types of faults having massive deviations in fault location and operational mode of LVDC microgrids
36	PP and PG fault in grid-connected as well as standalone mode	VMD-enabled current-based fault detection method	0.08 ms	High	VMD-based fault detection technique for an LVDC system with penetration of renewable sources using local end current measurements only
37	Low- and high-resistance DC fault	Inductance-based voltage balancing method	1.25 ms	High	Detect high-resistance ground faults by utilizing ground current at relay location
47	DC fault (PP and PG fault)	Transient FLTE-based fault location method	0.2 ms	High	The high accuracy of the proposed method based on the critical distance has been certified against different cable lengths with very low fault resistance to minimize the estimation error that does not require data synchronization regardless of voltage, current, and size of the converters connected to an LVDC feeder
48	High-resistance faults (both grid-connected and isolated microgrids)	Periodically-forced harmonic oscillator (PFHO)-based	400 µs	Very high	The fault occurrence and direction can be determined by the superimposed component-based technique equipped with IED-added PFHO input

Table IV Summary of major issues under different design aspects

Number	Specific area	Major issues
1	Existing topology of LVDC design	Bidirectional power conversion using DC–DC converter topology Switching loss
2	Converter design-based on isolated topology	Establishment of different Isolated converters Reduce power stages and switching loss Enhance efficiency
3	Converter design based on non-isolated topology	Establishment of different non-isolated converters Reduce power loss Enhance efficiency
4	Performance analysis of LVDC design	Improvement of voltage-balancing mechanism Harmonics elimination Voltage, power, and gain control Power balance Energy management

hybrid AC–DC coordinated energy management systems is needed. Therefore, the incorporation of innovative and qualitative design approaches may be a promising prospect for the future. Furthermore, the improvement of different control performances to maintain the stability and validate the efficiency will also be a point of interest for future research. On the other hand, decentralized generation of energy with the help of RES combined with daylight integration of energy storage systems in close proximity to the consumer is a futuristic novel solution for the green revolution. In addition to this, operational safety precautions in the utilization of LVDC distribution networks will become a satisfactory solution leading towards energy conservation concepts in microgrid systems.

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