Exploring MVDC in Distribution Systems: A Primer on Cybersecurity

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Abstract

Medium Voltage Direct Current (MVDC) systems are increasingly utilized in smart grids for integrating renewable energy sources, as well as in applications like DC rail distribution networks and standard AC ships. These systems enhance flexibility, power quality, and efficiency in power systems. This review examines the advancements in MVDC technology, including various architectures, components, control strategies, and applications such as electric vehicles and renewable energy integration. It also highlights the importance of cybersecurity, which is becoming a critical concern due to the widespread deployment of MVDC systems across industries. As MVDC systems continue to evolve, addressing cybersecurity will be essential for ensuring their safe and effective operation in smart grids and other applications.

Keywords: MVDC, Smart Grid, Renewable Energy Sources, Cyber security

INTRODUCTION

The power use argument was one of the first disputes in the early power grid where AC and DC grids ran together. However, because DC grid voltage and power levels were extremely low and voltage conversions were so complicated at that time, AC and DC grids are more prevalent. A more detailed explanation of several sources of generation and loads that form this MVDC bus is presented (1), (2), (3). Through the reduction of faults in it, DC is a better option (4), (5). In order to help the integration renewable generation, energy storage, and various end-use loads, the MVDC concept is intended to serve as a collection platform that will add an extra layer of infrastructure between transmission and distribution. These may extend the current narrow band of DC power system applications (6).

The blueprint is aimed at increasing the use of DC and the integration of the critical functions both in the building and outside the building, ensuring that DC deliver flexibility and reliability, energy saving and cost benefits, and foster the creation of zero-Energy-Balance Buildings i.e., buildings equally balanced between the energy exported and imported in terms of power (7).The prevailing MVDC architecture will lower the overall number of conversion steps, increasing energy efficiency (8). For example, the conversion methods can be simplified when low voltage renewable energy is integrated into an electric system.

The aim of this study is to measure the trade-off between selecting a more premium firm distributed generation (DG) connection that promises a full export capacity against a smarter Distributed Generation (DG) connection that offers limited export capacity (1), (9), (10), (11), (12). Originally created for the shipbuilding industry, the MVDC concept is now being examined for usage in DC grid power distribution networks (13). A clean, low-carbon, secure, and efficient power system can be obtained through MVDC due to the DC demands and distributed power's rapid development. The DC transmission technology in DC grids is a current area of intense research (14).

High Voltage Direct Current (HVDC) and Low Voltage Direct Current (LVDC) are the two categories into which DC transmission technology was split for distribution and transmission, where HVDC needs proper protection and fault detection (15), (16), (17), (18). With the increasing global adoption of HVDC technology in recent years, there has been a growing demand for HVDC transmission-line protection (19),(20),(21),(22).The MVDC link is necessary for power distribution because of an increase in distribution generators and DC loads in the distribution system in recent years (23). But it can compensate its pull draw backs such as ripple factor, regulation and capital station efficiency by using up-to-date power electronic devices, during power transfer within moderation that is MVDC only.

MTHODOLOGY:

MVDC Link:

MVDC acts as an enabling platform for interconnecting various renewable sources including wind power and solar power with mutual requirements for AC/DC, DC/DC conversion devices. The heavy loads of the future, such as industrial plants, data centers and electric vehicle charging stations, can be developed using MVDC technology. In the UK, a couple of pilot projects including the “Network Equilibrium” and “Flexible Urban Networks Low Voltage” programs tested the use of SOPs in medium and low voltage networks (24). The projects mentioned above used sequential VSC topologies to evaluate the impact of power electronics on the performance of distribution networks. The MVDC network plays an important role in traction, large-scale shipping and marine applications due to its low losses, reliability and controllability (25), (26). MVDC even with AC/DC or DC/DC converters, but still is better than Medium Voltage Alternating Current (MVAC) (27).

Components of MVDC:

The MVDC consists of different parts especially converters (27). The following are covered quickly here.

AC-DC converters**:** AC to DC converters convert an alternate (voltage or current) signal into a smooth signal. The applications of rectifiers are numerous (28), such as terminal converter substations at HVDC transmission lines, DC motors for industrial use, dc traction power with a.c. feeder lines, etc. (7), (29).

DC-DC converters**, a** DC-DC converter adjusts the transmitted DC voltage being transmitted to the load in a DC power device (7). The DC-DC converters are used as direct current feeders in many fields, in industry with electronic plants, in space applications, in laboratory sources, in electric traction driven by DC motors etc.

DC-AC converters**, t**hese converters are used as AC Feeds in the insulation sector, Uninterruptible Power Supply (UPS) plants, medium frequency ovens and speed controller on DC systems with AC engines. Therefore, these are the units (inverters) processing the input DC voltage into the output AC voltage and it can be then adjusted in terms of frequency & amplitude (7).

AC-AC converters, everything is fully controlled with a first or second phase of a rectifier in series to an inverter to set up an AC/AC converter (7). Applications for these converters include domestic appliances motor drives, aircraft power supplies with the two 70-V devices also available to support 400-V bus architectures.

MVDC for distribution network, the MVDC system makes use of control converters situated in the distribution network. MVDC has the great application prospect in distribution networks, urban cables, long overhead lines, power flow problems under medium low voltage, offshore wind farms, power plants for its following characteristics.

MVDC to reinforce substations, MVDC can also be used at the substation level to enable more power to be transferred without requiring costly and difficult upgrades to the existing cables or transformers.

- MVDC lines enable new ways of delivering electricity.
- They improve power quality problems.
- By expanding the network's control choices, it's possible to prevent voltage limits from impinging before thermal limits…

DISTRIBUTION SYSTEM

Long-distance transmission systems have demonstrated the benefits of HVDC systems over HVAC systems (30). Considering the increase in distribution generators and DC demands in recent years, the transition to a DC grid and distribution is imperative. Compared to the existing ac system, the MVDC distribution system offers several benefits, such as higher efficiency, simpler systems, fewer maintenance, lower operating costs, a simpler design, and longer system lifespan (31). And also, a variety of advanced approaches are required to ensure system dependability given the high penetration of Demand Response (DR) and Distributed Energy Resources (DER) within modern power grids (32), (33).

DC distribution networks are preferable to the current AC system owing to increased production of renewable energy sources, especially solar energy PV cell technology in India, where solar energy is frequently abundant and produces DC power, as well as government support to feed hybrid vehicles that use batteries for power and charging stations to accommodate such vehicles. Breakers and DC distribution serve as vital parts of the DC grid.

One of the most significant elements of the DC grid is the power electronic transformer, which is also multifunctional and small in comparison to other types of transformers and AC/DC converters. Smart TVs, radios, and resistive loads are just a few examples of the DC power

loads that will soon cohabit in parallel with ac loads. In contrast, most of the AC loads are used by home appliances including refrigerators, stoves, and heaters. Therefore, balancing AC and DC loads is currently one of the issues in sustaining a DC distribution system.
The advantages of the MVDC system over the MVAC system include the use of multiphase motors, the lack of problems with synchronous generators, the ability to decouple alternators' operating speed from the load, the simplicity of connecting energy storage devices like batteries, cable savings, low line losses, high efficiency, and reactive power suppression that improves power quality.

Medium-voltage direct current system architecture,

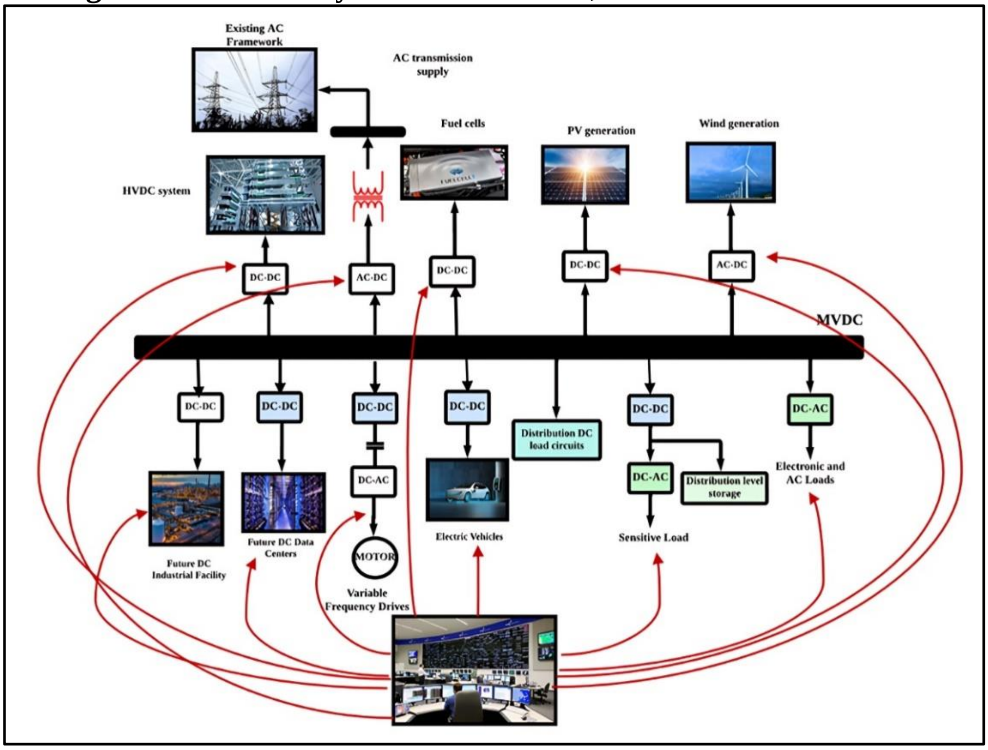

Fig.1 Framework of MVDC with a centralized control algorithm (6)

The MVDC grid with three-level NPC rectifiers and DC wire connecting five-MW permanent machine synchronous generators (PMSG) to the MVDC bus is shown in figure1.MW solar energy plants are connected to the MVDC bus using DCDC converters and DC cables. Among the main loads are a data center, a manufacturing complex, and an electric vehicle charging station.
The privatization of the energy market and the subsequent erection of massive solar and wind power stations at both the distribution and transmission level have increased the need for MVDC technology development. Consumers at the end adopt miniature versions of these same sorts of products, which have redundant DC connections, at the distribution levels (34). MVDC is commercially attractive, practically advantageous, and practicable in many instances when all of these many benefits and uses are combined, especially when local requirements coincide with a concentration of solar power.
The cost of engaging in MVDC transmission system is just 6.6% greater than that generating wind power (7), (34). An MVDC distribution grid has investment costs that are just 6.6% more than those of 400-VAC systems. Power electronics converter expenses are almost compensated by the reduced necessity of conduction material. The MVAC technology has roughly five times higher investment costs due to the significant quantity of transformer capacity required. MVDC can cut grid losses by 90.2%, whereas MVAC reduces ohmic losses by 89%.

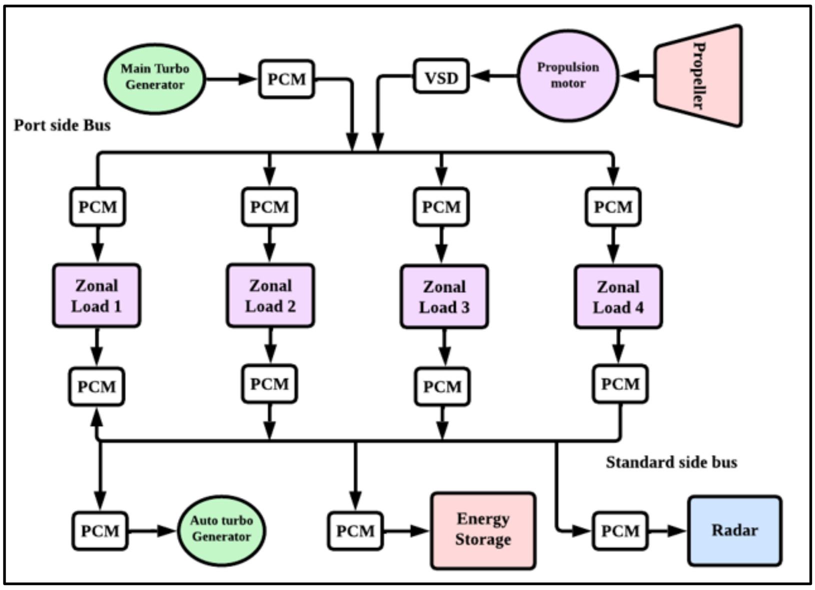

Fig.2 Single-Line Layout of MVDC shipboard Power System (35)

MVDC IN RAIL SYSTEM

Furthermore, there are no detectable electromagnetic effects of the MVDC system on the surrounding area. MVAC and LVDC/MVDC are incorporated in electric rail networks throughout the globe for intercity and high-speed lines. Inner city light rail systems function at LVDC/MVDC voltage levels.AC to DC switching happens at traction power substations; nevertheless, nominal power operation is restricted by frequent use in the lower-voltage DC circuits. A 24 kV electrification scheme is being proposed by the authors in order to fully realize the benefits of DC technology in the MVDC-RES. The basic structure of an MVDC-RES (Railway Electrification System) is displayed in Fig.3 (36). Transformers and multilevel AC-DC converters constitute TSSs, or traction substations. similar to the urban DC rail system's catenary system. The positive outcomes of the system and its extensive design are discussed in (36), (37). In DC railroads, the rail serves as a return path for the load current. Rail potential is the term used to describe the potential difference that the current that returns flowing through a rail creates when compared with rail and ground (38), (35), (39). A certain amount of the rail current that leaks into the ground is called stray current, and it is carried on by the rail potential. A part of this stray current also travels via metallic structures buried in the dirt near the traction line, where it causes corrosion (40).

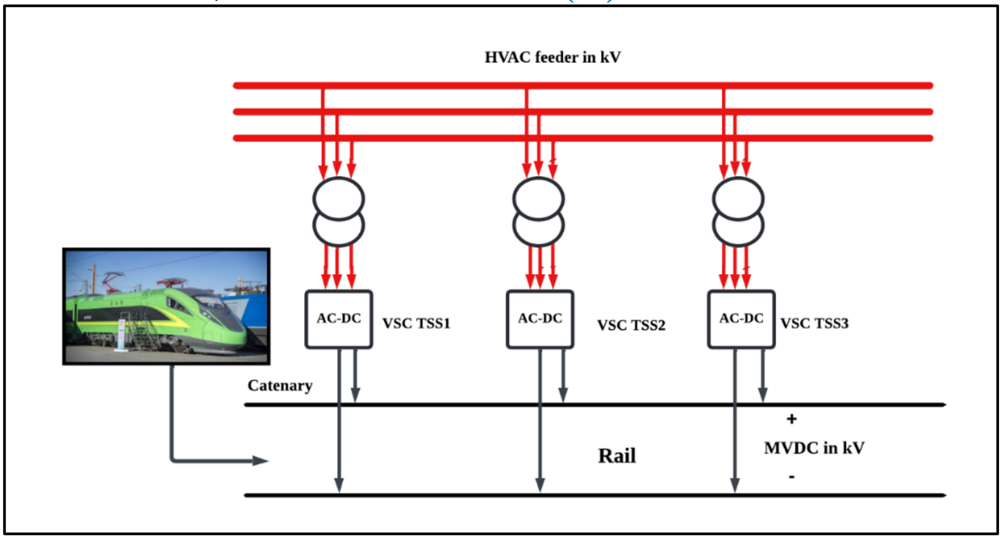

Fig.3 Schematic of MVDC Railway Electrification System (41)

Advanced MVDC rail systems (42), (43), which have emerged from prior LVDC/MVDC traction systems, offers an alternative to MVAC (44). Voltage losses, complicated substation design, and insufficient safeguards also created barriers to high-speed DC rail systems (45), (29).

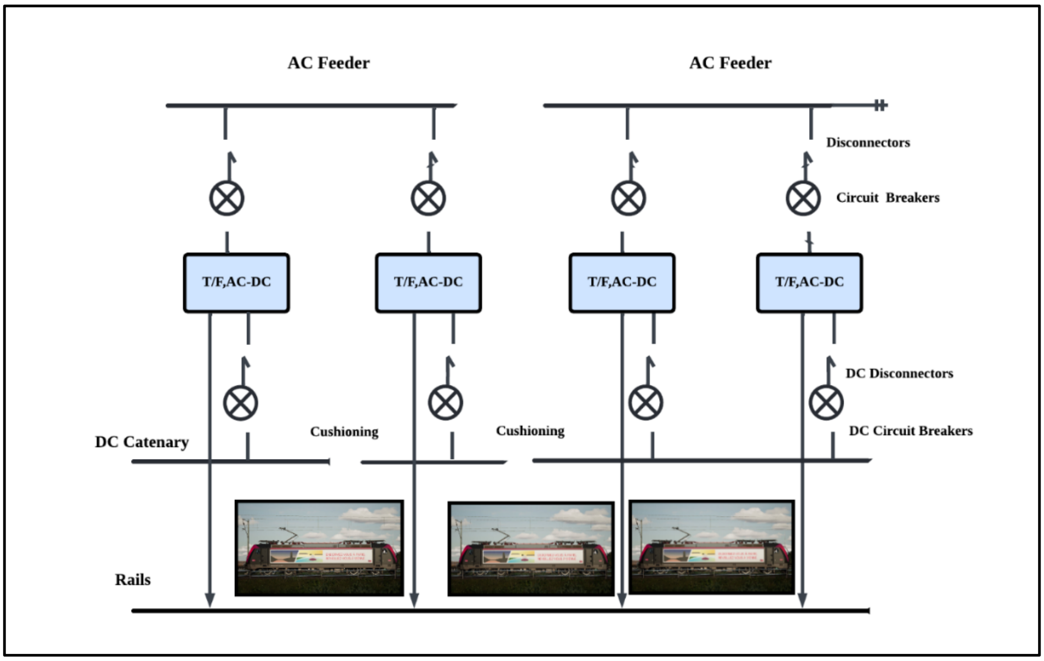

Fig.4 DC Rail Distribution System (44)

Innovations have been accomplished with MVDC technology, as well as is a considerable conversation about future distribution grids. Major advances are necessary for MVDC rail systems, especially eliminating the possibility of arcing, which diminishes power quality, radiates electromagnetic emissions, boosts temperature, and harms contact wires and strips. Applications for MVDC systems include DC rail distribution systems and standard AC ship applications (38), (47), (48).

MVDC LINK IN DISTRIBUTION SYSTEM:

Case studies on real distribution networks were carried out to assess the viability of MVDC link installation with GT-based control mechanism (23). The following contributions of this work include:

(1) promoting the GT-based control method, a revolutionary real-time MVDC link control technique that only requires communication links among the MVDC link controller and the grid transformers.

(2) developing control strategies that taken into consideration a number of objectives, comparing the network efficiency of different control methods, and investigating how an MVDC link affects the study's distribution networks performances.

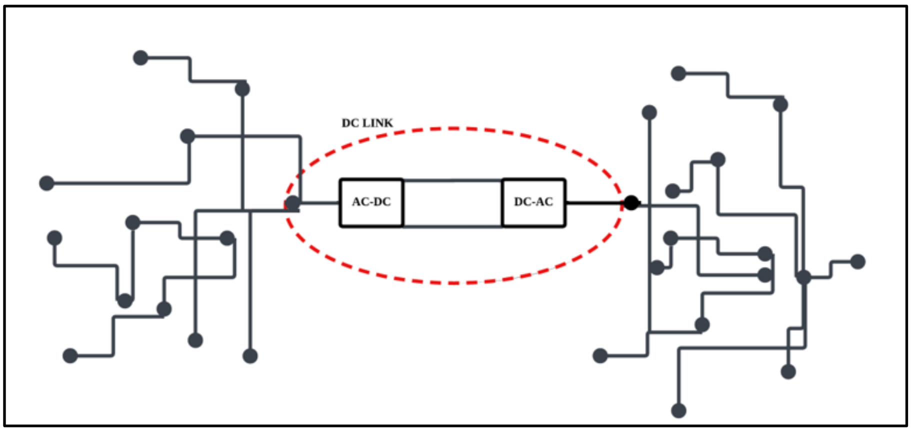

Fig.5 MVDC link between two distribution networks (49)

Fig.5 shows the setup of an MVDC link between two distribution systems linked with fully controlled voltage source converters (VSC) at either end in order to convert ac to dc and dc to ac. In MVDC cables, real and reactive power can be transferred between the two sides. The following controls are accessible on the voltage source converter: (V ac) iv) AC; (V dc) ii) Active strength (P); (iii) Reactive strength (Q); AC frequency (f) v) voltage (V ac). The following restrictions are shown while presenting an MVDC connection to evaluate how an MVDC interface affects network tasks. i) Capacity restrictions; ii) Reactive power limits; iii) Active power constraints, etc. Control curves for the MVDC link must be derived offline using historical data, and this past data has an impact on the control curves' performance. It is necessary to overcome the not being applicable of control curves, changes un network configuration, and the requirement for new offline studies. Research was done on the MVDC link performance of an electric distribution system with large penetrations of distribution generation (50).

The set points of the intended real-time control of the MVDC link were determined using active power flow at the grid transformer (51). Techniques for control that balance feeder loads, minimize power loss, and enhance voltage profiles. By employing the MOPSO method in offline research, some control techniques were developed. An MVDC link has the potential to increase the distribution network under consideration's hosting capacity for distribution generation by up to 15% as compared to AC operation.

BENEFITS AND ADVANTAGES OF MVDC:

Improving power supply reliability utilization, a MVDC link employs multiple power source converters to increase power supply dependability.

Increasing power supply capacity, compared to AC distribution, DC distribution offers a greater capacity for power delivery, which also expands the power radius.

Providing distribution interface for HVDC System, since the AC grid is not required for an MVDC system to link directly to an HVDC transmission system using a DC transformer, the number of conversion stages can be decreased and reliability can be raised.

Giving A Network Interface with high power DC sources, several high-power DC sources, including battery energy storage facilities, charging stations for electric vehicles, and converter stages with low cost and power loss, will be present in the future power grid. In Fig.1, the use of MVDC is depicted.

Utilization of cables, during transfer of AC power, the overheating of outer layer due to non-uniform current distribution with a conductor is called skin effect. Due to the non-isolating nature of DC current, the skin effect does not apply when DC power is transferred.

Here is a list of the advantages of MVDC technology:

- The capacity to transfer more power without adding new circuits is increased by using AC circuits at DC.
- Full control of power flows and better voltage regulation are made possible by MVDC technology.
- Network losses could be minimized with the right control approach. This decrease in network losses is substantial over the course of the assets' lifespan.
- In situations where thermal overloads or fault levels would otherwise occur, network NOPs could be stopped thanks to the degree of controllability provided by DC. As a result, the network's dependability might be increased.
- In some circumstances, the construction of a DC link could eliminate or postpone the requirement for a broader distribution network reinforcement. In situations where way leaves are likely to be a problem, an AC/DC conversion system could be implemented more quickly than a conventional reinforcement.

CONTROL METHODS

In order maintain power quality and promote increasing distributed generation penetrations, new techniques for voltage and power flow control require development (52).Grid transformer (GT)-based control techniques and a centralized control scheme are recommended for the MVDC Link (53). In a centralized control system, visibility throughout the entire network is required, which heavily depends on having the right communication infrastructure.

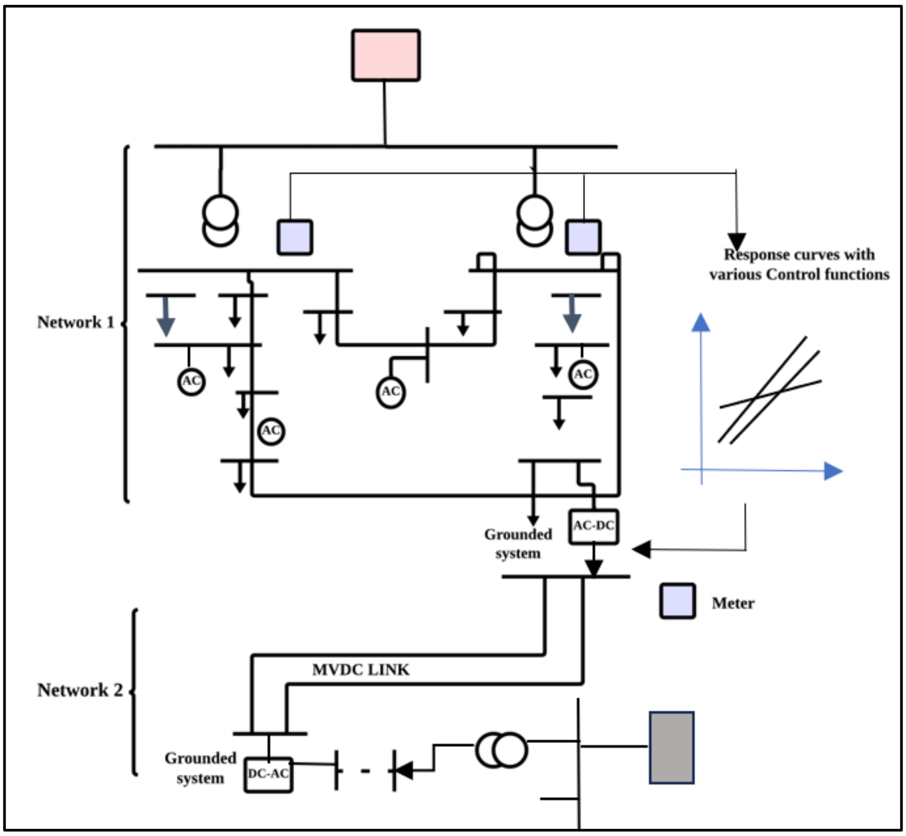

Fig.6 GT-Based control method (49)

On the other hand, GT-based control is less expensive and complicated. A possible GT-based control system is shown in Fig.6, where data is obtained directly from the grid transformer by the MVDC Link controller. Because of the high voltage and heat limits brought on by this problematic situation, Network 1 is much more concentrated than Network 2, as shown by the multiple huge distribution generators connected in Fig.6. Using a Grid Transformer based control strategy that makes use of the active power flow at grid transformers, the set-point of an MVDC Link was specified (54), (22), (23). Several objectives are taken into account by the control approach, including lowering power loss, balancing feeder loads, as well as improving voltage profiles. Some of the voltage control methods of smart distribution network are discussed (55).

CYBER SECURITY IN MVDC

Power systems have historically been managed by administrative control and data acquisition, or SCADA, systems. The SCADA system manages and regulates the electrical system's physical components, such as switches, breakers, transformers, and generators, from a centralized control center. The SCADA system is connected to these physical components by several communication protocols, including as DNP3, IEC 61850, and Modbus. Vulnerable communication protocols are often employed by SCADA systems, which makes it easy for attackers to access the system without authorization (56). Cyberattacks on power systems are malicious attempts to interrupt services by overloading the system with traffic, severing links between operators and equipment, or physically harming equipment (57). These attacks have the potential to cause operational disruptions such as blackouts, brownouts, frequency or voltage changes, equipment damage, or fires which makes detecting them crucial (58). In the recent past, cyberattacks against electrical grids had been deadly, driving down quick, broad blackouts (59).

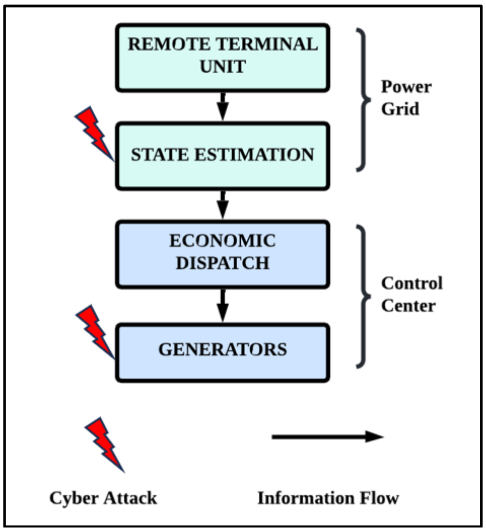

Fig.7 Cyber security and Threat identification

RESULTS AND DISCUSSION

To protect power systems from cyberattacks, comprehensive cybersecurity plans are to be tailored to the particular needs and vulnerabilities of the power grid must be put into action (60). Python programming offers a versatile toolkit for incorporating cybersecurity solutions in power systems. It is a good option for data analysis, task automation, and security policy creation because of its readability, ease of use, and extensive library support.

Python frameworks such as Scapy, PyCryptodome, and PyInstaller provide specific functionality including software distribution, network security, and encryption. In power systems, one of the primary objectives of cybersecurity is threat identification and mitigation. Python can be used to create intrusion detection systems (IDS) that track network activity, spot variations, and warn administrators of possible threats. By monitoring system logs and network packets, Python-based intrusion detection systems (IDS) are able to identify anomalous activity and quickly take precautions to lower risks.

Python programming can facilitate the implementation of security features such as access controls, authentication techniques, and encryption protocols. By developing special scripts and programs, cybersecurity professionals can put in place stringent security rules that are tailored to the particular requirements of power systems. Flask and Django are two examples of Python frameworks that provide for the secure online management of user access and authentication. In the event of a cyberattack, prompt incident response is required to minimize damage and get back to business as usual. Incident response methods can be improved by using Python's functions to automate forensic investigation, recovery, and incident triage procedures. Security teams can use Python scripts to collect and evaluate forensic data, uncover the main exposure site, and quickly take out necessary repairs.

CONCLUSION

The advantages of DC-link usage in distribution networks are discussed in this paper. A restricted distribution network will employ the DC link to control voltage and power flow at the same time. An MVDC link's dynamic operation under both faulted and normal network conditions was examined. Further research is required to understand its interaction with existing network devices during a fault. It is essential to incorporate the MVDC connection in the study of network failures in order to guarantee that it functions in harmony with the current distribution automation.

DC can now be used for the distribution of electric power more widely again due to developments in static converter technology, the use of renewable energy sources (like photovoltaic generation plants), and the emergence of new user categories operating directly in DC, such as data centers, electric vehicles, and distribution on board ships, especially military vessels (60).

The aims of this study are to provide a broad picture of the uses of DC, together with an understanding of the state of the art and possible future possibilities. The current distribution networks are under pressure due to the fast-rising demand and production. MVDC is a flexible approach for supporting the distribution network. It can help make the most use of the current network feasible by facilitating the incorporation of renewable power resources in the future.

Compared to centralized control, GT-based control significantly reduces the cost associated with communication and measurement equipment, even though it still requires measurement at the grid transformer. This control offers an effective MVDC link control method with the benefits of increasing network hosting capacity for distribution generators and reducing network losses. In order to prevent the spread of dangerous electromagnetic phenomena throughout the train network, research may be conducted in areas such as the DC railway system.

The researchers tend to concentrate on the application and viability of MVDC and LVDC systems (alternating current distribution systems) by establishing a comparison with the conventional distribution system. MVDC is starting to be considered as a technique to increase transfer capacity and power quality at distribution networks without affecting voltage variations, load flows, short-circuit levels, or phase angle variance-induced limits. The four-quadrant converters can support reactive power and control voltage at either end of the link, and multi-terminal is an additional option. One potential technological advance for the future is the conversion of existing AC lines to DC, which would improve current corridors.

It is crucial to use cybersecurity measures to protect MVDC systems in order to protect vital infrastructure from any cyber threats. These systems, which are growing ever more vital in many kinds of sectors including as electric automobiles and renewable energy, require robust defenses to be able to ensure uninterrupted operation and prevent hostile attacks.

To sum up, MVDC systems must be protected against evolving cyber threats by utilizing cybersecurity methods such network segmentation, access control, encryption, patch management, intrusion detection, firewall protection, employee training, and incident response planning. Organizations can improve the MVDC infrastructure's resilience and keep operations running in the face of hostile activity by implementing a multi-layered cybersecurity strategy.

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CONFLICT OF INTEREST:

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ETHICS APPROVAL:

This research was conducted ethically. All involved authors were consulted and asked for informed consent prior to their involvement, which meant that they were informed of the purpose and procedures of the study, the possible risks associated with it, and their right to stop at any time without repercussions. During the conduct of the research, confidentiality was maintained by adopting sound data management practices.

ABBREVIATIONS:

Medium Voltage Direct Current (MVDC)
Distributed Generation (DG)
High Voltage Direct Current (HVDC)
Low Voltage Direct Current (LVDC)
Medium Voltage Alternating Current (MVAC)
Uninterruptible Power Supply (UPS)
Demand Response (DR)
Distributed Energy Resources (DER)
Permanent Machine Synchronous Generators (PMSG)
Railway Electrification System (RES)
Grid transformer (GT)
Supervisory Control and Data Acquisition (SCADA)
Intrusion Detection Systems (IDS)

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