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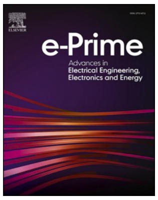

Stability and control of VSC-based HVDC systems: A systematic review

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ABSTRACT

The technological development in the area of power electronics has paved the way for the construction of High Voltage Direct Current (HVDC) systems. The utilization of HVDC grids alongside conventional High Voltage Alternating Current (HVAC) grids poses several challenges, especially, from stability and control points of view. Indeed, moving towards such systems in the context of conventional Alternating Current (AC) power systems cannot be possible without ensuring the overall stability of hybrid HVAC/HVDC grids. This paper analyzes different aspects of the stability of Voltage Source Converter (VSC)-based HVDC grids and presents various methods of improving stability based on a systematic and comprehensive review. In addition, this paper provides a concise classification of various control methods to improve the operation of such grids and the advantages of each method.

1. Introduction

Due to the increase in the use of Renewable Energy Sources (RESs), especially offshore wind farms, and the need to coordinate and integrate them into the existing power grids, the tendency to use overlay High Voltage Direct Current (HVDC) grids is increasing day-by-day [1,2]. Multi-Terminal High Voltage Direct Current (MT-HVDC) systems are a promising solution for the efficient integration of HVDC grids. One of the most important challenges in the deployment of MT-HVDC grids is protecting such systems against Direct Current (DC) faults [3–5]. The capacitive behavior of HVDC cables and their relatively low impedances lead to a significant increase in the DC fault current.

Using DC Circuit Breakers (DC CBs) is one of the most effective solutions for fast DC fault isolation [6–8]. Despite developments in DC CB technology, they still need relatively large DC reactors to limit the rate of rise of the DC fault current [9]. Capacitors and DC reactors connected to HVDC grids and inductance and capacitance of HVDC transmission lines are the determining factors in designing *LC* filters, which significantly affect the dynamic response of DC-link voltage and its instantaneous power in MT-HVDC grids, especially in long DC transmission lines [10].

There are two major power converter technologies for HVDC grids, namely thyristor-based classical technology, which are based on Line-Commutated Converters (LCC) and Voltage Source Converter (VSC) technology. Various types of HVDC converters are shown in Fig. 1.

VSC-based systems have numerous advantages compared to classical systems. Therefore, in recent years, due to the presence and development of VSC technology and its advantages over the LCC, it has had a prominent role in various HVDC projects [11]. Additionally, it has been proven that the Modular Multilevel Converter (MMC) technology has more advantages than the two-level and three-level VSC technology [12], and more focus should be on the development of HVDC grids based on the MMC technology [11,13].

From the stability point of view, in the case of an unexpected disruption or change in power systems, the traditional synchronous generators can supply the potential energy stored through their rotating parts [14]. One of the main factors in improving the stability of modern power systems is inertia improvement [15]. To date, various methods have been proposed to improve the system inertia. The presented methods in [16,17] enable the wind turbines to emulate inertia during the fault or disturbance on the Alternating Current (AC) side. In [17], the inertia of the system is emulated by controlling the output power of the inverter according to frequency oscillations. However, recovering/restoring the rotor speed after acceleration is the main issue with those methods. Although the presented time-derivative grid frequency control strategy in [18] is capable of adjusting the power and inertia via the LCC-HVDC converter, it has the same rotor speed recovery issue similar to the one presented in [17].

It should be noted that the controllability and flexibility of VSC-HVDC technology can improve the dynamics of the host AC systems.

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Nomenclature

AVR	Automatic Voltage Regulation
AC	Alternating Current
RES	Renewable Energy Sources
MICable	Mass-Impregnated Cable
XLPECable	Cross-Linked Polyethylene Cable
FDPM	Frequency-Dependent Phase Model
IGBT	Insulated-Gate Bipolar Transistor
SM	Submodule
SPDC − PFC	Serial-Parallel DC Power Flow Controller
FCL	Fault Current Limiter
PCC	Point of Common Coupling
GVD	Generalized Voltage Droop
SVC	Static Var Compensator
FGS − PLL	Fuzzy Gain Scheduling Phase Locked Loop
MPC	Model Predictive Control
LMI	Linear Matrix Inequality
SSO	Sub-Synchronous Oscillations
HVDC	High Voltage Direct Current
HVAC	High Voltage Alternating Current
MT − HVDC	Multi-Terminal High Voltage Direct Current
LCC	Line-Commutated Converter
VSC	Voltage Source Converter
DCCB	Direct Current Circuit Breaker
DC − PSS	Direct Current-Power System Stabilizer
MMC	Modular Multilevel Converter
EMT	Electromagnetic Transients
WPP	Wind Power Plant
FRT	Fault Right Through
FGS	Fuzzy Gain Scheduling
POD	Power Oscillation Damping
IPFC	Interline DC Power Flow Controller
PLL	Phase Locked Loop

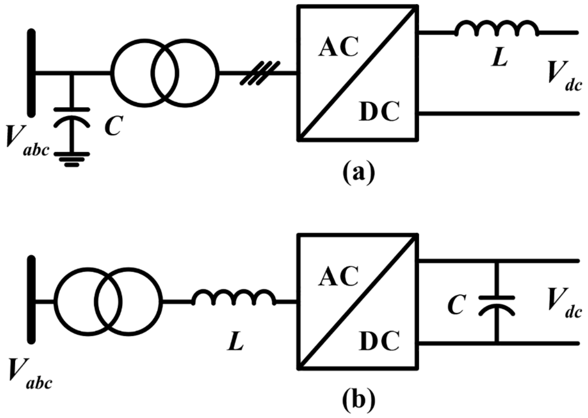

Fig. 1. HVDC converter technology: (a) LCC-HVDC, (b) VSC-HVDC.

However, large-scale power grids, which also have a large number of power electronic devices, can expect to have unwanted interactions with other grid components. Some of those interactions are identified and investigated in [19–26] due to the notable development of power electronic devices. Furthermore, in [27] and [28], the interactions among VSC-HVDC and STATic synchronous COMpensators (STATCOMs) are investigated.

Considering the previous research studies and the future trends in the expansion of HVDC transmission systems, the main focus of this paper is on the stability of VSC-based HVDC grids. Thus, the objective of this paper is to investigate the factors affecting the stability of VSC-based HVDC grids and to select proper methods to minimize the adverse impacts of such factors on the stability of VSC-based HVDC grids. This study analyzes various aspects of the stability of VSC-based HVDC grids and different methods of improving stability based on a systematic and comprehensive review. In addition, this paper provides a general classification of the various methods of stability improvement based on the operation and advantages of each method.

The rest of the paper is structured as follows. Section 2 describes the modeling of hybrid HVAC/HVDC grids. Section 3 presents a summary of the various control methods for VSC-HVDC converters. Section 4 discusses VSC-based HVDC grid stability issues. Section 5 provides recommendations for future research. Finally, Section 6 concludes this paper.

2. Hybrid HVAC/HVDC grids modeling

A typical configuration of hybrid HVAC/HVDC grids is shown in Fig. 2. It is well-known that hybrid HVAC/HVDC grids are beneficial as they can reduce transmission line loading, minimize operating costs, and increase the utilization of grid infrastructure by enabling higher power transfer capability. However, the overall efficiency of the system may be reduced as a consequence of power converter losses [29].

2.1. HVDC transmission lines model

2.1.1. Cables

The best option for long-distance offshore power integration into pwoer grids is to use cables. Depending on the cost and installation factors, Mass-Impregnated (MI) and Cross-Linked Polyethylene (XLPE) cables are widely used in VSC-based HVDC systems [30]. Currently, MI submarine cables are used up to 600 kV, and XLPE cables can only be used in VSC-based HVDC systems up to 400 kV (due to space charge phenomena) [31]. Among all the cable models, the most accurate model is the Frequency-Dependent Phase Model (FDPM) [32]. Therefore, with this type of modeling, it is possible to determine changes in the voltage and current along transmission lines for protection purposes. If a detailed cable model is not required in the analysis of a system, a simpler model can be considered for cable modeling [32]. In this regard, a mass model of the determining parameters of the cable, i.e., a series-connected resistor, a series-connected inductor, and a shunt capacitor, are added together to form a π circuit or a cascade π circuit [33]. Furthermore, the dynamics of DC cables can be removed from the

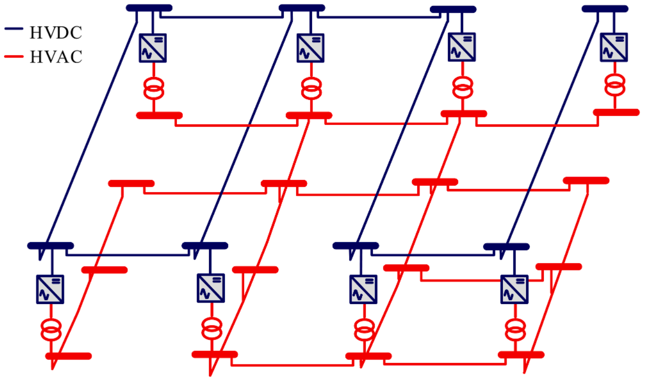

Fig. 2. A typical configuration of hybrid HVAC/HVDC grids.

calculations by showing pure resistance instead of the cable [33]. The representation of cables with an accurate frequency-dependent modeling is difficult in the state space, and it has a great deal of mathematical complexity. However, an accurate modeling of DC cables is very important for analyzing low-frequency oscillations in HVDC systems. In addition, in long cables, the lowest resonant frequencies within the cable determine the dynamics of HVDC converters [9,34,35]. Therefore, the importance of DC resistance and impedance characteristics in a wider frequency range in cable modeling cannot be ignored. Moreover, it is shown that disregarding the frequency-dependent characteristics of HVDC cables leads to a misleading assessment of traditional π-section models of the system [33]. Accordingly, a frequency-dependent π model (FD-π model) comprising a lumped circuit with several parallel RL branches in each π-section should be used to analyze the frequency-dependent characteristics of the cable [36]. Modeling of power converters and transmission lines are among the factors whose modeling has a great impact on the results of system analysis. In cable modeling, it should also be considered that a typical π-section model can show the performance of a cable only at a certain frequency. Therefore, an FD-π model can be used to analyze the frequency dependence of cable features [33]. Fig. 3 shows the cable model based on the π model [9]. Also, the cable model based on the FD-π model is shown in Fig. 4 [36]. In both figures, the number of the parallel branch is shown by m, and L_{br} and R_{br} are the inductance and resistance of the DC reactor, respectively.

2.1.2. Overhead lines

Overhead lines are used with both LCC and VSC technologies. Since overhead lines are always exposed to lightning and pollution, DC-link short circuit faults may occur due to insulation failure [37,38]. In MT-HVDC grids, this scenario can even be worse as non-permanent DC faults in each overhead line, which can lead to the instability of the entire grid. Since non-permanent DC faults in overhead lines are inevitable and the above scenario may occur occasionally, this severely undermines the reliability of power transmission systems. Therefore, to clear the fault and to perform an automatic and rapid system recovery, it is necessary to design a protection plan for non-permanent faults in overhead lines [37].

2.2. Converter stations modeling

As mentioned earlier, HVDC converter stations can be categorized according to their technologies, i.e., LCC-HVDC [39] and VSC-HVDC [40,41] technologies.

2.2.1. LCC-HVDC structure

In typical LCC-HVDC systems, each terminal consists of power converters, transformers, filters, power equipment, control systems, and other components. Due to some constraints, such as the Maximum Available Power (MAP) [42], voltage regulation, and susceptibility to commutation failure [43], the use of LCC-HVDC-based systems is more limited. In this regard, the main concerns are the complexity of the control system in a grid with several converter stations and the need for rapid communication links for the proper functionality of a central master control [44].

2.2.2. VSC-HVDC structure

VSC-HVDC systems can have significant impacts on power grids, and therefore, it is crucial to understand the dynamic behavior of power converters and their controllers under different operating conditions. Converters, including two-level and three-level types, are typically designed to maintain the voltage of DC-side capacitors at a nearly constant DC voltage level regardless of AC side current [9]. This type of power converter has a switching frequency of ∼1 kHz and consists of several power Insulated-Gate Bipolar Transistors (IGBTs) [45,46]. For the first time, MMC technology was proposed in 2002 and implemented in 2010 in the ±200 kV Trans Bay Cable project (San Francisco, CA) [47]. The linear small-signal MMC model is important for system stability analysis, and thus, the controller design and the dynamics of MMC should be considered in its design process. If the internal dynamics of the MMC are ignored, the MMC model can be simplified as a two-level VSC-HVDC system [48].

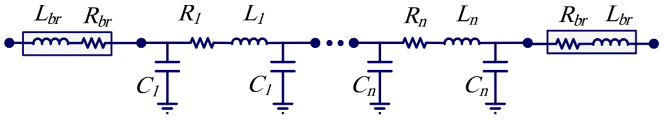

Fig. 3. The π model of power transmission lines.

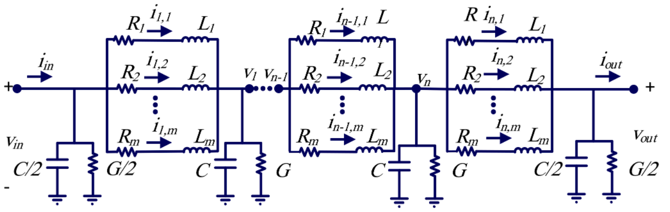

Fig. 4. The FD-π model of cable.

2.3. DC-DC power converters modeling

The methods of achieving DC-DC conversion in low- and medium-voltage are well-known [49–52]. However, it is not easy to use such methods in high-voltage grids. HVDC converters require the connection of several low-voltage components, such as power semiconductor switches [53] and/or low-voltage converters [50], which makes the direct use of classical conversion methods impractical. Rather than only the voltage regulation, advantages, such as power flow control, fault isolation, and interface of different DC transmission schemes, lead to more interest in using DC-DC power converters in HVDC grids [54–58]. An intelligent and fast pulse-width modulation-based type-II fuzzy controller for DC-DC boost converter is presented in [59]. The experimental results show that the controller has a faster and more robust response in comparison to the previously presented control techniques.

2.3.1. Voltage regulation

HVDC lines with various voltage levels need DC transformers for the integration into power grids [58]. However, it is not possible to use conventional transformers in HVDC networks for voltage conversion. There are different DC-DC power converter topologies for low-power applications, but most of those topologies cannot be easily utilized for hundreds of kilovolt and megawatt power ranges due to several technical constraints, such as power losses, operational costs, the size of the filters, and voltage rating of the semiconductors, etc. Therefore, new DC-DC power converter topologies based on modular structure have been recently presented that use the series connection of Submodules (SMs) instead of the series connection of semiconductors [60]. Based on galvanic isolation, two categories can be considered for new DC-DC power converter topologies, including isolated types [61–65] and non-isolated types [53,66–73]. In the presented method in [70], an additional SM branch is used at the low-voltage DC terminal to reduce the injected AC voltage. In [71], a specific type of DC autotransformer is introduced, in which a part of the total power is transferred through the AC transformer, and the remaining part is transferred through the DC branch. Also, a multi-port DC autotransformer topology is presented in [72]. In addition, a new hybrid cascaded DC-DC power converter is presented in [53], in which two branches of series-connected IGBTs and one branch of cascaded SMs are used. The voltage stability by considering the integration of MMC and LCC-HVDC into the Norwegian power systems is studied in [74].

2.3.2. Power flow controller

To mitigate line overloading and grid bottlenecks, a power flow controller is presented in [75,76]. Accordingly, compared to the costly solution of establishing new HVDC lines, power flow control in MT-HVDC grids has attracted research interests [77,78]. Some previous research studies in the literature introduce different DC-DC power converter topologies [54,79] and some introduce multi-port topologies for connecting to any number of transmission lines [80–82]. An efficient control framework that utilizes DC-DC power converters to achieve flexible power flow control in MT-HVDC grids is presented in [79]. The power flow control through a power converter with a different connection using a Serial-Parallel DC Power Flow Controller (SPDC-PFC) is investigated in [54]. The presented method in [83] for a multi-port interline DC power flow controller has fewer switches and series-connected diodes.

2.4. Fault current limiters and DC circuit breakers

According to the research conducted by CIGRE, the fault current is one of the most serious challenges in HVDC grids, because its rate of rise is very high and it reaches its maximum level within a few milliseconds. Therefore, it is necessary to design a controller with additional capabilities to limit the rate of rise of the fault current in its early stages. The use of Fault Current Limiters (FCLs) is a promising solution [84–89]. FCLs can be classified based on their operating principle and the key technological components. Generally, the method of implementing FCLs can be divided into several categories, including passive nonlinear elements [90–92], inductive devices [93,94], semiconductor switches [95, 96], and classified hybrid approaches [97–99]. However, due to power constraints and requirements related to the semiconductors and superconductors, few of them are appropriate for HVDC grids. The DC fault current waveform includes a high-frequency fault factor. Hence, one of the most effective developed methods is the use of a large inductor in the FCL structure, which can provide a very large impedance to the system with a high-frequency component [100,101]. Also, due to the dependency of the decaying constant δ of the fault current in HVDC systems on the inductance L, an effective solution is to increase L and reduce the rate of rise in the fault current [102].

In addition to some specific topologies designed for fault tolerance [103], VSC-HVDC converters have an inherent weakness of over-current [104]. The capacitive behavior of HVDC cables and their relatively low impedance leads to an increase in fault current. By blocking VSCs and transforming them into uncontrollable diode bridges to protect the switching devices, the entire HVDC grid should be shut down, which is undoubtedly unacceptable. Therefore, DC CBs are considered the most effective method for rapid fault isolation [105]. Even though, DC CBs are being manufactured with very short failure times, large DC reactors are still required to limit the rate of rise in fault current [106]. The breaking time and breaking capacity determine the size of this reactor (>100 mH) [9,107], which can lead to dynamic instability [9]. In HVDC grids, an important parameter of VSC stations connected to power grids is the DC-link voltage, which is determined based on voltage ripple and dynamics of controllers [108,109]. It should be noted that due to the advancements in MMC-based converters technology, connecting a large DC-link capacitor to DC grids is no longer required, but there are still some concerns about the inductive DC network problem for DC CBs and long DC lines [9]. The presence of a DC reactor leads to increased losses and affects the stability of the system. This is due to the fact that using a large DC reactor in any of the transmission lines of HVDC grids can lead to adverse fluctuations in DC voltage, and even, instability. In addition, increasing the size of the DC reactor reduces the propagation rate of dynamic changes in DC current from one terminal to another [9]. In addition, capacitors and inductors that are connected to DC grids and inductors and capacitors in DC transmission lines create an LC filter. This filter affects the dynamic response of DC-link voltage and power in HVDC systems, especially in long transmission lines. Therefore, the role of inductances and capacitances cannot be ignored [110]. Different parts of modeling a typical VSC-based HVDC system are shown in Fig. 5.

3. Control of VSC-HVDC power converters

Generally, the control system of VSC-HVDC stations has a cascade structure. The structure of the VSC-HVDC controller is shown in Fig. 6. The external controller (high-level) of power converters is usually based on vector control, which is responsible for controlling the input and output variables of the AC-DC converter. However, the structure of the internal controller (low-level) varies depending on the converter type.

As is shown in Table 1, a VSC-HVDC station may be connected to an AC grid or an offshore Wind Power Plant (WPP). According to Table 1, the outer controllers of power converters perform specific tasks. In cascade controllers, higher-level controllers operate at higher bandwidth and lower-level controllers operate at lower bandwidth [111, 112]. Typically, in an ideal system, the performance range of the lower-level controller must be at least 4 times (up to 10 times) faster than the previous higher-level control [113].

3.1. Low-level control

In HVDC grids, the lowest level of control in a hierarchical control structure must operate independently and maintain the system operational and stable without the need for external communication channels. The DC-link voltage can be used as a global decision-making parameter, and the control actions can be performed locally based on the DC-link voltage.

Since, in HVDC grids, each converter is part of a larger grid, controllers may have different control objectives, such as voltage margin control and droop controller [114–116]. In a voltage margin controller, which is an extended version of master-slave control, if the DC-voltage regulating converter fails to operate, the DC voltage stability is compromised. In the control scheme presented in [117], two or more converter stations of an HVDC grid are equipped with a droop controller and the rest of the converters have a power controller. In the case study of [117], several converters are involved in controlling DC voltage. A Generalized Voltage Droop (GVD) control strategy for control and power sharing in voltage source converters is presented in [118]. In the presented approach, the conventional voltage droop characteristics of voltage-regulating VSC stations are replaced by the GVD characteristics. The presented GVD control strategy can be operated in three different control modes, including conventional voltage droop control, fixed active power control, and fixed DC voltage control by proper adjustment of the GVD characteristics of the voltage-regulating converters. Hence, if a terminal is disconnected, the rest of the converters ensure the DC voltage stability, which is also called the master-salve with droop control. However, this control scheme is suitable for small-scale DC grids, and using it in larger grids requires difficult synchronization. Also, the primary control leads to inefficient use of the grid capacity. The

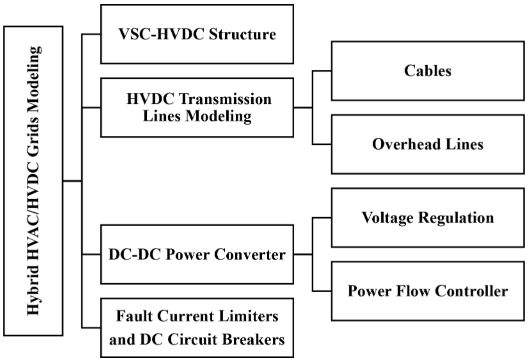

Fig. 5. Different parts of modeling a typical VSC-based HVDC system.

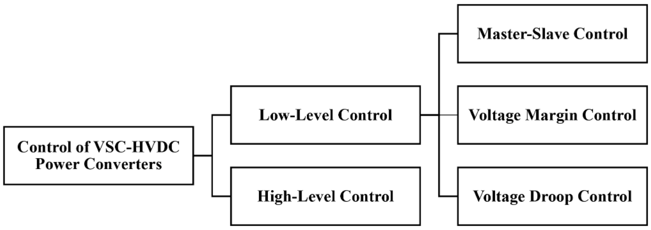

Fig. 6. The structure of the VSC-HVDC controller

Table 1
Control of VSC-HVDC Power Converters

Controllers for VSC-HVDC Power Converter	
VSC-HVDC Converter Connected to an AC Grid	VSC-HVDC Converter Connected to an Offshore WPP
• DC-Link Voltage (V_{dc}) Control	
• Input/Output Active Power Balance (P_{ac})	• AC Voltage Magnitude Control
• Reactive Power (Q_{ac}) or AC Voltage (V_{ac}) Control	• AC-Side Frequency Support
• Support for Point of Common Coupling (PCC)	

classification of such methods is shown in Table 2.

Low-level control strategies include master-slave control strategy [119], voltage margin control strategy, and droop control strategy [120].

3.1.1. Master-slave control strategy

In the master-slave control method, the main power converter should perform voltage control, and the rest of the power converters should regulate the flow of power. The main problem in this strategy is the instability due to not considering the reliability of the entire network. Therefore, DC voltage control is completely at risk and correct operation cannot be guaranteed in case of the main power converter outage [121]. In addition, in this control strategy, the main power converter should be connected to a stiff AC grid to ensure the quick conditioning of DC grids and avoid negative impacts on the AC side. However, the master-slave control is a suitable method for practical MT-HVDC systems, such as the current Zhangbei, Nan'ao, and Zhoushan HVDC projects in China. Since this type of control is suitable for power dispatching, the DC voltage control backup power converter is developed in the main control for fault conditions [122].

3.1.2. Voltage margin control

The voltage margin control method can be considered as an extended form of the master-slave strategy. In this control method, there are special power converters that are responsible for maintaining the DC voltage if the power exceeds its normal limits [123]. In addition, in this control method, backup power converters can be used to regulate the DC voltage in an emergency case [124]. In this control method, the main problem is instability, because changing the main power converter can lead to fluctuations in the DC voltage. It is also necessary to correctly choose the magnitude of the voltage margin as considering a small value for the voltage margin causes unnecessary displacement of the main power converter, while too high a value may lead to under-utilization of HVDC systems capacity [115].

Table 2
Comparison Among Low-Level Control Approaches

Presented Methods	Advantages	Non-Analyzed Topics
Voltage Margin Control	Reliable operation of HVDC systems without the need for fast communication systems	DC voltage instability due to the loss of DC voltage-regulating converters
Droop Control	Acceptable load sharing	Difficult coordination and complicated parameter tuning process when used in large-scale grids
Master-Slave with Droop Control	Acceptable load sharing and voltage control	Non-efficient use of DC network capacity due to the primary choice of a converter and complexity of the control scheme due to the large number of converter stations

3.1.3. Voltage droop control

Unlike the master-slave and voltage margin control strategies, which are based on centralized control, droop control is a decentralized control strategy [125]. Nowadays, droop controllers are very popular; however, this type of controller has limitations for some converter stations. Among these limitations is that this control scheme is not able to guarantee constant DC voltage and power sharing in all control modes. In [118], a uniform control strategy for DC voltage regulation and power sharing in HVDC networks is presented. In [126], a DC-PSS is added to the droop controller; however, in this method, the DC-PSS input signal is supplied from battery energy storage systems.

3.2. High-level control

It is well-known that the purpose of high-level control in HVDC systems is similar to the secondary control of AC systems, meaning that the high-level control is responsible for generating reference signals for the local controllers. In high-level control of HVDC grids, the power control loop (or optimal power control loop) provides an optimal setting for the outer controller [15]. In general, for HVDC grids and in the steady-state, the main objectives of the high-level or secondary control layer are as follows:

- Correcting and maintaining the power exchange across the entire grid
- Controlling the DC voltage

In a high-level control structure, the lower-level control always operates much faster than the upper control layer. In HVDC grids, unlike AC systems, where the frequency is a global parameter and is only monitored, all DC-link voltage must be controlled. In this regard, a DC voltage control and power sharing strategy for HVDC grids based on an optimal method of power and voltage-droop control is presented in [15, 127].

4. VSC-based HVDC grids stability

This section investigates the impacts of HVDC power converters and their control systems on the stability of VSC-based HVDC grids. In addition, various control and stability methods for grid stability are mentioned in this section. An investigation of previous research studies on stability shows that stability in power systems can be divided into several basic categories, including voltage stability, angle stability (under small and large disturbances), and frequency stability [128,129].

4.1. Voltage stability

In [130], the simultaneous impacts of LCC-HVDC and VSC-HVDC on a similar bus to check the voltage stability are investigated by considering the $P_{ac} - Q_{ac}$ controller and the $V_{ac} - Q_{ac}$ controller. Some issues with designing LCC-HVDC are the susceptibility to commutation failures, voltage regulation, and maximum available power in a weak network. Several structures are common for controlling the voltage, among which a vector control structure with an internal current loop is more common. This controller provides better performance compared with resonant controllers in steady-state and phase errors [113,131].

The advantages of the method presented in [130] are the improvement of the maximum available power and the reduction of overvoltage. Due to the variety of controllers for HVDC systems, the stability of voltage of LCC-HVDC systems is investigated in the literature using VSC-HVDC and LCC-HVDC [132–134]; however, those research studies use a simplified model of AC grids. Despite the independence of voltage controllers in VSCs, the interaction among power converter controllers has been the subject of many recent research studies. In [135], the interaction between the dynamics of load and LCC-HVDC without considering the dynamics of AC systems is discussed. As investigated in [136,137], the use of the DC Power System Stabilizer (DC-PSS) can reduce the DC voltage oscillations caused by the DC reactors and improve the stability of the entire grid.

The dynamic and static models of the load with the impact of the current limitations are considered in [138] to determine their consequences on $P_{ac} - Q_{ac}$ and $V_{ac} - Q_{ac}$ control methods. The voltage stability by considering the integration of MMC and LCC-HVDC into the Norwegian power systems is studied in [74]. A new control method is introduced in [139] by adding an extra control loop to the secondary control system. Also, a control algorithm based on the eigenvalue sensitivity is presented in [140] to improve coupling capabilities and enhance the quasistatic voltage stability. A modified droop control structure for simultaneous power sharing and DC voltage oscillation damping in MT-HVDC grids is presented in [120].

Table 3 shows the summaries of the aforementioned methods based on their advantages and analyzed topics.

4.2. Angle stability

4.2.1. Small-disturbance angle stability

The small-signal rotor-angle stability of power grids should be considered in the design process of VSC-HVDC stations. The controllers affect the electromechanical behavior of AC systems and stabilize the low-frequency oscillations of power systems.

In [141], the impacts of VSC-HVDC link control and bandwidth on the electromechanical conditions of AC systems are investigated. From the analysis of a systematic comparison of the reduced model and the realistic model of the British system, it can be concluded that DC-link performance, the structure of the network, and control of the AC voltage have direct impacts on the inter-area oscillations of the host AC system. This method has no significant overshoot, but has a 10%-90% rise time of 0.1 s with no steady-state error. In [142], the dynamic interactions between an HVDC network based on MMC converters and the AC system following AC disturbances are investigated. The controllability of MMC-VSC-HVDC systems on inter-area and local oscillations in interconnected power systems are studied in [143]. The procedures for tuning a parameter of the general Power Oscillation Damping (POD) considering the impact of the Automatic Voltage Regulator (AVR) and the marine WPP constraints are addressed in [144]. The presented method in [145] provides maximum relative control capability without the need for connection among DC terminals in Nordic 32.

Tuning parameters of PI controllers may result in a higher overshoot, settling time, and steady-state error [146]. The presented controller in [147] shows reasonable performance for coordinating control between the VSC-HVDC network and offshore wind generation networks. However, the possibility of employing such a multi-faceted controller in an accurate system requires extra thorough evaluation. POD based on H_∞ complex sensitivity theory for MT-HVDC grids is presented in [148]. It should be noted that the strategy of the controller using the H_∞ mixture sensitivity theory suffers from poor selection of weighting function. The enhancement of the small-signal stability of power systems is given by the optimal controller allocation within VSC-HVDC systems [149]. However, the presented controller has an incomplete scenario. A robust control strategy using a finite set of non-local signals for multiple embedded DC links is presented in [150].

Table 3
Comparison of Voltage Control Methods of VSC-HVDC Power Converters

Presented Methods	Test Systems	Tuning Methods	Advantages	Non-Analyzed Topics
[74]	Norwegian power systems with LCC and MMC	Yes	Improving the AC voltage regulation	Disregarding the impacts of the controller on the overall stability of the system
[130]	LCC and VSC stations with a single generator in a host AC grid	No	•• Improving the maximum available power • Reducing voltage transients	Disregarding AC system dynamics
[135]	LCC and VSC stations with two generators in a host AC grid	No	Providing the interaction between the dynamics of load and LCC-HVDC	Disregarding AC system dynamics
[138]	Power systems in western Denmark with LCC, VSC, and two generators in a host AC grid	No	• Considering various load models • Examining the impact of current limitations • Providing an adaptive current limitation scheme to overcome the constant current limitation in VSC-HVDC systems	Disregarding the impacts of the controller on the overall stability of the system
[139]	A network including three connected areas by AC overhead lines with DC lines in parallel with two 380-kV AC overhead lines	No	Supporting the dynamic voltage after short circuit faults	Providing little information and limited results about the control scheme
[140]	6-bus and 118-bus test systems with and without Static Var Compensators (SVCs)	No	Providing supplementary control algorithm based on the eigenvalue sensitivity that utilizes the capabilities of VSC-based embedded HVDC systems	Disregarding the case for all MT-HVDC systems

An alternative control method for a VSC-HVDC point-to-point link is presented in [151] to mimic the behavior of synchronous generators. However, it should be noted that the presented controller differs from well-established vector control. A full characterization of the acceptable power injections of dynamically controlled HVDC links is presented in [152]. One of the factors affecting the small-signal stability is the VSC-HVDC design, which can significantly change the overall stability of the system [153].

Table 4 shows the categorization of the above-mentioned methods based on their merits and not-analyzed topics.

4.2.2. Large-disturbance angle stability

Modeling of VSC-HVDC systems by considering transient stability conditions is investigated in [154]. Despite the significant impacts of the complexity of modeling and bandwidth control on the transient stability of the system, the provided results are not generalizable as the system is not a complex one, and VSC-HVDC systems control parameters are not

Table 4
Methods for Small-Disturbance Angle Stability

Presented Methods	Test Systems	Tuning Methods	Advantages	Non-Analyzed Topics
[141]	• A classical two-area AC system with a point-to-point VSC-HVDC link • United Kingdom transmission system with detailed models of the generator, excitation systems, and PSSs	No	Demonstrating of probable negative impacts of the controller on AC voltage fluctuations	• Disregarding the limitations in a simple general model of an AC voltage controller • Disregarding the network code adaptation current limitation scheme for AC side faults
[142]	5 MMC stations and 10 turbine generators	No	• Utilizing each MMC as a fixed power supply to operate during transient electromechanical fluctuations • Improving dynamic interactions between AC subsystems that are only connected via the HVDC network	• Not giving the information of controllers • Disregarding the impacts of different control approaches • Disregarding the dynamic interaction during DC-side disturbances • Not contributing to damping of the AC system oscillations during AC-side disturbances
[143]	A two-area power system connected by a point-to-point HVDC system with three generators in AC side	No	Demonstrating the controllability of MMC-VSC-HVDC systems on inter-area and local oscillations in interconnected power systems	Disregarding the dependence of the model for dynamic behavior reproduction on parameter recognition techniques
[144]	IEEE 12-bus system with VSC-HVDC at Bus 1	No	Providing power oscillation damping on offshore wind power plants by modulating active and reactive power injection	Disregarding the coordination between active and reactive power modulation
[145]	Nordic32 test system	No	Providing maximum relative control capability without the need for connection among DC terminals	Unacceptable performance during major events, such as disconnection of the power converter pole or AC line without a robust damping controller
[147]	An offshore wind farm connected to a mainland AC grid via VSC-HVDC links	No	Providing a coordinated power oscillation damping control through offshore wind farms and onshore VSC-HVDC power converters	A lack of explanation of the implementation of the presented method in HVDC systems and also a lack of comparison of the performance of the presented controller with the existing methods
[148]	A 6-machine 3-area system and a 16-machine, 5-area system	No	Designing a damping controller based on H_∞ mixed-sensitivity formulation in the Linear Matrix Inequality (LMI) framework	Providing a poor selection of weight performance in design
[149]	Four-machine grid with two-area test system and a VSC-HVDC link	No	Improving small-signal stability of power systems by the optimal controller allocation in VSC-HVDC systems	Providing an incomplete scenario
[150]	Multi-infeed with two DC links	No	Reducing communication delays	Considering a simple network (point-to-point DC links)
[151]	Weak AC systems consist of a DC line with two synchronous units	Yes (residues method)	Providing a control strategy of HVDC transmission yielding increased power transfer capacity and enhanced transient stability of weak interconnected systems	A lack of detailed analysis and validation
[152]	A two-area AC system	No	Deriving the HVDC constraint set based on the AC grid model and the original voltage and current bounds	Using a simple AC network model
[153]	CIGRE test system	No	• State-space and small-signal analyses based on the linearization about an operating point and calculating the eigenvalues • Improving the stability of MT-HVDC by ensuring the optimized value of the DC-link capacitor and tuning the controller	Using non-exact conventional models to describe the dynamic characteristics of the system, especially when the filter cutoff frequency is close to the switching frequency

well-determined. The impacts of VSC-HVDC systems on the transient stability of the Belgian network are investigated in [155]. The impacts of both VSC-HVDC and LCC-HVDC power converters on transient stability with different HVDC control strategies are analyzed in [156], and it is evident that the improvement in the VSC-HVDC systems performance in some operating conditions is significant compared to the LCC-HVDC one. In addition, the current constraints on power control of VSC-HVDC systems affect the transient stability of the AC system. The results of the transient stability analysis for the Danish power system are presented in [157]. The amount and direction of the power in HVDC links have a significant impact on transient stability [158].

The dynamics of AC-DC systems using Fault Ride Through (FRT) after a fault is discussed in [159]. The test system in [159] is a realistic model representing the future power system of northwestern Europe. It is also shown that as the topology of the system does not have much impact on transient stability, the rate of active power recovery can affect the improvement of transient stability.

In [160], it is noticed that the parameters of the droop controller significantly affect the AC-DC system dynamics. However, the structure of the HVDC network has a slight impact on the interactions. The impacts of the controller of power converters and Phase Lock Loop (PLL) parameters on the transient stability of AC systems are investigated in [161]. To ensure the precise operation of the power converter's inner current controller, it is important to estimate the grid frequency, which is achieved by the PLL [162]. It is shown in [163] that by adding additional transfer functions, a more accurate model can be achieved to evaluate PLL dynamic effects and delayed measurements. In [164], a Fuzzy Gain Scheduling PLL (FGS-PLL) is presented that has a robust performance in severe voltage drops and even phase jump conditions. In the presented method, a fuzzy gain scheduling technique is used to adjust the proportional and integral gains during amplitude, phase, and frequency changes in the grid voltage waveform to create a flexible PLL. In [165], it is indicated that fast control of AC voltage can improve the transient stability of the system. Since changing the reactive power mode can change the angular separation between generators and affect the transient stability of the system, it is necessary to consider different active and reactive power for various control modes [166,167].

A method for correctly placing power electronics-based devices, such as VSC-HVDC systems, is presented in [152] to improve transient stability. However, the stability of AC systems should be considered during the HVDC network planning stage [168–170].

A supplementary active power controller is employed in [171] to improve the transient stability of the system. However, the results provided in [171] for a simple system cannot be generalized to other types of external controllers. A supervising global Model Predictive Control (MPC) based on the relative frequency error between the AC system and generators for VSC-HVDC systems is presented [172] to improve the transient stability. A transient stability improvement method based on MPC for the representative Great Britain system is also provided in [173]. However, since MPC design for large systems is complicated, the possibility of using such a control method in real power systems is not assessed. In [174], VSC controllers for MT-HVDC transmission systems are used and it is shown that the peak overshoot of the MPC controller with a value of 2.86 is smaller than the PI controller with a value of 8. In [175], the time optimal power injection modulation control strategy for HVDC systems based on Lapanov's theory with the aim of rotor angle stability of AC systems is presented. A robust control-based modulation slider is presented in [176]. Although, this method has a problem with nonlinear control in power systems. The impacts of local frequency and mean weight in power loops on transient stability are investigated in [177,178].

One of the common phenomena in power systems is low-frequency inter-area power oscillations [179], which are in fact the main reason for cascading failure [180]. Damper windings of modern synchronous devices and digital electronic control systems cannot effectively reduce intra-area fluctuations without measuring the global signal [181]. In [181], a concept called homotopy is used to derive a diagonal block controller from a set of full controllers to ensure specified closed-loop performance for various operating conditions.

Table 5 summarizes the aforementioned methods based on their advantages and non-analyzed topics.

4.3. Frequency stability

Despite the limitations of DC voltage controller and the choice of droop rate that can disrupt the design performance, the frequency control based on droop control in onshore converters is presented in [182–184]. The impacts of changing the gains of the droop controller of VSC-HVDC systems to support the AC frequency system are discussed in [185]. To support system inertia, a controller for artificial inertia is presented in [18,186,187] that relies on the energy of the DC-link capacitor. The advantage of this method is that it can reduce the time delay problem of communication by limiting the amount of intrinsic energy available in VSC-HVDC systems with the capacitor size. In [188], a method for the simultaneous use of capacitor energy of VSC-HVDC and WPP inertia to initial frequency and inertia support for a point-to-point HVDC link is presented. The scheme presented in [189], which is based on a DC voltage management strategy, regulates the active power so that each terminal in HVDC systems has a minimum frequency slope. The presented cascading control method in [190] for a four-terminal HVDC network demonstrates the effectiveness of a communication-less frequency response mechanism. A method for the load angle synchronism of a synchronous machine for inertia mimicry control is emulated in [191]. An integrated reference controller for the control and operation of HVDC networks is presented in [192]. In [193], the issues with the possibility of exchanging primary reserves are investigated in an HVDC network that connects asynchronous AC networks. In [194], a distributed dynamic controller is presented for sharing both frequency oscillation damping and restoration reserves of asynchronous AC systems connected via HVDC links. Moreover, this control strategy can optimize the performance of HVDC systems by minimizing the quadratic cost functions of voltage deviation and power generation.

Compared to the conventional two-level VSCs, the MMC needs more complicated internal controllers to properly control the system dynamics. Additionally, the internal energy storage of the MMC may provide a potentially enhanced capability to stabilize the AC systems as well as the DC networks [180]. A dynamic controller for frequency control and restoration of asynchronously connected networks via HVDC networks is presented [194], which uses only local information to tune the controller and adjust the DC voltage in HVDC systems.

Table 5
Technical aspects related to large-disturbance angle stability and HVDC link

Presented Methods	Test Systems	Tuning Methods	Advantages	Non-Analyzed Topics
[154]	MMC and VSC-HVDC models	No	• Model complexity with a significant impact on transient stability • Comparing the transient stability dynamics of various mixed AC-DC models with different generators and VSC-HVDC models.	Not properly defining the parameters of the controllers
[156]	A two-area four-machine power system without an HVDC link	No	Improving transient stability of HVDC links generally by increasing the critical clearing time	Reducing transient stability through inappropriate handling of current limits of VSC by reducing either active or reactive power
[159]	The future Northwestern European power systems	No	Providing several important sensitivities, such as FRT implementation, the post-fault active power-recovery rates, the AC network dynamic characteristics, and the HVDC topology	Not delivering continuous active power to the system during the fault condition
[161]	MMC and VSC-HVDC models	No	Investigating the dynamic behavior of PLL on system stability	• Longer time required for nonlinear simulation • Providing less information about stability and oscillations of the system observed in the time-domain responses
[165]	A synchronous generator, an MMC-VSC system, and Thévenin equivalents of large power systems	No	• Improving transient stability improvement by using a VSC with fast AC voltage control • Using the critical fault clearing time as the indicator of the stability of power systems	Disregarding different reactive power injections for reactive power control modes
[171]	A VSC-HVDC system connected to a synchronous generator	No	Improving the transient stability by supplementary active power controller	Analyzing the performance of the presented method in a simple system
[173]	Great Britain system	No	Providing coordinated control action without limiting pre-fault transfer levels	A lack of testing the presented method in real power systems

(continued on next page)

Table 5 (*continued*)

Presented Methods	Test Systems	Tuning Methods	Advantages	Non-Analyzed Topics
[175]	Nordic32 test system	No	Power oscillation damping of an AC system by active power injection	Disregarding the interactions in the control loop and effects on the performance of controllers

Controller interactions at a higher frequency range (100-1000 Hz) are challenges due to the increasing number of power electronics-based devices [195,196]. It is shown in [196] that resonances in the control system can lead to instability of HVDC systems. The impacts of controllers and their bandwidth on the system stability are investigated in [197], and it is shown that MMC-HVDC systems have much more complex internal dynamics. Similarly, in [198], the impacts of the ratio between the bandwidths of the interconnected areas are assessed by analyzing the Sub-Synchronous Oscillations (SSOs) and harmonic resonance in the interconnection of a WPP and VSC-HVDC systems.

In [199], by retuning the control parameters and using an artificial bus for converter-grid synchronization, the dynamic stability of HVDC systems of VSC-HVDC systems is improved. Time domain simulations with Electromagnetic Transient Analysis (EMT) for evaluating the harmonics based on HVDC-MMC links are presented in [200]. In addition, the harmonic analysis of a system with an MMC-HVDC link connected to AC grids is presented in [19]. It is shown in [201] that operation in less wind conditions can cause instability of HVDC systems. A state-space method in [202] is presented to evaluate the interaction between a network with a simple structure and MMC-HVDC links. It is observed that the weak internal state of MMC can be a source of instability [202]. One method for evaluating stability in HVDC systems is the impedance analysis method. The impact of VSC-HVDC systems on the sub-synchronous damping characteristics of a nearby synchronous generator is assessed in [203] and the power synchronization control strategy instead of the conventional vector control is applied to VSC-HVDC systems. According to field experiences, it is noticed that SSOs mainly occur in direct-drive wind farms with VSC-HVDC systems. In [204], a dynamic mathematical model of direct-drive wind farms with VSC-HVDC systems is developed in which the characteristics of SSOs are analyzed through the eigenvalue method. It is also reported that by considering the participation factor, SSOs should be affected by the grid-side converter controller of wind turbine units, VSC-HVDC rectifier controller, and also the system parameters.

Table 6 shows the major characteristics of the aforementioned methods, which are based on frequency stability.

5. Recommendations for future research

As mentioned earlier, challenges associated with stability and control are among the major issues in developing HVDC grids alongside conventional AC power systems. The main discussion about stability and control strategies can be summarized as follows:

- Most case studies are small-scale experimental testbeds and/or prototypes under laboratory conditions.
- Since HVDC grids are overlaid on conventional AC power systems, the dynamics of AC systems must also be considered in stability determination and improvement.
- Due to the use of multiple MMCs in power systems, it is necessary to consider the internal dynamics of MMCs and DC networks in the design of the controllers.
- Due to the existence of multiple droop controllers in HVDC grids, it is required to further investigate the issues related to the simultaneous improvement of DC voltage oscillations and network power.

Table 6
Comparison among methods for frequency stability of HVDC grids

Presented Methods	Test Systems	Tuning Methods	Advantages	Non-Analyzed Topics
[191]	CIGRE test system	No	Adding inertia mimicry capability to a VSC-HVDC converter station in an HVDC grid connected to a weak AC or islanded grid	A lack of providing complete demonstration of transient analysis and experimental validation in the presence of network frequency changes
[192]	CIGRE test system	No	Introducing the concept of inertial sharing for control and operation of HVDC networks	Providing simplified and linearized models for power systems components
[194]	IEEE 14-bus networks connected through a six-terminal HVDC system	Yes	Allocation of dynamic controllers for sharing both frequency oscillation damping and restoration reserves of asynchronous AC systems connected through a multi-terminal HVDC grid	A lack of detailed theoretical analysis
[196]	Multi-infeed HVDC system with two power converters	No	• Investigation of instability due to an increase in the control bandwidth • Considering higher frequency dynamics	A lack of analyzing instability when the VSC control bandwidth is close to the frequencies of the high-frequency oscillation modes of AC power systems
[197]	An offshore wind farm based on two-level full-power back-to-back converters and an MMC HVDC system comprises converter transformer, submarine DC cables, wind farm side of MMC, and grid side of MMC	No	• Prediction of possible instabilities of interconnected systems through Nyquist diagrams • Investigation of MMC circulating current control in the stability of interconnected systems	• Disregarding arm current and insertion indices, including significant second harmonics due to circulating current in the developed models • Disregarding the type of synchronization with the AC network using a PLL or other methods
[198]	HVDC systems consisting of converter transformers, offshore HVDC rectifiers, submarine DC cables, and onshore HVDC inverters	No	Providing a small-signal impedance model and stability analysis based on a series-parallel structure for HVDC systems seen from the DC terminal	Requiring a detailed modeling of the power electronics converter's control system to derive the analytical model of the impedances

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Table 6 (*continued*)

Presented Methods	Test Systems	Tuning Methods	Advantages	Non-Analyzed Topics
[199]	Conventional VSC-based HVDC system connected to a PCC	Yes	Using control parameters and an artificial bus to synchronize the converter network and change the maximum theoretical active power in a very weak grid	A lack of evaluating the performance of the presented method under disturbances
[200]	The generic control structure of an MMC station	No	Investigation of resonances that are mainly due to control system parameters and AC network settings	Considering a harmonic that exists only in normal operating conditions and settles in a certain time period
[202]	MMC and AC networks	No	Improving damping of internal harmonic modes in comparison with a passive filter used for the same purpose by employing an active circulating current suppression scheme	Using a non-standard system for testing the presented method
[205]	An HVDC-MMC link embedded in an AC line	No	Analyzing the operation and interaction of MMC-HVDC links embedded in an AC grid	Disregarding internal dynamics of MMC in the course of developing small-signal models, which leads to the small-signal model analogous to that of a two-level VSC system
[206]	A Danfoss 2:2 kVA converter connected to the grid with an *L*-filter	Yes	• Providing an infinite gain to reach a zero steady-state tracking error • Presenting a frequency-adaptive resonant controller	Not achieving proper performance in the steady-state and in case of phase faults
[207]	A point-to-point HVDC system for wind farm connection	No	Improving frequency and inertia by simultaneously using the capacitor energy of VSC-HVDC and WPP inertia	Using a non-standard system for testing the presented method

6. Conclusions

This paper discusses VSC-based HVDC grids stability issues in a systematic approach and presents various control strategies to improve the stability of VSC-based HVDC grids. Critical factors affecting the stability and challenges related to the control of VSC-based HVDC grids are investigated and reported. The approaches to enhance the stability of VSC-based HVDC grids in several fundamental categories, including voltage stability, angle stability (under small and large disturbances), and frequency stability, are systematically and comprehensively investigated. Moreover, the importance and superiority of each method are discussed, and a classification of various control methods to enhance control of VSC-based HVDC grids is provided.

Authors biographies

Authors do not want to include their biographies in the paper.

CRediT authorship contribution statement

Fazel Mohammadi: Writing – original draft, Writing – review & editing. **Neda Azizi:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Hassan Moradi CheshmehBeigi:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Kumars Rouzbehi:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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