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REVIEW

Direct current power system stabilizers for HVDC grids: Current status

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Abstract

A power system stabilizer (PSS) is a control system integrated into the control structure of specific generation units within AC grids. It monitors current, voltage, and machine shaft speed. Analysing these variables, the PSS generates appropriate control signals to the voltage regulator unit, aiming to damp system oscillations. With the advancement of high-voltage direct current (HVDC) overlaid high-voltage alternative current (HVAC) grids, it is anticipated that direct current power system stabilizers (DC-PSS) will be developed to perform a similar role as their AC counterparts. DC-PSS will be responsible for monitoring and controlling DC voltage levels, ensuring stable operations. This paper focuses on DC-PSS in HVDC grids, designed to ensure stable operation and mitigate voltage fluctuations. Unlike conventional AC power systems, HVDC includes only DC voltage and power. The input signal for DC-PSS is the variations in DC voltage, and the output signal is proportional to the power changes at the specific bus where the DC-PSS is installed, aiming to minimize DC voltage oscillations. These characteristics pose significant challenges in DC-PSS. The paper addresses the challenges and highlights issues such as inertia and low-frequency oscillations associated with DC-PSS. Various control methods are presented and a comparison is made among these methods.

1 | INTRODUCTION

Voltage source converter (VSC) stations' control system in HVDC grids is analogous to the control system of synchronous generators in conventional AC systems [1, 2]. The control system of synchronous generators in AC grids and the control system of VSC stations in HVDC grids are shown in Figure 1.

In an AC grid, the governor is responsible for controlling the frequency (or active power) and the exciter is responsible for controlling the AC voltage (or reactive power). An analogous arrangement is designed for the control system of a VSC power converter station in the HVDC grid. In the VSC power converter control arrangement, the active power (or AC frequency) is controlled through the active power channel of the VSC power converter control, and the reactive power (or AC voltage) is controlled by the reactive power channel [1, 3].

The major differences between the conventional AC system and the DC networks are related to energy storage elements (inductors and capacitors) and frequency. In AC networks, active power is related to the frequency of the network, and reactive power is related to the AC voltage. There is a slight interaction between the frequency control and the voltage control loops reported in reference [4]. Instead, in HVDC grids, active power is only related to the DC voltage [5].

There are important differences between DC voltage control and frequency control [1].

1. The frequency in the AC network is a global parameter, while the DC voltage has different values in different buses of an HVDC grid.
2. The main goal of AC network frequency control is to maintain the frequency at a reference value which is constant throughout the entire system, while the purpose of DC voltage control is to maintain the DC voltage of each bus at a certain value, which is not constant throughout the system.

As shown in Figure 1, in AC networks, the reactive power control channel is formed by an automatic voltage regulator

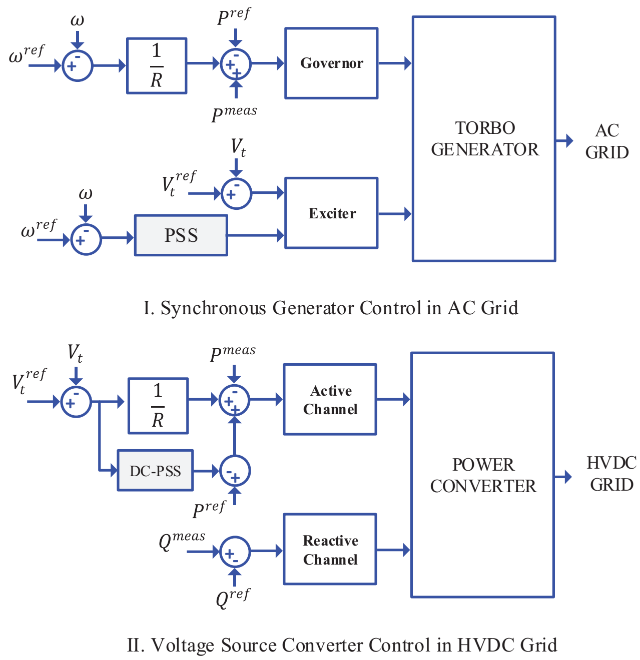

FIGURE 1 Similarities between a synchronous generation unit control and voltage source converter control.

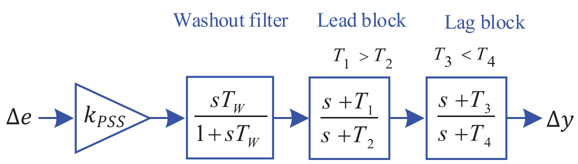

FIGURE 2 A conventional power system stabilizer control structure.

(AVR) and power system stabilizer (PSS) [6]. To add additional damping torque to the system, the PSS is installed in AVR control system. The damping signal of the PSS acts on the voltage control output of the generating unit [7]. Rotor speed, power integral, and terminal frequency are among the commonly used signals as the PSS input. The configuration of the conventional PSS in the AC system is shown in Figure 2. In Figure 2, Δe is the input signal and Δy is the output signal. The gain k_{PSS} affects signal amplification or attenuation. As shown in Figure 2, T_{W} is the time constant of the washout filter. The time constant of the lead block is shown by T_1 and T_2. Moreover, the time constant of the lag block is shown by T_3 and T_4.

VSCs are considered the most promising type of power converters to be used in HVDC grids [8]. An important challenge in HVDC grid development is system protection, especially against DC-side faults. It should be noted that the relatively low impedance of HVDC cables leads to a significant rise in the fault current [9]. In this case, the best way to deal with the fault currents is fast separation, which is being done using HVDC circuit breakers direct-current circuit breakers (DCCBs) [10]. However, currently, these devices rely on a relatively large DC reactor to limit the increase in fault current [11]. The DC reactor size of DCCB depends on DCCB reaction time and maximum current and affects its cost [12]. The size of these reactors is typically more than 100 mH [13]. Large reactors of DCCBs combined with the capacitors of HVDC transmission lines lead to the creation of an LC filter that largely disturbs the dynamic behaviour of DC buses and their power, particularly in lengthy lines in HVDC grids [14, 15].

Another important parameter related to VSC stations in an HVDC grid is the DC-link capacitors [16, 17]. In addition, the presence of a DC reactor leads to an increase in losses and costs and harms the stability of the entire grid [13]. In recent years, in several cases, new types of fluctuations caused by the interaction between the main grid and the power converters have been observed around the world [18–21].

In addition to the above challenges, the lack of reactive power as one of the main control signals and the trade-off between DC voltage and power in HVDC networks are considered key challenges for the safe operation of hybrid AC/DC power systems [5, 22]. While numerous studies have focused on the dynamic behaviour of VSC-HVDC systems, the transient fluctuations in DC bus voltages and line powers have often been overlooked.

Considering these challenges, the authors in reference [23] have proposed an optimization algorithm based on hybrid AC/DC modular multilevel converters (MMCs). Using this method can minimize power losses and reduce DC voltage deviations. In addition, in reference [24] a method based on a distributed observer in order to estimate the average voltage of power converter stations is proposed. The proposed method does not use global data in centralized secondary controllers. Also, in reference [25], a hybrid control structure including independent control and hierarchical control is proposed. To improve the stability of the DFIG-based DC power systems and to overcome the complexity of the control systems of different parts, a superconducting magnetic energy storage (SMES) is proposed in reference [26].

In reference [27], decentralized-based methods are proposed, but most of these methods do not examine sensor gain errors, the influence of cable resistance, and the trade-off between voltage regulation and power sharing. Another type of control method is the power oscillation damping (POD) controller. The most important advantage of these methods is improving fluctuations' damping. The method in reference [28] provides improvement of the maximum available power and the reduction of additional voltage. In reference [29], the dynamical performance of a multi-in-feed HVDC system without the corresponding AC system dynamics and with two LCC-HVDCs and a VSC-HVDC is investigated. The authors in references [30] and [31] propose several coordinated control schemes established based on the master–slave control (MSC) method; however, two drawbacks of the proposed method in these references are that (i) the VSC-HVDC power converter station is analysed by stopping the power converter and (ii) the controller function is affected by communication delays [32]. However, direct current power system stabilizers (DC-PSS) can improve the transient stability with damping of the DC voltage oscillation.

In reference [33], it is shown that the parameters of the droop controller of DC voltage significantly affect the AC–DC system dynamics. However, the structure of the HVDC network has a slight influence on interactions. The impacts of the controller of the power converters and phase lock loop (PLL) parameters on the transient stability of the AC system are investigated in reference [34]. To ensure the precise operation of the power converter's inner current controller, it is important to estimate the grid frequency, which is performed by the PLL. The authors in reference [35] have shown that by adding additional transfer functions, a more accurate model can be achieved to evaluate PLL dynamic effects and delayed measurements. In reference [36], a fuzzy gain scheduling PLL (FGS-PLL) is proposed. The FGS-PLL has a robust performance in severe voltage drops and even phase jump conditions. The proposed method uses a FGS technique to adjust the proportional and integral gains during amplitude, phase, and frequency changes in the grid voltage waveform to create a flexible PLL. In reference [37], it is shown 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 powers for control modes. A dynamic controller distributed for frequency control and repair of asynchronously connected networks via the HVDC network is presented [38], which uses only local information to design the controller and adjust the DC voltage in the HVDC system. Current reference generation techniques for tuning controllers in the conventional PLL reference frame and frequency locked loop reference frame are investigated in reference [8]. A type of VSC controller is provided to generate a generator simultaneously with a different configuration than conventional PLL [39]. In addition, authors in reference [40] compare wide-area and Local POD Control.

Considering the mentioned issues and inspired by PSS in conventional AC power systems, the concept of an effective DC voltage damping controller as a DC-PSS is introduced to increase the overall DC voltage/power stability of the HVDC grid [41].

There are differences and similarities between PSS in conventional AC systems and DC-PSS in HVDC grids as will be described in order from the simplest type of DC-PSS to more advanced structures, in the following sections.

2 | DC-PSS

In HVAC/HVDC power systems [42], the main goal for the DC side is to control the DC voltage, reduce the power imbalance in transient conditions, and maintain the voltage level in the acceptable range [43]. Hence, here, a basic structure of DC-PSS for the entire grid voltage stability enhancement is described [41]. This is achieved by injecting damping signals into the control loop of certain power converter stations.

A basic configuration of the proposed DC-PSS is also shown in Figure 3.

In this control structure, the locally measured DC voltage is used as an index of the power balance in HVDC grids. This DC stabilizer produces a supporting damping signal at the output which is proportional to the input signal. Just like a PSS [44] in conventional AC power systems, DC-PSS is designed as a lead–lag compensator considering an operating point.

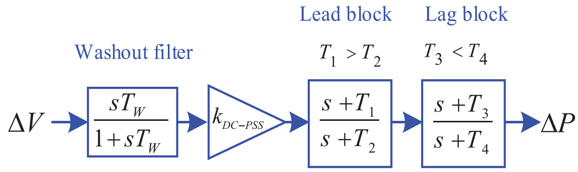

FIGURE 3 A generic direct current power system stabilizer control structure.

Figure 3 shows the proposed structure of DC-PSS is made of several blocks with specific tasks. The task of the lead compensating block (with $T_1 > T_2$ as the time constant of DC-PSS) is to improve the speed response and reduce the peak of the transient oscillation, and the task of the lag block (with $T_3 < T_4$ as the time constant of DC-PSS) is to improve the steady-state response. Also, the amount of damping produced by DC-PSS is determined by the gain of DC-PSS ($k_{\text{DC-PSS}}$). In the proposed structure, the washout filter is designed in such a way that only signals related to the DC voltage fluctuations are allowed to pass without change and filter the steady-state offset in the output. The washout filter prevents the impacts of the DC-PSS on the system in the steady-state condition. The time constant of the washout filter is T_{W}. The DC-PSS input is the measured local DC voltage and its output is proportional to the power oscillations. The DC-PSS structure is designed in such a way that, in steady-state conditions, if an HVDC converter station is equipped with DC-PSS, it will behave exactly like a conventional power converter in active power control mode.

There are two important factors in the successful design of PSS in conventional AC power systems: determining the parameters and finding the optimal place to install the PSS. Although it may be easier to use PSS in all generation units, there are several factors that raise the importance of the optimal placement of PSS. Some of these factors include the high penetration rate of renewable energies, and the damping of low-frequency fluctuations [42]. Similar to the AC power system, it is necessary to choose the optimal place to install the DC-PSS in the HVDC grid [45] due to the undesirable interaction between several DC-PSS and determine the optimal parameters of DC-PSS [43].

3 | DC-PSS INTEGRATION INTO VSC POPULAR CONTROL STRUCTURE

In the control structure of VSC power converters, power-sharing management is the responsibility of V_{DC}–P droop controller, similar to the power–frequency droop control in the conventional AC power system. The most important issue related to the use of DC-PSS in HVDC grids is to improve voltage stability without affecting the power sharing of the entire grid. Because considering the trade-off between two DC voltage and power signals in the droop controller, any change in DC voltage will lead to a change in power. This point is considered in the design of the basic structure of the DC-PSS and

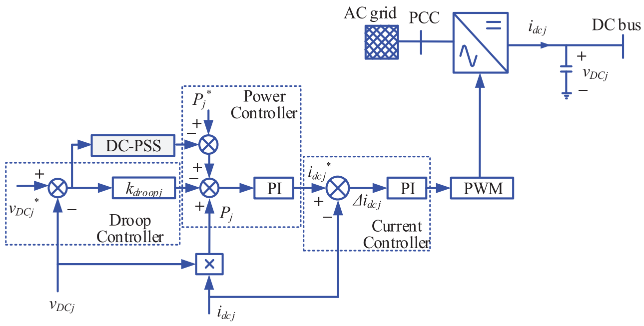

FIGURE 4 V_{DC}–P droop controller structure for a typical HVDC converter station with DC-direct current power system stabilizers.

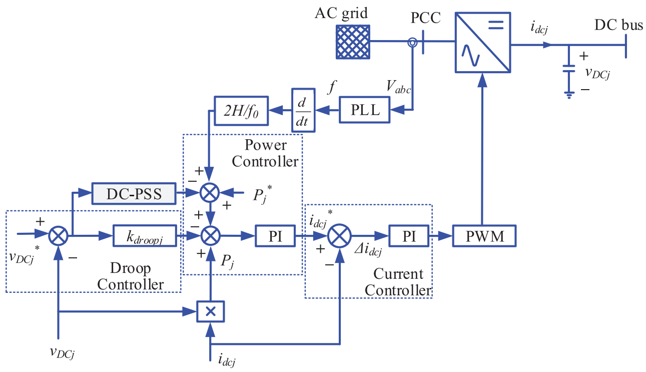

FIGURE 5 Control structure for a power converter station using direct current power system stabilizers with inertia.

the proposed structure is used alongside the droop controller to show that the grid stability is improved without affecting the power sharing. The structure of the proposed control system using the DC-PSS is shown in Figure 4. In this control method, a supplementary signal from the DC-PSS enhances the stability of the HVDC grid through the VSC station equipped with the V_{DC}–P droop controller.

In Figure 4, k_{droopj} is the gain of the conventional droop controller, P_j* is the reference of the power controller, and v_{DCj} is the reference of the droop controller.

However, applying the DC-PSS in the HVDC grid with a basic structure, and considering the interaction of DC voltage and power in the droop controller, can only lead to the improvement of DC voltage oscillation damping. It means that the proposed controller has no effect on the power stability and frequency oscillations of the AC side of the power converter station, and even has a negative impact [41].

4 | FURTHER IMPROVING DC VOLTAGE CONTROL AND FREQUENCY STABILITY

The DC-PSS with its basic structure cannot address the issues of inertia and low-frequency oscillations together. To address the mentioned issue, a DC-PSS-based method to virtually increase the inertia that works alongside the droop controller in a way that does not interrupt the power sharing in the HVDC grid is proposed [46]. Because the basic DC-PSS does not affect the inertia of the system, a modified droop controller (M-Droop) method based on the conventional structure of the DC-PSS is introduced in reference [47] that provides an extra virtual capacity by using the energy stored in the grid, in the event of faults. M-Droop can supply HVDC grid stability without dependency on the frequency measurement and the PLL. In DC-PSS with its conventional structure, the objective is to take voltage changes as input and create a signal corresponding to the power signal, in such a way that improves the damping of oscillations. However, the trade-off between voltage and power in the droop controller makes the use of DC voltage changes as DC-PSS input does not have a positive effect on the power. Therefore, since the frequency is presented as an independent signal on the AC side of the power converter station in the HVDC grid and it has no interaction with the droop controller, reference [46] proposes that by keeping the basic DC-PSS structure, frequency signal changes and converting it into a power signal are used, which this has led to the introduction of a new type of stabilizer based on DC-PSS. The energy required to implement this method is supplied through the sub-module capacitors of MMC [48]. The main idea for the proposed method in reference [46] is based on the observation that the energy stored in the capacitors of HVDC grids and the inertia of the synchronous generators of AC systems are analogous [1, 49]. Therefore, by converting the frequency changes and consequently the power changes on the AC side of the power converter and converting these changes to the power changes of the MMC capacitors on the DC side, it is possible to use the energy stored for inertia emulation.

In the proposed scheme, the measured AC side frequency combined with inertia and DC-PSS damping signal is injected in the droop control loop. Then, the frequency, inertia, and DC-PSS signal with the measured active power are used as power references in the power controller. As mentioned before, this method does not prevent the proper operation of the droop controller and power sharing. As a result, the voltage level does not change any part of the system. The control system of a typical MMC station connected to the AC network is shown in Figure 5.

The noteworthy point in this control approach is that by using this method, in addition to the DC voltage stability enhancement, the stability margin of the frequency of the AC side also increases.

However, the DC-PSS with inertia does not provide any solution to use the energy stored in the grid in fault events.

5 | DC VOLTAGE OSCILLATIONS DAMPING IMPROVEMENT AND POWER SHARING

Because the basic DC-PSS has no effect on the inertia of the system, a M-Droop method based on the conventional structure of the DC-PSS is introduced in reference [47] that provides

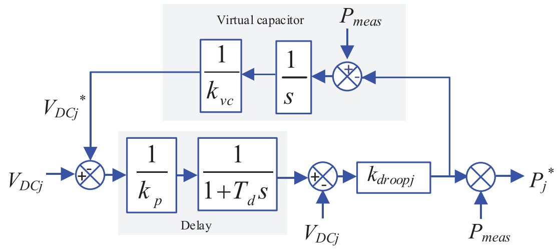

FIGURE 6 M-droop controller structure.

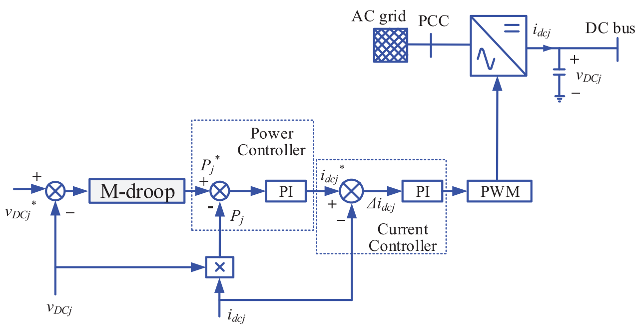

FIGURE 7 Proposed control structure for a typical HVDC converter station with M-droop controller.

an extra virtual capacity by using the energy stored in the grid, in the event of faults. M-Droop can supply HVDC grid stability without dependency to the frequency measurement and the PLL. The proposed method in reference [47] can improve the damping for DC voltages of HVDC grids in transient situations. In this structure, the additional signal of the M-droop controller is used instead of the normal V_{DC}–P droop controller. The configuration of the proposed M-droop controller is shown in Figure 6. The function of this M-droop controller is to provide an additional auxiliary virtual capacitor, where k_{vc} represents the coefficient of the provided virtual capacitor. Also, in order to filter the measurement noises and delay, a low-pass filter with T_d as the time constant is added to the control structure. As shown in Figure 6, in the proposed M-droop controller, the DC reference voltage is compared with the measured local DC voltage. Then this signal is compared with the voltage after passing through a coefficient ($\frac{1}{k_{vc}}$) and the low-pass filter, and the formed signal after passing through a droop gain (k_{droopj}), it is converted into a power reference of the jth power converter station. However, in the proposed structure, the power reference is passed through an integral block and a gain and is added to the DC voltage reference as a virtual capacitor by a feedback loop.

Reference [47] shows that by employing power variations, the M-droop controller can emulate the behaviour of the virtual capacitor without changing the amount of capacitors of the DC link.

Figure 7 shows the structure of the proposed control system using an M-droop controller.

6 | INTEGRATION OF BATTERY ENERGY STORAGE SYSTEMS

The lack of reactive power and the trade-off between DC voltage and power in HVDC networks are considered key challenges for the safe operation of hybrid AC/DC power systems. To address this issue, one solution is that the DC-PSS input signal is supplied from an external source [50]. Therefore, future developments of DC-PSS can be using this controller with an energy source as its input signal source.

7 | COMPARISON BETWEEN THE PROPOSED STABILIZERS CONTROL STRUCTURES

Here, three methods are presented to improve the stability of HVDC grids.

The first method is to use the DC-PSS with a basic structure. If the parameters of DC-PSS are tuned correctly and the DC-PSS is installed at the optimal place, it is able to improve DC voltage oscillations by injecting a supplementary signal. However, the disadvantage of this method is that DC-PSS with the basic structure has no effect on the frequency fluctuations of the AC side of the power converter station, and in some cases, it can also increase the power oscillations.

The second method is the use of a control scheme that, alongside with basic structure of the DC-PSS, can improve the inertia of the HVDC grid and increase the damping of DC voltage and frequency fluctuations, in such a way that does not affect power sharing. However, this method does not provide any solution to use the stored energy of the HVDC grid in the fault events.

The third method is to use a concept called M-droop, which is able to provide an additional virtual capacitor by using the energy stored in the grid. This method can use the energy stored in the grid to improve the stability of DC voltage and power.

Since the objective of this paper was to investigate the different methods presented in terms of advantages, disadvantages, and their effects on the DC voltage stability and power of the power converter stations to improve stability in entire HVDC grid, it is necessary to introduce an error criterion. Using (1), by calculating and integrating the area under the DC voltage oscillation curve and the area under the active power oscillation curve for n AC/DC buses during the specified time, the transient error and the amount of grid fluctuations are reached. In this regard, E_{DC} is defined as an error criterion for Cigré DCS3 test HVDC grids [46, 51]. In (1), the number of all busses of the grid is shown by n, DC voltage variations of the specific bus is shown by ΔV_{DC_b}, and the power variations of the specific bus is shown by ΔP_b. t is the running time of the simulations.

$$E_{DC} = \sum_{b=1}^{n} \left(\int_0^t t \left(\left| \Delta V_{DC_b} \right| + |\Delta P_b| \right) dt \right) \quad (1)$$

In order to investigate available DC-PSS control structure, the achieved values of E_{DC} by using the calculated parameters

TABLE 1 Comparison of calculated E_{DC} according to using the different stabilizers.

	E_{DC}		
Fault scenarios	**Conventional DC-PSS**	**DC-PSS with inertia**	**M-droop controller**
Three-phase short circuit	0.091	0.0734	0.0638
Decreasing load	0.283	0.165	0.122
Increasing load	0.287	0.184	0.167

in each paper are compared following three scenarios of faults. The results of the comparison of calculated E_{DC} according to using the different stabilizers are reported in Table 1. In all simulation studies, the proposed method was applied to Cb-B1 [43] of the Cigré DCS3 test HVDC grid [51].

As the result of the error criterion for different scenarios in Table 1 shows, the M-droop method provides a better response than DC-PSS with inertia. Moreover, DC-PSS with inertia compared to the basic structure of DC-PSS provides a better response. It means that the methods presented in each step have been able to improve the stability of the grid compared to the previous step.

8 | CONCLUSIONS

This paper examined various control approaches to enhance stability under different scenarios. First, the addition of a basic-structured DC-PSS as a stabilizer to the conventional droop control was proposed to improve the dynamic performance of DC voltage in HVDC grids. Next, the integration of DC-PSS with a droop-controlled VSC station was explored to enhance DC voltage oscillation damping while maintaining power sharing. The paper then introduced a method to further improve DC voltage control and frequency stability, specifically targeting DC power oscillations and working in conjunction with the DC-PSS. Additionally, a novel control structure called the M-droop controller, based on the droop controller concept, was presented. This method emulates the behaviour of a virtual capacitor, utilizing the stored energy in the grid during fault events, without relying on frequency measurement or PLL. Finally, all the proposed methods were compared in terms of their effectiveness in improving stability and increasing damping of DC voltage and power oscillations.

AUTHOR CONTRIBUTIONS

Neda Azizi contributes in conceptualization, methodology, software, writing original draft. Hassan Moradi has done supervision, reviewing and editing of the manuscript. Kumars Rouzbehi contributes in investigation phase, Software, validation, and data curation. Ali Mehrizi-Sani has done conceptualization, reviewing and editing of the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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