Research Article

Bidirectional Virtual Inertia Control Strategy for Hybrid Distributed Generations Integrated Distribution Systems

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The bidirectional ac/dc converter between the ac and dc subgrids plays a crucial role in enhancing the inertia support ability and ensuring the stable operation of the hybrid ac/dc distribution systems. In this paper, the bidirectional virtual inertia control strategy of hybrid distributed generations (DGs) integrated distribution systems is proposed for desired inertia support ability of both ac frequency and dc voltage. Firstly, the active power droop characteristics of the bidirectional ac/dc converter are analyzed, which reveals the steady power-sharing relationship between the ac and dc subgrids. Then, based on the dynamic power balance of the bidirectional ac/dc converter, the bidirectional virtual inertia control is proposed by introducing the virtual capacitor and moment of inertia, which can enhance the interactive inertia support ability of the hybrid distribution system. Finally, the effectiveness of the proposed control scheme is verified with a hybrid DGs integrated distribution simulation system in the PSCAD platform.

1. Introduction

Recently, with the exhaustion of traditional fossil energy and the aggravation of environmental pollution, the energy problem has become a severe challenge to the economic and social development nowadays. Distributed generation (DG) such as photovoltaic and wind power becomes the focus of governments, industry, and academia all over the world as a clean and environmentally friendly flexible power generation technology [1–3]. DG has the advantages of local consumption, low construction cost, and economic and environmental protection, and the grid-connected voltage level of the DG unit is generally below 10 kV [4]. The flexible integration of the DGs with the energy storage to form the hybrid ac/dc distribution systems is conducive to maximizing the utilization efficiency of clean and renewable energy and is an important measure to achieve green power, energy saving, and emission reduction [5, 6].

Due to the intermittent and uncertain characteristics of DG units, the power fluctuation in hybrid ac/dc distribution systems becomes the main issue affecting the stable operation of the system. At the same time, the hybrid distribution system dominated by converters [7] faces the issue of lower inertia performance, which is unable to improve the transient characteristics of frequency and voltage like the traditional synchronous generator when the system suffers external power fluctuation [8, 9]. Especially, when the higher-level electricity grid is weak to provide any inertia support, the ac grid and dc grid suffer the impact of external power disturbance at the same time [10]. Many studies on the frequency and voltage stability of the hybrid distribution system have been published at present. In [11], the small-signal stability of islanded hybrid ac/dc microgrids is conducted, which uses a linearized state-space model for establishing adequate frequency and voltage stability margins in hybrid microgrid operations. In [12], the impact of the power flow direction on the small-signal stability of
islanded droop-based ac/dc hybrid microgrids is investigated. In [13], an enhanced dynamic stability control scheme with locally measured signals only is proposed to enhance the dynamic stability of a low-inertia hybrid AC/DC microgrid. Although the frequency and voltage stability study of the hybrid system is carried out through the small-signal modeling method, stability interaction behavior analysis, and so on, the inertia response characteristics and support ability of the hybrid system are not involved, which play an important role in the system ability to resist external disturbances.

In order to improve the inertia support ability, the concept of virtual inertia by simulating the electromagnetic and mechanical equations of a synchronous generator is proposed in [14, 15], and the transient response can be similar to those of the synchronous generator when the power fluctuation occurs in the system. However, for the hybrid ac/dc distribution systems, parallelly connected DGs within the same bus with the virtual inertia control may cause the power oscillation issues [16, 17]. Therefore, the bidirectional ac/dc converter between the ac and dc subgrids plays a crucial role in enhancing the inertia support ability and ensuring the stable operation of the distribution system. In [18], a smart and autonomous integration concept for dc microgrids into the ac grid is proposed based on the virtual synchronous machine, which utilizes the dc-ac converter as a universal virtual synchronous machine-based interface between the ac grid and DGs connected on the dc side. In [19], a novel control of the bidirectional interlinking converter for enhancing the transient performance of an islanded hybrid ac-dc microgrid is proposed based on the virtual synchronous generator. In [20], an inertial improvement strategy for the bidirectional power converter is proposed which contains two stages of converters and a built-in capacitor, which can improve the dc subgrid inertial response by regulating the built-in capacitor. In [21], an improved two-stage control scheme for the bidirectional converter that interfaces the two subgrids to prevent this total blackout is proposed, where the first stage is controlled as a virtual-synchronous machine to form the AC grid and support the voltage and frequency, while the second stage controls the voltage to the build-in supercapacitor. In [22], an adaptive coordinated control strategy for the networked AC/DC microgrids is proposed to enhance the frequency and dc voltage stability based on the synchronverter and virtual dc machine. However, the existing researches generally ignore the dynamic power balance relationship and bidirectional inertia support ability between the ac and dc subgrids, which is the major issue to be solved in this paper.

In this paper, the bidirectional virtual inertia control strategy of hybrid DGs integrated distribution systems is proposed for desired inertia support ability of both ac subgrid frequency and dc subgrid voltage. The main contributions and innovations of this paper are as follows:

(1) The active power droop characteristics of the bidirectional ac/dc converter are first analyzed, which reveals the autonomous and proportional power-sharing relationship between the ac and dc subgrids

(2) To enhance the interactive inertia support ability of the hybrid distribution system, the dynamic power balance relationship of the bidirectional ac/dc converter is derived, and the bidirectional virtual inertia control is proposed by introducing the virtual capacitor and moment of inertia

(3) To analyze the control characteristics of the bidirectional ac/dc converter based on the proposed bidirectional virtual inertia control, the small signal analysis model is established, and the response characteristics of the frequency and dc voltage with the proposed control are performed

Finally, the effectiveness verification of the proposed control is carried out with the simulation cases of a hybrid DGs integrated distribution system in the PSCAD platform.

2. Systems Structure

Figure 1 shows an example configuration of the ac and dc hybrid DGs integrated distribution systems. Various ac and dc DGs are integrated into the distribution systems to form the ac subgrid and dc subgrid. When the point of common coupling (PCC) is disconnected from the utility grid, the system operates in islanding mode, and the bidirectional ac/dc converter plays the role of smooth power sharing between ac and dc bus. It can supply power from ac to dc bus to support the power balance in the dc subgrid. In return, the dc subgrid can also provide necessary power support to the ac subgrid through the bidirectional ac/dc converter. Therefore, the control scheme for the bidirectional ac/dc converter is the key issue to realize the autonomous power sharing and stable the distribution systems.

For the DGs with stable output in ac or dc subgrid, the decentralized peer-to-peer control based on droop characteristics [6] can be used to realize the autonomous power sharing without the information exchanged. Since the distribution systems with various DGs and converters perform low-inertia characteristics, the improved droop control combined with a virtual inertia loop has been proposed to enhance the inertia support ability of the distribution systems. However, for the ac and dc hybrid DGs integrated distribution systems, parallelly connected DGs within the same bus may cause the power oscillation issues. Hence, the hybrid distribution systems need to manage the droop characteristic of ac and dc DGs in their respective subgrids and form the bidirectional virtual inertia control strategy through the bidirectional ac/dc converter for inertia enhancement.

3. Bidirectional Virtual Inertia Control Strategy for the Hybrid Distribution Systems

3.1. Active Power Droop Characteristics of the Bidirectional AC/DC Converter. The active power droop characteristics of the bidirectional ac/dc converter are both associated with the ac bus frequency and dc bus voltage. The equations in (1) show the DGs with droop control in ac and dc subgrids, where $f_{ac}$ and $f'_{ac}$ are the actual and rated ac frequency; $P_{ac}$
and $P_{ac}$ are the actual and rated active power of each DG in ac subgrid; $U_{dc}$ and $U_{dc}^*$ are the actual and rated dc voltage; $P_{dc}$ and $P_{dc}^*$ are the actual and rated active power of each DG in dc subgrid; $k_{ac}$ and $k_{dc}$ are the droop coefficients of ac and dc droop control, respectively; the subscripts $(1, \ldots, x)$ and $(1, \ldots, y)$ represent the source index in ac and dc subgrids, respectively.

$$\begin{align*}
\frac{f_{ac}}{f_{ac}^*} & = k_{ac1} (P_{ac,1}^* - P_{ac,1}), \\
\cdots & \\
\frac{f_{ac}}{f_{ac}^*} & = k_{acx} (P_{ac,x}^* - P_{ac,x}), \\
\frac{U_{dc}}{U_{dc}^*} & = k_{dc1} (P_{dc,1}^* - P_{dc,1}), \\
\cdots & \\
\frac{U_{dc}}{U_{dc}^*} & = k_{dcy} (P_{dc,y}^* - P_{dc,y}).
\end{align*}$$

(1)

To ensure that each DG can share the load power in proportion to their capacity, the droop coefficients should satisfy

$$\begin{align*}
k_{ac1}P_{ac,1}^* = k_{ac2}P_{ac,2}^* = \cdots = k_{acx}P_{ac,x}^* = K_{ac}, \\
k_{dc1}P_{dc,1}^* = k_{dc2}P_{dc,2}^* = \cdots = k_{dcy}P_{dc,y}^* = K_{dc},
\end{align*}$$

(2)

where $K_{ac}$ and $K_{dc}$ are the positive constants. As for the bidirectional ac/dc converter, it merges the ac and dc droop controls to form the autonomous active power sharing among the ac and dc subgrids. According to the ac frequency and dc voltage, the active power sharing of the bidirectional ac/dc converter can be described [23] as follows:

$$\begin{align*}
f_{ac} = f_{ac}^* + \frac{K_{ac}}{P_{bicon}} (P_{bicon}^* - P_{bicon}), \\
U_{dc} = U_{dc}^* + \frac{K_{dc}}{P_{bicon}} (P_{bicon}^* - P_{bicon}),
\end{align*}$$

(3)

where $P_{bicon}$ and $P_{bicon}^*$ are the actual and rated transmission power of the bidirectional ac/dc converter. Since the power sharing of the bidirectional ac/dc converter is constant, the following active power droop characteristics are satisfied in steady state:

$$\frac{f_{ac} - f_{ac}^*}{U_{dc} - U_{dc}^*} = \frac{K_{ac}}{K_{dc}}.$$  

(4)

Therefore, if the ratio of the frequency deviation and the dc voltage deviation is set as the input, and compared with the command value $K_{ac}/K_{dc}$, the autonomous and proportional power sharing of the hybrid systems can be realized.

3.2. Bidirectional Virtual Inertia Control for the Hybrid Distribution Systems.  

The active power droop characteristics of (4) reveal the steady power-sharing relationship through the bidirectional ac/dc converter, but the inertia support ability of the bidirectional converter is not given. Figure 2 shows the dynamic power balance of the bidirectional ac/dc converter, which can be seen that the charge and discharge process of the capacitor $C_{dc}$ of the bidirectional ac/dc converter determines the dynamic characteristics of dc voltage, and is shown as

![Figure 1: The ac and dc hybrid DGs integrated distribution systems.](image)
From Figure 2, in the steady operation state, the power from the ac subgrid to dc subgrid is constant when the loss power of the bidirectional ac/dc converter is neglected. However, during the transient process, the charging or discharging process of the capacitor \( C_{dc} \) exists, and this can be reflected in the fluctuation of dc voltage. The energy storage of the capacitor shown in (5) indicates that the fluctuation of dc voltage response. Nevertheless, the capacitance \( C_{dc} \) on the dc side of the bidirectional ac/dc converter generally is not large enough to support the dc voltage fluctuation mitigation. Besides, when there is frequency fluctuation caused by power disturbance on the ac subgrid, the bidirectional ac/dc converter cannot respond to provide enough frequency support according to (5). Therefore, it needs to regulate the transient power mismatch among ac and dc subgrids based on the frequency and dc voltage fluctuation deviations to enhance the inertia support ability for desired dynamic response of ac and dc bus.

The inertia support energy can come from the ac or dc subgrid through the bidirectional ac/dc converter. For example, when there is power disturbance in the dc subgrid and causes the dc voltage fluctuation, the bidirectional ac/dc converter should transmit more transient power from ac subgrid according to dc voltage fluctuation deviations. In turn, the bidirectional ac/dc converter could also transmit transient power from dc to ac subgrid according to frequency fluctuation deviations when there is power disturbance in the ac subgrid. What’s more, to imitate more inertia energy for dc voltage and frequency support, the stored inertia energy reference is defined as

\[
\begin{align*}
W_{dc}^* &= \begin{cases} 
\frac{1}{2}C_{dc}U_{dc}^2 + \frac{1}{2}C_{vir}(U_{dc}^2 - U_{dc}^{*2}), & P_{bicon} > 0, \\
\frac{1}{2}C_{dc}U_{dc}^2 + \frac{1}{2}f_{vir}(f_{ac} - f_{ac}^{*2}), & P_{bicon} < 0, 
\end{cases}
\end{align*}
\]

where \( C_{vir} \) is the imitated virtual capacitance; \( f_{vir} \) is the moment of inertia. Here, the positive direction of \( P_{bicon} \) is defined from ac subgrid to dc subgrid. The equation of (6) indicates that when \( P_{bicon} \) is positive, the virtual inertia energy is imitated according to dc voltage deviation to support its recovery. Similarly, the virtual inertia energy can also be imitated to support the frequency recovery when \( P_{bicon} \) is negative. Therefore, by introducing the virtual capacitor \( C_{vir} \) or moment of inertia \( f_{vir} \), the dc voltage or frequency support during transient can be realized. Then, by replacing \( W_{dc}^* \) in (5) with (6), it yields

\[
\begin{align*}
W_{dc} &= \begin{cases} 
\frac{1}{2}C_{dc}U_{dc}^2 + \frac{1}{2}C_{vir}(U_{dc}^2 - U_{dc}^{*2}), & P_{bicon} > 0, \\
\frac{1}{2}C_{dc}U_{dc}^2 + \frac{1}{2}f_{vir}(f_{ac} - f_{ac}^{*2}), & P_{bicon} < 0.
\end{cases}
\end{align*}
\]

From (7), it can be seen that with the introduction of virtual capacitor \( C_{vir} \) or moment of inertia \( f_{vir} \), the equivalent inertia energy is enhanced to prevent an abrupt change of the dc voltage or frequency. For example, when the transmission power is from the dc to ac subgrid and the ac frequency decreases due to some power disturbance, a frequency regulation signal will be generated according to the term \( f_{vir}f_{ac}df_{ac}/dt \). As a result, more transient power is transmitted from dc to ac subgrid for frequency inertia recovery. The situation is the same when the transmission power is from dc to ac subgrid and dc voltage inertia support is needed. The overall bidirectional virtual inertia control of the bidirectional ac/dc converter is shown in Figure 3.

In Figure 3, the autonomous active power-sharing control loop is based on the active power droop characteristics as shown in (4). The difference between actual deviation ratio \( (f_{ac} - f_{ac}^{*})/(U_{dc} - U_{dc}^{*}) \) and the reference value \( K_{ac}/K_{dc} \) is fed into the PI (proportional integral) controller to eliminate the steady error for proportional power sharing among ac and dc subgrids of the hybrid systems. The additional bidirectional virtual inertia control loop consists of the dc voltage inertia imitation and frequency inertia imitation. The direction discriminant logic of the transmission power \( P_{bicon} \) is used here to decide whether the dc voltage or frequency needs the inertia support. With the bidirectional virtual inertia control implemented, the bidirectional ac/dc converter can be controlled to work in either inverter or rectifier mode for desired inertia support ability of both the ac subgrid frequency and dc subgrid voltage.
4. Small Signal Modelling and the Characteristics Analysis

4.1. Small Signal Modelling of the Bidirectional AC/DC Converter

To analyze the control characteristics of the bidirectional AC/DC converter based on the proposed bidirectional virtual inertia control, the small signal analysis is conducted in this section. The topological structure of the bidirectional AC/DC converter is given in Figure 4, where $E_{abc}$ and $i_{abc}$ are the AC side voltage and current; $R$ and $L$ are the equivalent resistance and impedance.

To establish the small signal modelling of the bidirectional AC/DC converter, the mathematical dynamic equations in the synchronous rotating d-q reference frame are

$$
E_{sd} - U_{sd} - \omega L i_{sq} = R i_{sd} + L \frac{d}{dt} i_{sd},
$$

$$
E_{sq} - U_{sq} + \omega L i_{sd} = R i_{sq} + L \frac{d}{dt} i_{sq},
$$

where the subscript $d$ and $q$ indicate the $d$ and $q$ axis components. Generally, the PI controller is used for the current regulation and yields

$$
\begin{align*}
G_{id}(s)(i_{sdref} - i_{sd}) &= (R + Ls)i_{sd}, \\
G_{iq}(s)(i_{sqref} - i_{sq}) &= (R + Ls)i_{sq},
\end{align*}
$$

where $G_{id}(s)$ and $G_{iq}(s)$ are the transfer functions of the PI controllers; $i_{sdref}$ and $i_{sqref}$ are the converter current references; $s$ is the differential operator. The state variables are decomposed as the steady state and small disturbance term, and then, the small signal model of the current control is shown as follows:

$$
\begin{align*}
\frac{\Delta i_{sd}(s)}{\Delta i_{sdref}(s)} &= \frac{G_{id}(s)}{R + Ls + G_{id}(s)}, \\
\frac{\Delta i_{sq}(s)}{\Delta i_{sqref}(s)} &= \frac{G_{iq}(s)}{R + Ls + G_{iq}(s)}.
\end{align*}
$$

[Figure 3: The bidirectional virtual inertia control of the bidirectional ac/dc converter.

Figure 4: Topological structure of the bidirectional ac/dc converter.]
where Δ indicates the small disturbance term, and the second-order term in (10) is ignored.

Then, the small signal model of the bidirectional ac/dc converter power is given as follows:

$$\Delta P_{\text{bicon}} = \frac{3}{2} \left( E_{ac} \Delta i_{ac} + \Delta E_{ac} \right).$$  \hspace{1cm} (11)

In Figure 3, the small signal model of the bidirectional ac/dc converter is given in (12) where only the virtual inertia control is considered.

$$\Delta P_{\text{ref}} = \begin{cases} \frac{1}{G_{ac}(s)} \Delta f_{ac}(s), & P_{\text{bicon}} > 0, \\ \frac{1}{G_{dc}(s)} \Delta U_{dc}(s), & P_{\text{bicon}} < 0, \end{cases}$$  \hspace{1cm} (12)

Furthermore, the small signal transfer functions of the bidirectional ac/dc converter power are obtained as following with (10)–(12).

$$\Delta P_{\text{bicon}}(s) = \begin{cases} \frac{2Ls + 2R + 2G_{sv} \Delta f_{sv}(s) + 3E_{sv} G_{sv}(s) G_{p}(s)}{3s J_{sv} f_{ac} G_{sv}(s) G_{p}(s)}, \\ \frac{2Ls + 2R + 2G_{sv} \Delta f_{sv}(s) + 3E_{sv} G_{sv}(s) G_{p}(s)}{3s C_{sv} U_{dc} G_{sv}(s) G_{p}(s)}, \end{cases}$$  \hspace{1cm} (13)

where $G_{p}(s)$ is the converter power PI control; $G_{ac}(s)$ and $G_{dc}(s)$ are the transfer functions of the frequency and dc voltage when there is disturbance on the bidirectional ac/dc converter, respectively, and given as follows:

$$\begin{align*}
G_{ac}(s) &= \frac{2s + 2R + 2G_{sv} \Delta f_{sv}(s) + 3E_{sv} G_{sv}(s) G_{p}(s)}{3s J_{sv} f_{ac} G_{sv}(s) G_{p}(s)}, \\
G_{dc}(s) &= \frac{2s + 2R + 2G_{sv} \Delta f_{sv}(s) + 3E_{sv} G_{sv}(s) G_{p}(s)}{3s C_{sv} U_{dc} G_{sv}(s) G_{p}(s)},
\end{align*}$$  \hspace{1cm} (14)

To perform the response characteristics of the frequency and dc voltage of the bidirectional ac/dc converter with the proposed virtual inertia control, the step response of the small signal model (14) is plotted in Figure 5 with the varying virtual inertia parameters $J_{sv}$ and $C_{sv}$.

Figure 5(a) shows the variation of the frequency when there is a unit power disturbance when the virtual moment of inertia $J_{sv}$ varies from 0 to 1000, while Figure 5(b) shows the step response of dc voltage when the virtual capacitor $C_{sv}$ varies. It can be concluded from Figure 5 that when there is power disturbance, the frequency variation gets smaller with the increasing of virtual moment of inertia $J_{sv}$, which indicates that the system inertia to prevent frequency from sudden disturbance is enhanced. Similarly, Figure 5(b) shows that the dc voltage variation also gets smaller when the virtual capacitance $C_{sv}$ gets larger, and system inertia to mitigate the abrupt change of dc voltage is also enhanced. However, the virtual inertia parameters $J_{sv}$ and $C_{sv}$ cannot be too much large in actual practical application since the derivative link in Figure 3 may lead in unexpected high frequency noise with large $J_{sv}$ and $C_{sv}$. Hence, the system inertia can be obviously enhanced with the proposed bidirectional virtual inertia control for interactive support ability between ac and dc subgrids.

5. Case Study

To verify the validation of the proposed control strategy, the hybrid DGs integrated distribution system shown in Figure 6 is established in the PSCAD platform. There exist two DG units in the ac subgrid with the rated capacity of 40 kW, while the dc subgrid also has two DGs with the rated capacity of 40 kW. The rated ac frequency is 50 Hz, and the dc voltage is 700 V. There is a bidirectional ac/dc converter between the ac and dc subgrid. The control parameters are given in Table 1.

5.1. Case 1. The initial active load in the ac subgrid is 80 kW, and the initial load in dc subgrid is also 80 kW. At time 4 s, the load power in the dc subgrid decreases to 60 kW. The system simulation results with and without the proposed control are shown in Figure 7.

The system simulation results show the power sharing, ac frequency, and dc voltage response of the hybrid distribution system. The initial load power of the system is 160 kW, while each DG should supply 40 kW active power, and the bidirectional ac/dc converter transmits no power between the ac and dc subgrids. After 4 s, the active load in dc subgrid decreases to 60 kW, and each DG should supply 35 kW active power, which means that the bidirectional ac/dc converter needs to transmit 10 kW power from dc to ac subgrid. The power sharing of the whole hybrid distribution system is shown in Figures 7(a)–7(f). From the simulation results of Figures 7(a)–7(c), the variation of frequency and dc voltage gets smaller when the proposed bidirectional inertia control is implemented during the load power fluctuation. Under the conventional power sharing without inertia support ability, the frequency and dc voltage suffer impacts and show larger overshoots in the transient process. The bidirectional inertia control can force the dc grid to provide the inertia support to the ac grid and hence mitigate the frequency variation and improve the system transient response. In return, the dc voltage variation can also be alleviated during the improved transient process. From Figures 7(g) and 7(h), it is seen that with the increasing of the virtual inertia parameters, the system transient process can be better improved. Therefore, the inertia of the hybrid distribution system can be significantly enhanced under the proposed bidirectional inertia control with properly chosen virtual inertia parameters.

5.2. Case 2. In this case, the initial active load in ac and dc subgrids is still 80 kW, respectively. At time 4 s, the load in dc subgrid decreases to 60 kW, and one DG unit in ac grid quits operation. The system simulation results with and without the proposed control are shown in Figure 8.

The simulation results show that when there exists power disturbance in both the DG output power and load power, the transient process has deteriorated with the conventional power-sharing control. However, when the bidirectional virtual inertia control works, the variations of ac grid frequency and dc grid voltage can still be decreased. The active power of the bidirectional ac/dc converter shown in Figure 8(d) presents the transmission power between the ac
and dc subgrids and indicates the transient support power at time 4 s. It can be concluded from the above cases that the proposed bidirectional inertia control can significantly enhance the inertia of the hybrid distribution system for superior transient response of the system and improved the antidisturbance ability.
Figure 7: The simulation results of case 1. (a) AC subgrid frequency, (b) dc subgrid voltage, (c) ac subgrid voltage, (d) active power of bidirectional ac/dc converter, (e) active power with proposed control, (f) active power with conventional control, (g) ac frequency with different virtual inertia, (h) dc voltage with different virtual inertia.
6. Conclusion

This paper presents the bidirectional virtual inertia control strategy of the hybrid DGs integrated distribution systems for inertia support ability of both ac frequency and dc voltage. The active power droop characteristics of the bidirectional ac/dc converter are first analyzed, which reveals the steady power-sharing relationship between the ac and dc subgrids. To enhance the interactive inertia support ability of the hybrid distribution system, the dynamic power balance of the bidirectional ac/dc converter is then given, and the bidirectional virtual inertia control is proposed by introducing the virtual capacitor and moment of inertia. Finally, the effectiveness verification of the proposed control is carried out in the PSCAD platform with the simulations of a hybrid DGs integrated distribution system.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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