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Performance Analysis Distributed Generation System using Renewable Energy Fed DPFC

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ABSTRACT

This paper presents a comprehensive performance analysis of a Distributed Generation (DG) system utilizing renewable energy sources, integrated with a Distributed Power Flow Controller (DPFC) to enhance power quality and ensure efficient distribution. The study focuses on the implementation of DPFC in a renewable energy-fed DG system to address issues related to voltage stability, power flow control, and harmonic distortion. By employing a dynamic simulation model developed in MATLAB/Simulink, the paper evaluates the effectiveness of the DPFC in managing the power distribution from various renewable sources, including solar and wind. The analysis demonstrates the DPFC's capability to improve the system's voltage profile, optimize power flow, and reduce total harmonic distortion (THD), thereby enhancing the overall performance and reliability of the DG system. The results offer valuable insights into the potential of integrating DPFC technology with renewable energy systems for improved power quality and distribution efficiency, contributing to the advancement of sustainable and resilient power networks.

KEYWORDS: Distributed Generation System, Renewable Energy, Distributed Power Flow Controller (DPFC), Power Quality, Voltage Stability, Total Harmonic Distortion.

1. INTRODUCTION

Recent developments in the electric utility industry are encouraging the entry of power quality issue [1]. Extending from the generation units to the utility customers, power quality is a measure of how the elements affect the system as a whole [2]. From customer point of view, the power quality issue is concerned about current, voltage or frequency deviation which results in power failure [3]. To solve the power quality problem in such a situation, the power electronic devices such as flexible alternating-current transmission system (FACTS) and custom power devices (DVR) which are used in transmission and distribution control, respectively, should be developed [4], [5], [6]. The impact of transient parameters in majority of transmission lines problems such as sag (voltage dip), swell (over voltage) and interruption, are also considerable [1]. To mitigate the mentioned power quality problems, the utilization of FACTS devices such as power flow controller (UPFC) and synchronous static compensator (STAT-COM) can be helpful [7], [8]. In [9], the distributed power flow controller (DPFC) is presented which has a similar configuration to UPFC structure. As shown in Fig. 1, the DPFC is composed of a single shunt converter and multiple independent series converters which is used to balance the line parameters, such as line impedance, transmission angle and bus voltage magnitude [9], [10]. To detect the voltage sags and determine the three single-phase reference voltages of DPFC, the SRF method is also proposed as a detection and determination method. The work in this paper is organized as follows: introduction to DPFC and operation principle is debated in Section II. In Section III, the control strategy of DPFC. The impact of DPFC in power quality enhancement is investigated in Section IV. Finally, the case study and its simulation results are analyzed in the last part of this work.

2. INTRODUCTION TO DPFC

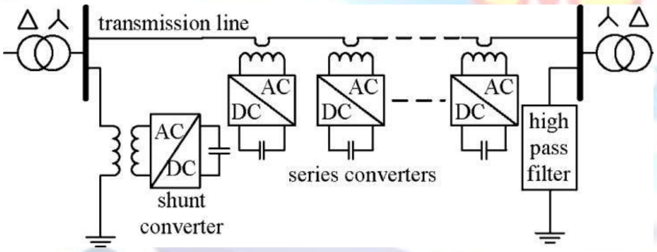


Fig 1: DPFC configuration.

The DPFC consists of one shunt and several series-connected converters. The shunt converter is similar as a STATCOM, while the series converter employs the D-FACTS concept, which is to use multiple single-phase converters instead of one large rated converter. Each converter within the DPFC is independent and has its own dc capacitor to provide the required dc voltage. The configuration of the DPFC is shown in Fig 1 , besides the key components, namely the shunt and series converters, the DPFC also requires a high-pass filter that is shunt connected at the other side of the transmission line, and two Y–Δ transformers at each side of the line. The unique control capability of the UPFC is given by the back-to-back connection between the shunt and series converters, which allows the active power to exchange freely. To ensure that the DPFC have the same control capability as the UPFC, a method that allows the exchange of active power between converters with eliminated dc link is the prerequisite. Within the DPFC, there is a common connection between the ac terminals of the shunt and the series converters, which is the transmission line. Therefore, it is possible to exchange the active power through the ac terminals of the converters. The method is based on the power theory of non sinusoidal components.

According to the Fourier analysis, a non sinusoidal voltage and current can be expressed by the sum of sinusoidal functions in different frequencies with different amplitudes. The active power resulting from this non sinusoidal voltage and current is defined as the mean value of the product of voltage and current. Since the integrals of all the cross product of terms with different frequencies are zero, the active power can be expressed by

$$P = \sum_{i=1}^{\infty} V_i I_i \cos \varnothing_i$$

By applying this method to the DPFC, the shunt converter can absorb active power from the grid at the fundamental frequency and inject the current back into the grid at a harmonic frequency. This harmonic current will flow through the transmission line. According to the amount of required active power at the fundamental frequency, the DPFC series converters generate a voltage at the harmonic frequency, thereby absorbing the active power from harmonic components. Assuming a lossless converter, the active power generated at fundamental frequency is equal to the power absorbed from the harmonic frequency. For a better understanding, Fig. 3 indicates how the active power exchanges between the shunt and the series converters in the DPFC system. The high-pass filter within the DPFC blocks the fundament frequency components and allows the harmonic components to pass, thereby providing a return path for the harmonic components. The shunt and series converters, the high-pass filter, and the ground form the closed loop for the harmonic current. Due to the unique characters of third-harmonic frequency components, the third harmonic is selected to exchange the active power in the DPFC. In a three-phase system, the third harmonic in each phase is identical, which is referred to as "zero-sequence." The zero sequence harmonic can be naturally blocked by Y–Δ transformers, which are widely used in power system to change voltage level. Therefore, there is no extra filter required to prevent the harmonic leakage to the rest of the network. In addition, by using the third harmonic, the costly high-pass filter, as shown in Fig. 3, can be replaced by a cable that is connected between the neutral point of the Y–Δ transformer on the right side in Fig. 2 and the ground. Because the Δ winding appears open circuit to the third-harmonic current, all harmonic current will flow through the Y-winding and concentrate to the grounding cable, as shown in Fig. 3. Therefore, the large-size high-pass filter is eliminated.

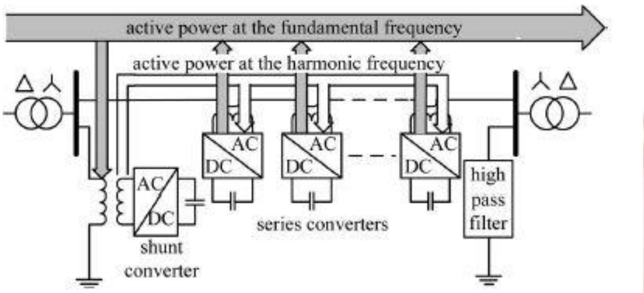


Fig. 2. Active power exchange between DPFC converters

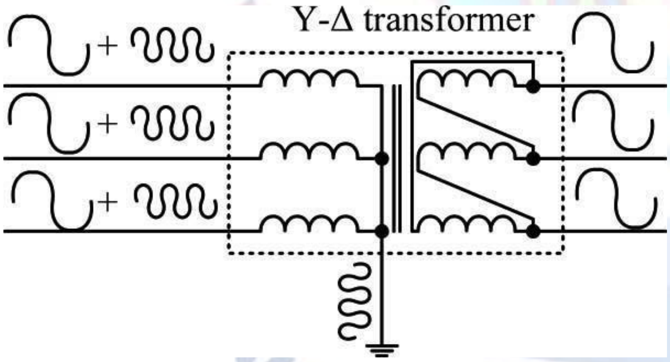


Fig 3 : Utilize Grounded Y–Δ transformer to provide the path for the zero-sequence third harmonic

Another advantage of using third harmonic to exchange active power is that the way of grounding of Y–Δ transformers can be used to route the harmonic current in a meshed network. If the branch requires the harmonic current to flow through, the neutral point of the Y–Δ transformer at the other side in that branch will be grounded and *vice versa*. Fig. 4 demonstrates a simple example of routing the harmonic current by using a grounding Y–Δ transformer. Because the transformer of the line without the series converter is floating, it is open circuit for third-harmonic components. Therefore, no third-harmonic current will flow through this line.

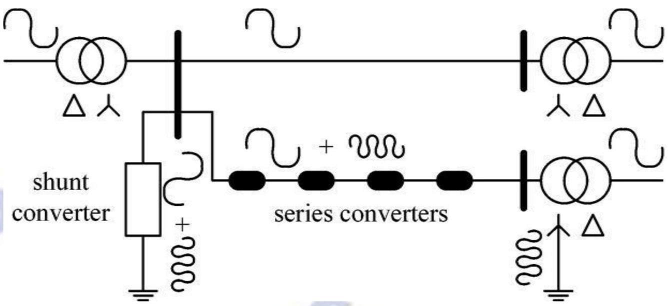


Fig.4 Route the harmonic current by using the grounding status of the Y–Δ transformer

Theoretically, the third-, sixth-, and ninth-harmonic frequencies are all zero-sequence, and all can be used to exchange active power in the DPFC. As it is well known, the capacity of a transmission line to deliver power depends on its impedance. Since the transmission-line impedance is inductive and proportional to the frequency, high transmission frequencies will cause high impedance. Consequently, the zero-sequence harmonic with the lowest frequency—third harmonic is selected.

3. DPFC CONTROL

The DPFC has three control strategies: central controller, series control, and shunt control, as shown in Fig. 5.

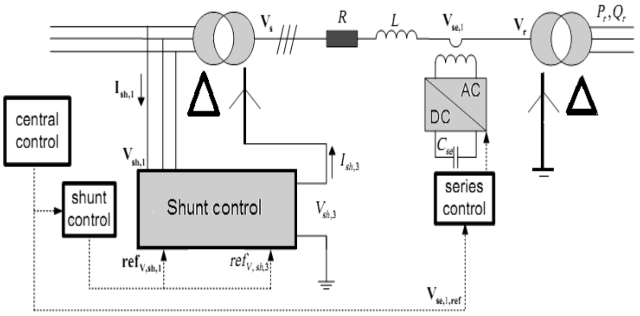


Fig. 5. DPFC control structure.

A. Central Control

This controller manages all the series and shunt controllers and sends reference signals to both of them.

B. Series Control

Each single-phase converter has its own series control through the line. This controller inputs are series capacitor voltages, line current and series voltage reference in dq-frame.

The expressions for voltages in dq-frame is

$V_d \cos \omega t$ (1)

$V_q \sin \omega t$ (2)

Now the reference voltage in fundamental component is

$V_{ref\,1} = V_d \cos \omega t + V_q \sin \omega t$ (3)

The error signal in dc link capacitor voltage is given by the difference between the reference voltage in dc link capacitor and the actual voltage and the expression is given as,

$V_{dc\,se} = V_{ref,dc} - V_{dc}$ (4)

The reference voltage in third harmonic component is given by,

$V_{ref,3} = V_{dc,se}.\ \sin 3\omega t$ (5)

Now the total voltage in series converter is,

$V_{ref} = V_{ref,1} + V_{ref,3}$ (6)

By using sinusoidal pulse width modulation we are generating the gate pulses for series converters.

Any series controller has one low-pass and one 3rd-pass filter to create fundamental and third harmonic current respectively. Two single-phase phase lock loop (PLL) are used to take frequency and phase information from network [11]. The simulated diagram of series controller is shown in Fig. 6

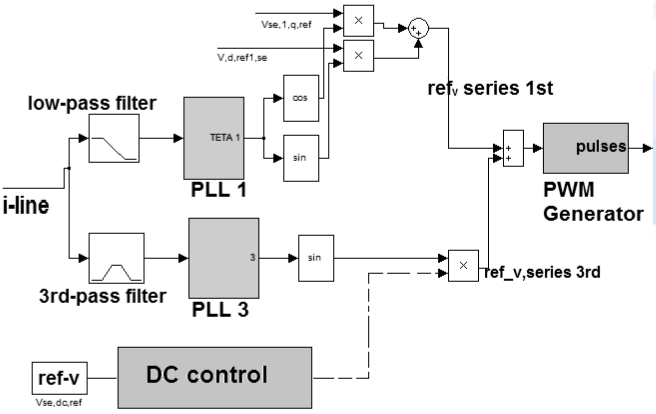


Fig. 6. The series control structure.

C. Shunt Control

The shunt converter includes a three-phase converter which is back-to-back connected to a single-phase converter. The three-phase converter absorbs active power from grid at fundamental frequency and controls the dc voltage of capacitor between this converter and single-phase one. The shunt control structure block diagram is shown in Fig. 7.

The voltages in dq-reference frame is V_{dref} and V_{qref} Now, the dqo is transformed into abc by using park's transformation.

$V_a = V_{dref} \sin\omega t + V_{qref} \cos \omega t + V_o$ (7)

$V_b = V_{dref} \sin(\omega t - 120) + V_{qref} \cos (\omega t - 120) + V_o$ (8)

$V_c = V_{dref} \sin(\omega t + 120) + V_{qref} \cos (\omega t + 120) + V_o$ (9)

By using PWM technique gate pulses are generated for shunt control circuit.

D. Third Harmonic Control

In third harmonic control circuit we have to change the fundamental frequency in to third harmonic frequency so, here we are multiplying with 3 to the frequency.

The voltages in dq0-reference frame is

$V_d = V_\alpha \cos 3\omega t + V_\beta \sin 3\omega t$ (10)

$V_q = V_\beta \cos 3\omega t - V_\alpha \sin 3\omega t$ (11)

$V_0 = 0$ (12)

Now, the dqo is transformed into abc by using park's transformation by using the equations (7), (8) and (9). By using PWM technique gate pulses are generated for third harmonic control circuit.

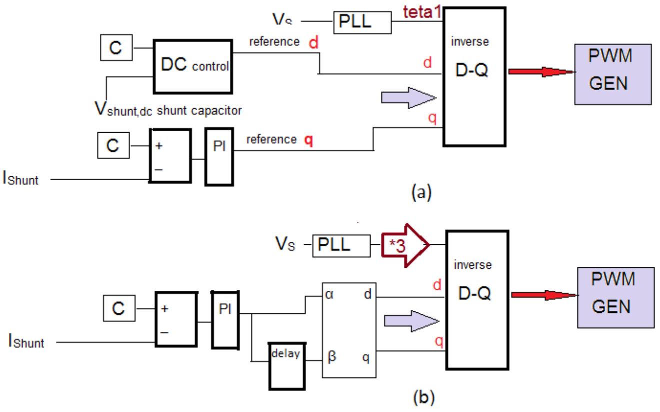


Fig. 7. The shunt control configuration: (a) for fundamental frequency (b) for third-harmonic frequency.

4. ADVANTAGES AND LIMITATIONS OF DPFC

The DPFC can be considered a UPFC that employs the D-FACTS concept and the concept of exchanging power through the 3rd harmonic. In this way, the DPFC inherits all their advantages:

- High controllability: the DPFC can simultaneously control all the parameters of the transmission network: line impedance, transmission angle and bus voltage.
- High reliability: the redundancy of the series converter gives high reliability with- out increasing cost. In addition, the shunt and series converters are independent and failure of one will not influence the other converters.
- Low cost: there is no phase-to-phase voltage isolation required between the series converters of different phases. The power rating of each converter is also low. Because of the large number of the series converters, they can be manufactured in series production. If the power system is already equipped with the STATCOM, the system can be updated to the DPFC with only low additional costs. However, there is a drawback to using the DPFC:
- Extra currents: Because the exchange of power between the converters takes place through the same transmission line as the main power, extra currents at the 3rd harmonic frequency are introduced. These currents reduce the capacity of the transmission line and result in extra losses within the line and the two Y-_ transformers. However, because this extra current is at the 3rd harmonic frequency, the increase in the RMS value of the line current is not large and through the design process can be limited to less than 5% of the nominal current.

5. POWER QUALITY ENHANCEMENT

This modelling has been developed using MATLAB/Simulink environment as shown in Fig. 8. The system is simulated with a three-phase source connected to a non-linear load. The simulation parameters are listed in Table 1. The supply is connected to load through the parallel transmission lines including the transmission line 1 and 2. The parallel transmission lines have same length. The DPFC is incorporated in transmission line 2. For analyzing dynamic performance, the inductive and capacitive loads are connected. The fault should be connected near the load to receive transient analysis. The shunt three-phase converter is connected to the transmission line 2 in parallel through a Y-Δ three-phase transformer, and series converters are distributed through this line.

6. SIMULATION RESULTS

The case study, considering sag/swell condition is implemented in single machine infinite bus system and analyzed results are as follows. To analyze voltage dip, a three-phase fault near the system load, as shown in Fig. 8 is created. The time duration for this fault is 0.5 seconds (500-1000 ms). The three-phase fault causes observable voltage sag during this time, as shown in Fig. 9. The voltage sag value is about 0.5 per unit. The DPFC can compensate the load voltage sag effectively. The voltage sag mitigation with
DPFC is shown in Fig. 10

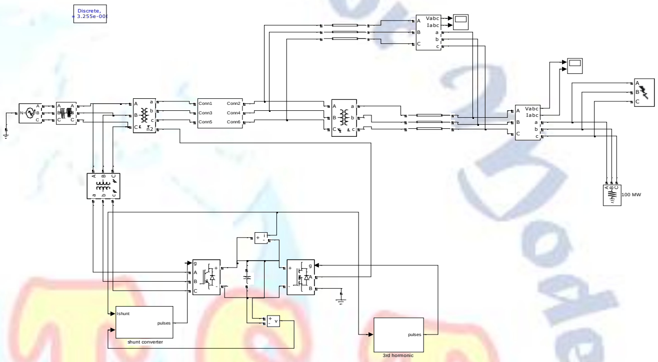


Fig. 8. Simulated model of the DPFC.

After creating three-phase fault, Fig. 11 depicts the load current swell around 1.1 per unit. The fault time duration is 0.5 seconds. In this case, after implementation of the DPFC, the load current magnitude is comparatively come down. The current swell mitigation for this case can be observed from Fig. 12. The load voltage harmonic analysis, using fast fourier transform (FFT) of power GUI window by *simulink*, as shown in Fig. 14. It can be seen, after DPFC implementation in system, the odd harmonics are reduced within acceptable limits and total harmonic distortion (THD) of load voltage is minimized.

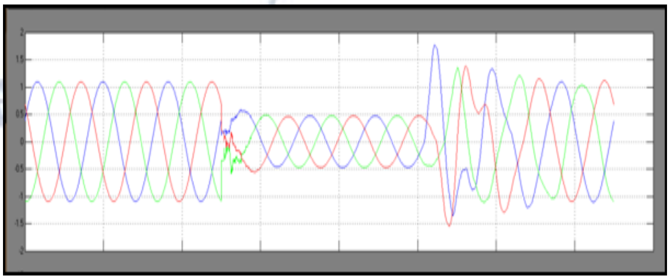


Fig. 9. Three-phase load voltage sag waveform.

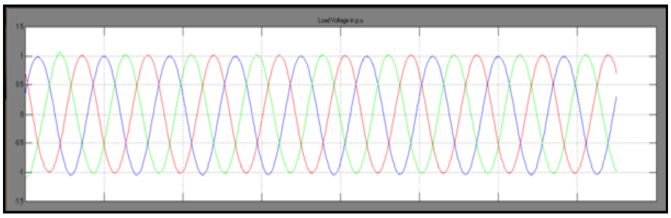


Fig. 10. Mitigation of three-phase load voltage sag with DPFC.

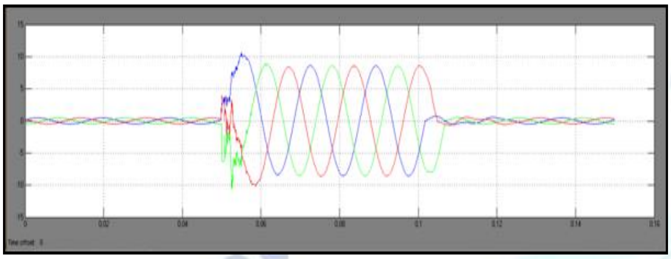


Fig. 11. Three-phase load current swell waveform.

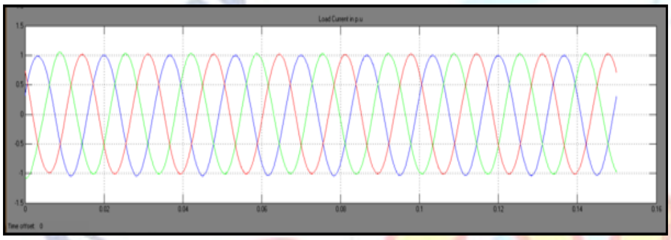
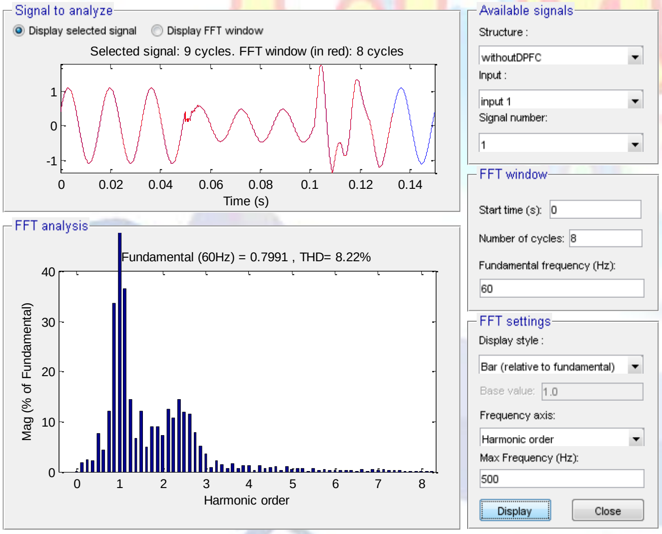


Fig. 12. Mitigation of load current swell with DPFC.



Signal to analyze

● Display selected signal ○ Display FFT window

Selected signal: 9 cycles. FFT window (in red): 8 cycles

FFT analysis

Fundamental (60Hz) = 0.7991 , THD= 8.22%

Available signals

Structure : withoutDPFC

Input : input 1

Signal number: 1

FFT window

Start time (s): 0

Number of cycles: 8

Fundamental frequency (Hz): 60

FFT settings

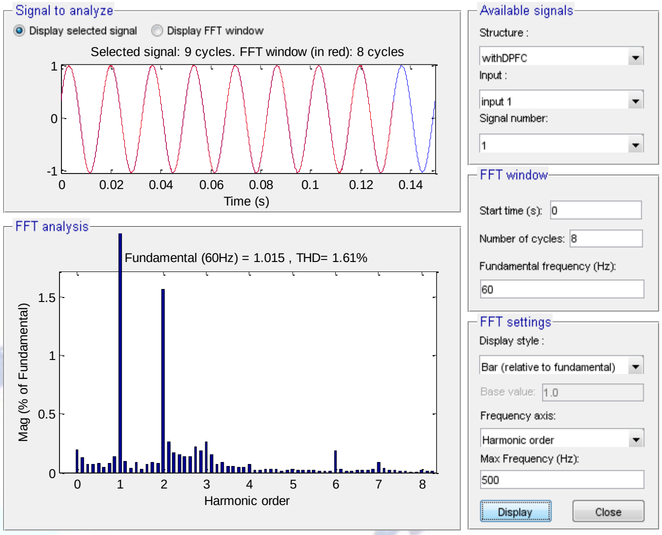
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 500

Fig. 13. The load voltage THD.



Signal to analyze

● Display selected signal ○ Display FFT window

Selected signal: 9 cycles. FFT window (in red): 8 cycles

FFT analysis

Fundamental (60Hz) = 1.015 , THD= 1.61%

Available signals

Structure : withDPFC

Input : input 1

Signal number: 1

FFT window

Start time (s): 0

Number of cycles: 8

Fundamental frequency (Hz): 60

FFT settings

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 500

Fig. 14. The load voltage THD.

7. CONCLUSIONS

The power quality enhancement of the power transmission systems is an vital issue in power industry. In this study, the application of DPFC as a new FACTS device, in the voltage sag and swell mitigation of a system composed of a three-phase source connected to a non-linear load through the parallel transmission lines is simulated in Matlab/Simulink environment. The voltage dip is analyzed by implementing a three-phase fault close to the system load. To detect the voltage sags and determine the three single phase reference voltages of DPFC, the SRF method is used as a detection and determination method. The obtained simulation results show the effectiveness of DPFC in power quality enhancement, especially in sag and swell mitigation.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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