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Design and Implementation of Hybrid Controller for Dynamic Power Management in a DC Microgrid

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Abstract: Nowadays more and more devices and appliances are operated with electricity, thus the electrical crisis is increasing exponentially day by day. In order to avoid the occurrence of electricity crisis, various power generation resources are used at the utility side to enhance the power generation to meet the consumers’ demand for electricity. Hence, a suitable control scheme has to be implemented at the microgrid to reduce the electrical fluctuation, power loss and manage the power quality. The Adaptive Proportional Integral Voltage Controller (APIVC) and hysteresis current controller (HCC) are integrated to enhance the quality of power generated. The electrical fluctuation is reduced by the proposed efficient hybrid parallel source controller model for DC Microgrid. The proposed model exerts decentralized control, which is an advanced droop control where communication is not required. The outer voltage control loop and inner current control loop provide faster control to maintain the grid voltage constant. The grid voltage is set as the reference value and the actual value is sensed to generate error value, which sets the reference value of current. The error signal is processed to provide switching signals for the converters. The performance analysis and simulation results show that the proposed mechanism performed better than the conventional methods such as Hysteresis Band Current Controller (HBCC) with Pulse Width Modulation (PWM) and Proportional Integral Voltage Controller (PIVC) with Hysteresis Current Controller (HCC), in terms of the electrical fluctuation, power loss and manage the power quality in the microgrid.

Keywords: Proportional integral voltage controller (PIVC); Hysteresis current controller (HCC); DC microgrid; Distributed energy sources (DES); Hysteresis Band Current Controller (HBCC); Pulse Width Modulation (PWM)

1. Introduction

The Microgrid (MG) forms a localized electrical network, which consists of interconnected loads, communication systems, and distributed energy sources (DES). This grid can be standalone or in the network. The efficiency and reliability of the system increase with the grid connection of the microgrid. In rural electrification system, the standalone microgrid has many advantages [1]. At present, as the performance of electronic equipment increases, the integration of micro-sources and DC loads can be achieved better in microgrid design. The system is also more efficient in transmitting DC power in the absence of skin effect and reactive power [2].

The microgrids use the static power converter between the loads and micro sources as the power interface. These converters’ output voltage is important for the microgrid for various purposes. The voltage of the converter is controlled with two methods: i) Proportional integral voltage controller (PIVC); ii) Hysteresis current controller (HCC).

The first method increases the system reliability without the need of communication and in the second method among the converters proper communication is required [3, 4].

In terms of PIVC technique, the output voltage of the converter is determined with the help of each source connected. The proposed method improves the voltage controller and comparative analysis of PI and HCC [5]. In literature, it is understood that linear controllers are less robust against the disturbance, therefore a non-linear controller is considered for better performance and regulation [6].

The main purpose of this research is to reduce electrical fluctuation, power loss, and manage the power quality. The proposed method efficiently integrates the two models such as an adaptive proportional integral voltage controller (APIVC) and hysteresis current controller (HCC).

This paper consists of the following sections: Section 1 Introduction; Section 2 Methodology of Proposed Work; Section 3 Mathematical Model for the Proposed Work; Section 4 Description of the Working Principle of Hybrid Parallel Source Controller Model for DC Grid; Section 5 Modeling and Simulation and Conclusion. Here, to make the system faster and to increase the steady state performance of a PIVC-based integrator, Hysteresis Mode Controller is adopted. A microgrid is modelled in the MATLAB/Simulink environment with three resistive load and solar sources. The DC Microgrid general block diagram is shown in Figure 1 and corresponding simulated results in terms of average power and DC grid voltage are reported [7, 8].

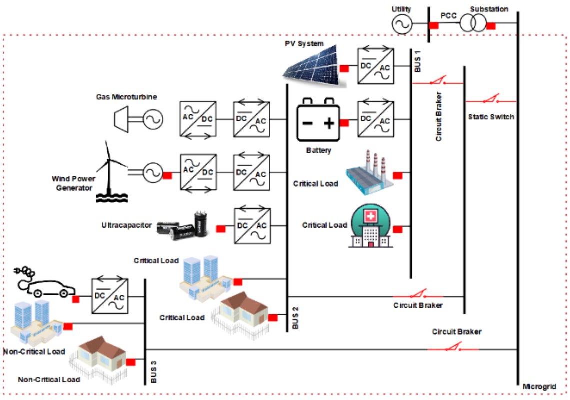

Figure 1. DC microgrid general block diagram

2. Methodology

2.1 Double Loop Control Using PI Controller

The PI controller is a classical controller which has been widely used in the control of microgrid. It finds application in many process control industries due to its robust performance. The DC offset gets removed by the integral action in the PI algorithm [9-11]. The PI controller has slower time response which reduces the maximum overshoot and improves the damping and causes zero offset values. The major limitation of this controller is the increase in rise time. In the microgrid, the error signal is obtained by subtracting the measured voltage from the desired voltage. The PI controller can regulate the frequency at AC bus of the microgrid and causes very few oscillations when the load fluctuates [12]. For a PI controller, the standard Eq. used to denote the output signal is given in Eq. (1):

$$y(t) = y_o(t) + K\, e(t) + \frac{K}{\tau}\int_0^t e(t)dt \tag{1}$$

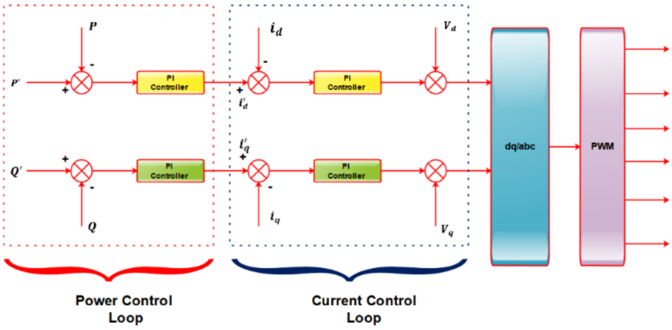

Figure 2. Double loop control scheme using PI controller

where, y(t) is the desired output fed into the system or processed as the modulated input; K is the controller gain and τ is the integral time constant of the controller. The PID controller is a linear controller and has low current Ripple with improved steady-state purpose [13-15]. A sinusoidal waveform with better quality can be obtained using a PID controller. It possesses good dynamics and high overload rejection. Figure 2 shows the PI control implemented in PWM Voltage Source Inverters (VSI). A Proportional resonant (PR) controller can be used to replace the conventional PID controllers in many systems. The PR controllers can achieve better performance in rejection of disturbance and sinusoidal reference tracking [16-18]. Compared to the conventional PI controller, this controller has better performance in terms of disturbance rejection capability and controller's inability to track sinusoidal reference with zero steady state error [19]. A PR controller can be implemented through discretizing pre-Tustin transformation to attain robustness in power flow [20]. The parameters of the PR controller can be adjusted through performing frequency response analysis to obtain desired performance of the controller. The frequency response analysis helps in altering the parameters of the controller to improve the overall performance. The LQR is basically a proportional controller, to which an integral action can be added to cancel the steady state error [21, 22]. The gain scheduling control algorithm will allow this controller to extend its application from small signal to large signal operation. LQ resonator (LQR) behaves like a proportional controller and causes a reduction in the static errors. The LQR includes improved voltage regulation, balanced load sharing and secured data in the system. However, the external noise that penetrates into the system cannot be avoided by this controller. If Kalman filter is used along with this system it can minimize the variance of the estimation error by taking into consideration the white noise (zero mean Gaussian random noise) [23]. If linear system has to be controlled, all of its states are calculated and has the criterion as a quadratic function of the states and control signal, then a linear quadratic (LQ) control system has to be designed [24].

The Hysteresis Mode Controller (SMC) is considered as a robust controller and exhibits better stability. The controller has changeable modes with switching criterion to toggle between on-off commands. The robustness and fast convergence properties of the Hysteresis mode control make it an attractive alternative for applications like unmanned aerial vehicles [25]. However, there exists the chattering phenomenon when the controller traces a reference control variable. The phenomenon of chattering no doubt causes physical damage to different parts in the system and requires increased energy for a better efficiency in performance. The states decide the hysteresis variable and the hysteresis surface represents the relationship among the state variables. It is a tedious task to design a hysteresis mode control to offer suitable transient and steady state performance. It is an extremely challenging task to design a hysteresis mode control to offer suitable transient and steady state performance [26]. If a suitable feed forward controller is connected to the hysteresis mode control, zero tracking speed will improve along with the improvement of performance of non-overshoot transients. An adaptive SMC has been used by the authors [27] to improve the efficiency of the grid connected photo voltaic array with three level neutral point clamp inverter.

2.1.1 Hysteresis current controller

The hysteresis controller is simple in design and implementation, which has fast response. This controller incorporates feedback current control method. The comparator compares the actual current value with the desired current value within a hysteresis band. The subtraction of the instantaneous values of reference currents from the actual source currents in the respective phases gives the error in current values [28-30]. Hysteresis controller is a simple nonlinear controller with no complex control circuitry involved for the current control. In this controller's action, a VSI makes the grid current to follow a reference pattern. The error generated by the controller produces the switching waves, as shown in Figure 3:

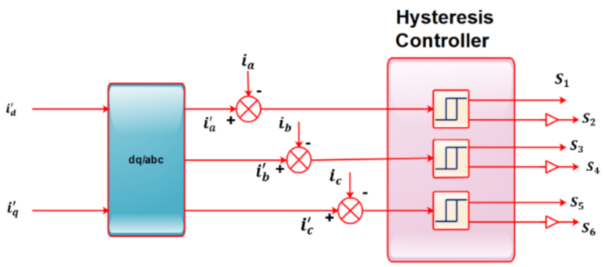

Figure 3. Hysteresis current controller

A hysteresis band with the minimum width is maintained in order to minimize the error. The authors [31] described a double band hysteresis current controller that monitors and controls the active power and reactive power flow from RES to the utility grid along with a voltage source inverter. In this work, in order to have efficient performance of the controller, three modes of operation have been discussed depending on availability of RES.

2.2 Paralleled Sources Control

The arranging of converters in parallel structure has more advantages compared to one single high-power converter. The PIVC and HCC are the two different methods to control paralleled energy sources used in a microgrid.

2.2.1 Proposed Proportional Integral Voltage Controller

Figure 4 shows the voltage controller scheme to control parallel connected energy sources used in a microgrid. The output voltage of the converter reduces automatically when the current supplied raises and the controller exhibits an impedance behavior. This PIVC provides sharing proper current between converters connected in parallel. Figure 5 shows the voltage controller of the dc-dc converter. From Figure 4, we can find out P_{ref} as given in Eq. (2).

$$P_{ref} = G(s)[V_{ref} - (\frac{w_{LP}}{S + w_{LP}})V_{dc}]V_{dc} \tag{2}$$

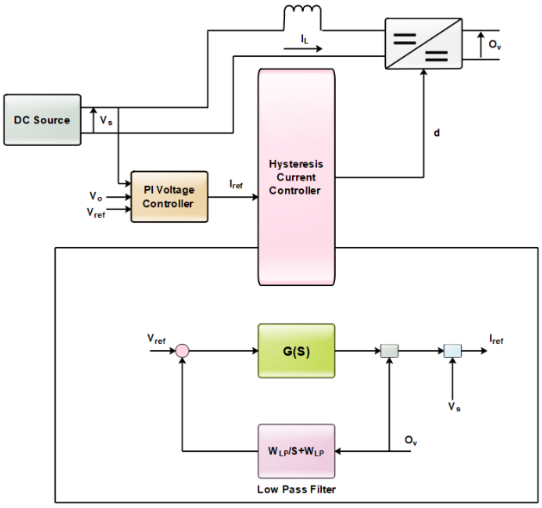

Figure 4. Voltage control scheme- DC-DC converter using parallel source controller

where, P_{ref} is described as power reference of DC-DC converter, V_{ref} is identified as voltage reference, and H(s) represents cut-off frequency of low pass filter, S is described as input source, and V_{dc} is described as converter output voltage. From Eq. (3), we can find required current reference for each converter, where V_s is the DC source voltage.

$$I_{ref} = \frac{P_{ref}}{V_s} \tag{3}$$

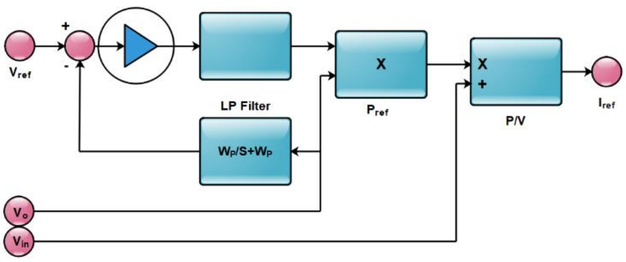

Figure 5. Voltage controller of the dc-dc converter

2.2.2 Adaptive master slave control

In the adaptive master slave control method, one converter acts as Adaptive master and others are acts as slaves. The master block provides the reference current to converts of slaves and grid DC voltage is controlled by the master block. Therefore, it needs fast communicating network to make the system less reliable and higher cost than normal voltage controller method.

2.3 Design of an Efficient Hybrid Parallel Source Controller Model for DC Microgrid

In the regulation curve, the voltage controller characteristic has negative slope. However, the higher the slope, it provides the poor voltage regulations and better current sharing accuracy. Hence, always there is tradeoff between these parameters in the design process. In the present work, controller PI is used to control the microgrid's parallel-connected converters.

2.3.1 Proposed adaptive controller design

The APIV controller forward path transfer function is provided in Eq. (4), where controller integral time constant is denoted as T_i and the proportional gain is denoted as k_p. In this case the effect of controller proportional gain is the same as the series of connected resistance to the dc source.

$$G(s) = k_p[1 + \frac{1}{sT_i}] \tag{4}$$

Hence, the gain k_p can be represented as Eq. (5).

$$G(s) = k_p = \frac{1}{R_{d,i}} \tag{5}$$

where, the converter number is represented by subscript i. The Eq. (6) can be simplified as follows by considering the rated power of the source with 0dB gain.

$$P_{rated,i} = \delta_i(1 - \delta_i)\frac{v_{ref,i}^2}{R_{d,i}} \tag{6}$$

where, rated power nominal droop rate is represented as δ_i, R_d is a controller resistance which is found through assigning P_{rated}, V_{ref}, and δ_i for each converter. There is the need of steeper controller characteristic for better sharing of load, bit it provides poor voltage regulation. Hence it requires optimum value of δ_i which is given in [32]. The authors in [33] described the time constant T_i of PI which is given in Eq. (7). Table 1 shows the proposed method's parameters for the efficient voltage controller.

$$T_i = \frac{4}{w_{LP}} \tag{7}$$

Table 1. APIV controller parameters

Parameter	Value
$T_i(ms)$	12.73
k_p	3.5

2.4 Design of Hysteresis Mode Controller

The voltage controller scheme based on the Hysteresis Mode Control is discussed. Between each solar source and grid, a boost converter is connected as a power interface. The Eq. (8) represents the state space of boost converter [34-36].

$$\begin{bmatrix} l_i \\ o_v \end{bmatrix} = \begin{bmatrix} 0 & -\frac{(1 - d_c)}{L} \\ \frac{(1 - d_c)}{O_c} & -\frac{1}{L_o O_c} \end{bmatrix} \begin{bmatrix} l_i \\ o_v \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ O \end{bmatrix} V_s \tag{8}$$

In Eq. (8), d_c represents the duty cycle, l_i and o_v is the inductor current and converter output voltage, and the load resistance is denoted by L_R. Table 2 shows the parameters consider during converter process [37-40].

Table 2. Converter parameters

Parameter	Range
L_R	$7\Omega\ (700W)$
L	$1mH$
O_c	$6mF$

The inductor current and DC microgrid voltage is controlled simultaneously, for each converter the hysteresis surface is given in Eq. (9), and the law of control of proposed adaptive PI Controller is given in Eq. (10) [41-44].

$$A_p(e_{ai} - \tau) = k_v e_v + k_i e_i \tag{9}$$

where

$$e_v = \left(V_{ref} - O_v\right)\ and\ e_i = (i_{ref} - i_L) \tag{10}$$

where, A_p represents the Adoptive PI controller circuit parameter, and e_{ai} is described as the efficiency of APIVC. The law of control is given in Eq. (11) [45-49].

$$c(\tau) = \delta(\tau) = \begin{Bmatrix} 1, & if\ A_p(e_{ai}, \tau) > 0 \\ 0, & if\ A_p(e_{ai}, \tau) < 0 \end{Bmatrix} \tag{11}$$

The existing and reaching conditions is satisfied by taking into account the above law of control as given in Eq. 12 and Eq. (13) [50-52].

$$A_p(e_{ai}, \tau) < 0, if\ d_c(\tau) = 1 \tag{12}$$

and

$$A_p(e_{ai}, \tau) > 0, if\ d_c(\tau) = 0 \tag{13}$$

From the derivative of (6), the gain $k = \frac{k_v}{k_i}$ can be found out as given in Eq. (14) and Eq. (15). The results are described by Eq. (16):

$$A_p(e_{ai}, \tau) = -kO_v - l_i < 0 \tag{14}$$

$$k\left[\frac{1}{O_r - O_c}\right] < \left[\frac{V_s}{L}\right] \tag{15}$$

$$k < \frac{O_r O_c}{L}\frac{V_s}{O_v} \tag{16}$$

Over a wide range of operation to guarantee stability, the Hysteresis mode coefficient is found as given in Eq. (17):

$$k < \frac{O_r O_c}{L}\frac{V_{s,min}}{O_{v,min}} \tag{17}$$

The value of k is determined by replacing the converter parameters used in the Table 1 and mathematical condition as shown in Eq. (18).

$$k = \frac{k_v}{k_i} < 4.56 \tag{18}$$

To obtain the robust and fast response against the system disturbances, $k_v = 0.6$ and $k_i = 11$ were chosen for the hysteresis coefficients. Also, stability of the system is improved as compared to normal voltage controller.

3. Modelling and Simulation

At present, three solar modules were connected in parallel. The boost converter is connected to each source hence it produces constant output voltage irrespective of the variations in solar input. The bus voltage used for simulation was 60V. Figure 6 shows the proposed voltage controller diagram. The produced reference current of voltage controller feeds to the hysteresis controller. The hysteresis controller output is in duty ratio required for the boost converter. A hysteresis band of $\pm 2A$ is used. During the first time of study for each DC sources, 24 V ideal sources were used and power rating of each source is 600W. In the designing of Proposed Adaptive Proportional Integral Voltage Controller, $R_{di} = 0.285$ Ώ is used. The parameters of PI are determined by considering $W_{LP} = 100\pi\, rad/s$ and $\partial_i = 5\%$. Figure 7 and Figure 8 show the comparison analysis between the proposed and conventional methods with respect to the bus voltage and average power respectively, with the grid voltage of steady state value being 57.5V and 0.3s time is taken by the converter to find its final value. During the analysis of the renewable sources shared average power of the grid, the final value is 182W and the time is 0.3 s.

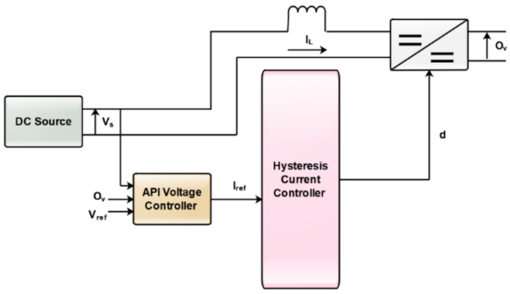

Figure 6. Simulink block diagram of proposed voltage controller

In the second time of study, the same load and sources are used for the simulation. But, APVC output is connected to the SM controller. Also reference voltage is determined using PI controller for the VDC in normal voltage controller technique.

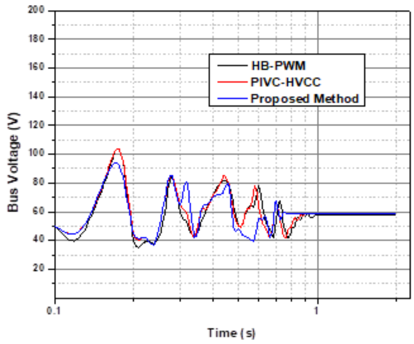

Figure 7. Comparison analysis between proposed model and conventional methods with respect to the bus voltage at grid voltage 57.5V

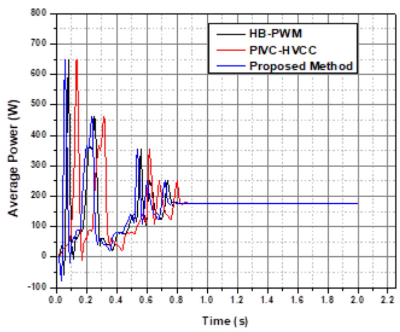

Figure 8. Comparison analysis between proposed model and conventional methods with respect to average power supplied by sources at grid voltage 57.5V

The bus voltage and average power sharing among each source for proposed controller and conventional controllers is shown in Figure 9 and Figure 10. The grid voltage of 58.5 V forms steady state value. As compared to the SM, more regulated output voltage is produced as compared to PI controller. In producing the voltage regulation, the integral component is playing an important role in the voltage controller. The time of settling the output voltage of SM controller is 0.15 s. The response of SM controller is much faster than the PI controller. The sources average power shared is around 190W, which is also better as compared to 182W in Voltage Controller. However, the integrator used in the voltage controller may cause the increase of overshoot in the system. The stable system is also not stable in varying load conditions with constant value of controller resistance. Therefore, to have system stable in varying load conditions an adaptive Hysteresis Mode controller is suggested in future work. Figure 11 shows various parameters comparison like bus voltage fluctuation and average power for the proposed and conventional methods for two different grid voltage.

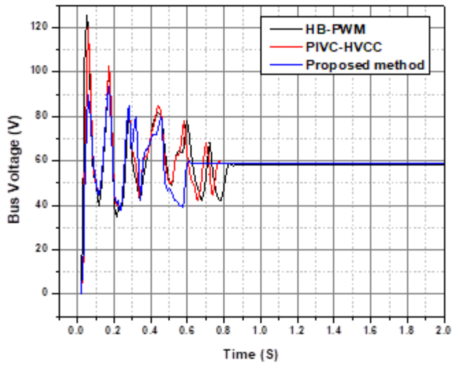

Figure 9. Comparison analysis between proposed model and conventional methods with respect to the bus voltage at grid voltage of 58.5V

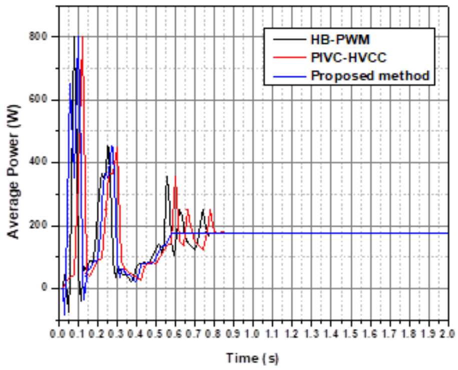

Figure 10. Comparison analysis between proposed model and conventional methods with respect to average power supplied by sources at grid voltage 58.5V

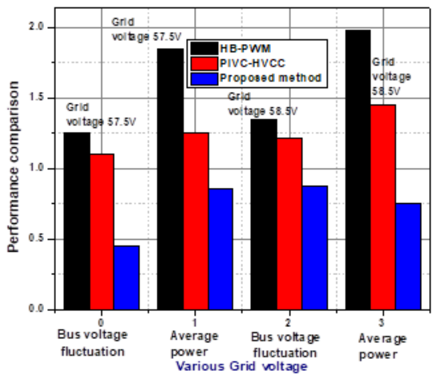

Figure 11. The various parameters comparison like bus voltage fluctuation, average power for the proposed and conventional methods for two different grid voltages

4. Conclusion

In this paper, a hybrid controller for dynamic power management of a DC Microgrid has been implemented. Multiple energy resources are connected to DC bus via boost converters. The proposed system is compared with conventional system on a DC microgrid fed by multiple renewable energy sources. The DC bus voltage reference is taken as 60V. The grid voltage of the conventional controller maintained at 56.2V and the grid voltage of the proposed controller scheme maintained at 57.8V, which shows better voltage regulation of the DC microgrid by the proposed controller. The settling time of the output voltage by the conventional controller is 0.32s and the proposed controller is 0.15s. This shows the proposed controller has a quick response and reduced settling time, increasing margin of stability. The system is capable of handling different renewable energy sources at the utility side and also avoids fluctuation in electricity and also minimizes power loss at consumer side.

Future Scope: The system can be improvised by adding other available energy resources. The system can be made smart by the implementation of IoT and energy consumption data can be made available to consumers.

Data Availability

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

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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