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Impact of wind shear and tower shadow on the small signal stability of power systems incorporating wind turbines

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Abstract

This paper investigates the influence of 3p oscillations caused by wind shear and tower shadow on the power output of wind turbines and small signal stability of power systems incorporating wind turbines. First, the time-domain inputs of factors that affect 3p oscillations are modelled and its effect on power system small signal stability are determined via modal analysis. The whole system is modelled using power system toolbox in Matlab environment. Some of the key results reveal that 3p oscillations could result into fluctuating electric power fed to the grid, however, it may not necessarily result into small signal instability of the grid.

Keywords: Wind shear, tower shadow, small signal stability, wind turbine

1. Introduction

In recent years, wind energy has been identified as one of the potential solutions to meet the ever increasing demand for energy in a sustainable and environmentally friendly manner [1]. However, with the increase of grid connected wind farms, the power system operates closer to its stability limits as a result of stochastic nature of wind power. Wind turbines are basically of two types: the variable speed wind turbines which make use of doubly fed induction generators or directly driven synchronous generator, and the fixed speed wind turbines usually of squirrel cage induction generators. Fluctuation in output power is less of a concern in the variable speed turbines compared to fixed speed wind turbines [2]. This is because the variable speed wind generators do compensate for power output fluctuations using the associated power electronic converters.

In spite of the advantages of variable speed wind turbine technologies, there are still many wind farms around the world that make use of fixed speed wind technologies as a result of its cost effectiveness, ruggedness and high maintainability [3]. However, there are oscillatory challenges associated with the use of fixed speed wind turbines due to wind shear and tower shadow commonly referred to as 3p oscillations.[4]. Wind shear is the variation of wind speed with reference to height while tower shadow is the effect resulting from redirection of wind flow due to the presence of the wind turbine hubs and blades [5]. The surplus and shortage of energy stemming from transient gusts and oscillation are transferred to the grid, causing power fluctuations [6] as a result of inability of fixed speed wind turbine technology to change speed in excess of the slip speed (1–2%). The fluctuating wind power resulting from this oscillation possesses the ability to force oscillations at frequencies close to the natural frequency of the power system. [7] which could trigger small signal instability on the grid. Small signal stability problems occur when there is an insufficient damping of system oscillations as a result of changes in the operating parameters of a power system [8].

In this paper, a fixed speed wind power generator is used to analyze the instantaneous effects of wind

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shear and tower shadow on the power output of a wind turbine as well as the small signal stability of a power system using IEEE two Area network.

2. Wind Speed Model Due to Tower Shadow and Wind Shear

The equivalent wind speed extracted by the turbine blades due to wind shear and tower shadow can be written as:

$$V_{eqT} = V_h + V_{eqws} + V_{eqtw} \tag{1}$$

where V_h is the nominal wind speed at the hub height, V_{eqws} is the equivalent wind speed due to wind shear and V_{eqts} is equivalent wind speed due to tower shadow.

2.1. Wind speed disturbance and equivalent wind speed due to wind shear

Wind speed increases with height, therefore, upward facing blades would experience higher wind speeds compared to downward facing blades. The interaction of the turbine rotating blades with the varying wind speed causes fluctuation in the torque and power produced by the turbine. In one full revolution, turbine blades of a three bladed wind turbine would experience a dip in output power three times due to the three blades on the wind system [3]. The wind turbine system showing the upward and downward blades is depicted in Fig. 1 while the respective azimuthal position of a three bladed turbine in one revolution is depicted in Table 1.

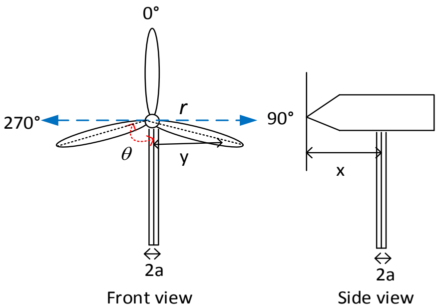

Fig. 1. The wind turbine system showing upward and downward blade

Table 1. Respective azimuthal position of a three bladed turbine in one revolution.

1st blade	0	30	60	90	120	150	180	210	240	270	300	330	360
2nd blade	120	150	180	210	240	270	300	330	0	30	60	90	120
3rd blade	240	270	300	330	0	30	60	90	120	150	180	210	240

A well-known wind shear model is generally written as:

$$V(z) = V_h (Z / H)^{\alpha} \tag{2}$$

where H is the tower height, V_h is the nominal wind speed at hub height H , Z is the elevation above ground, α is the empirical wind shear exponent and its values for different terrains are given in Table 2.

Table 2. Exponential shear values for different terrains

Terrain	α
Smooth, hard ground, lake ocean	0.1
Smooth, level, grass covered	0.14
Tall row crops, low bushes with few trees	0.2
Many trees, occasional buildings	0.24

Equation (2) can be re-written in terms of function of R (radial distance from rotor axis) and θ (blade azimuthal angle) as follows [3]:

$$V(r,\theta)=V_h\left[\frac{r\cos\theta+H}{H}\right]^{\alpha}=V_h\left[1+W_s(r,\theta)\right] \tag{3}$$

where r is the radial distance from the rotor axis, $W_s(r,\theta)$ is the disturbance seen in wind speed due to wind shear and can be approximated by a third order truncated Taylor's series as follows:

$$W_{(r,\theta)}=\alpha(\frac{r}{H})cos(\theta)+\frac{\alpha(\alpha-1)}{2}(\frac{r}{H})^2 cos^2(\theta)+\frac{\alpha(\alpha-1)(\alpha-2)}{6}(\frac{r}{H})^3 cos^3(\theta) \tag{4}$$

Therefore, the equivalent wind speed due to wind shear is given by:

$$Veqws=\frac{2V_H}{3r^2}(\sum_{b=1}^{3}\int_0^R r^2(\frac{\alpha}{H})\cos^2(\theta_b)+\frac{r^3\alpha(\alpha-1)}{2H^2}+\frac{r^4\alpha(\alpha-1)(\alpha-2)}{6H^3}\cos^3(\theta_b)dr \tag{5}$$

2.2. Wind speed disturbance due to tower shadow

Wind speed is affected by the presence of tower, this is because the wind directly in front of the tower is redirected and thereby reduces the torque at each blade when in front of the tower. The torque pulsations due to tower shadow are most significant when a turbine has blades downwind of the tower [9]. Using the reference frame, the wind speed with tower shadow disturbance is given as:

$$V_{(x,y)}=V_H+V_{tw}(x,y) \tag{6}$$

where $V_{tw}(x,y)$ is the disturbance observed in the wind speed due to the tower shadow and can be expressed as:

$$V_{tw}(x,y)=V_H\left[1+\frac{a^2\left(y^2-x^2\right)}{\left(x^2+y^2\right)^2}\right] \tag{7}$$

Equation (7) can be re-written in terms of radial distance R and azimuthal angle θ as follows:

$$V_{tw(r,\theta,x)}=V_h\frac{a^2(r^2 sin(\theta)^2-x^2)}{(r^2 sin(\theta)^2+x^2)^2} \tag{8}$$

It should be noted that (7) and (8) are only valid when the blades are in the lower hemisphere of its orbital i.e. $90°\le\theta\le 270°$. Tower shadow effects are absent when the blades are in the upper hemisphere of orbital as depicted in Table 3, this is due to the absence of the tower behind the blades.

Table 3. azimuthal position of a three bladed turbine in one revolution due to tower shadow.

1st blade	0	0	0	90	120	150	180	210	240	270	0	0	0
2nd blade	120	150	180	210	240	270	0	0	0	0	0	90	120
3rd blade	240	270	0	0	0	0	0	90	120	150	180	210	240

Therefore, the equivalent wind speed due to tower shadow is obtained as:

$$V_{eqtw}=\frac{2V_h}{3r^2}\sum_{b=1}^{3}\int_0^R\left[\frac{ma^2(r^3 sin^2(\theta_b)-rx^2)}{r^2 sin^2(\theta_b)+x^2}\right]dr \tag{9}$$

where m is the coefficient of wind turbine and is given as:

$$m=\left[1+\frac{\alpha(\alpha-1)r^2}{8H^2}\right] \tag{10}$$

2.3. Equivalent torque due to tower shadow and wind shear

The total equivalent torque consisting of the nominal torque, torque due to wind shear and torque due to tower shadow is determined as: [3]

$$T_{aero}(t,\theta)=\frac{1}{2}\frac{\rho A V_h^{3} Cp(\psi)}{\omega_{rotor}}+\sum_{n=1}^{3}\int_0^R \frac{2\rho A V_h Cp(\psi)}{3R\psi} R(V_{eqT}-V_h)dR \tag{11}$$

Simplified equivalent torque representing aerodynamic torque due to kinetic energy in wind as well as torque due to tower shadow and wind shear is obtained as:

$$T_{aero}(t,\theta)=\frac{1}{2}\frac{\rho A V_h^{3} Cp(\psi)}{\omega_{rotor}}+\frac{\rho A V_h Cp(\psi) R}{\psi}\left[V_{eqws}+V_{eqts}\right] \tag{12}$$

where R is the radius of the rotor blade, A is the cross sectional area of the blade, ω_{rotor} is the turbine rotor speed, Cp is the fraction of available wind power that is converted to turbine mechanical power and is a function of the tip speed ratio (ψ), V_{eqws} and V_{eqts} are the equivalent wind speed due to wind shear and tower shadow as given in equations (5) and (9), respectively.

The mechanical power generated by the wind turbine can therefore be written as:

$$P_m(t,\theta)=T_{aero}(t,\theta)\times\omega_t \tag{13}$$

where ω_t is the wind turbine rotor speed.

3. Modelling of the Small Signal Stability of Analysis

It is intuitive to believe that the fluctuation in wind speed extracted by wind turbine blades as a result of wind shear and tower shadow could trigger small signal instability due to fluctuation in aerodynamic torque produced by the turbine. Therefore, there is need to understand the influence of the 3p oscillation on the damping of a power system. Generally, a power system can be represented by (14) and (15):

$$\dot{k}=f(k,u,t) \tag{14}$$

$$q=g(k,u,t) \tag{15}$$

where

$$k=(k_1,k_2,.....,k_n)^T$$
$$u=(u_1,u_2,....,u_n)^T$$

k is the state vector, u is the input vector and q is the output vector.

Modal analysis can be used to study the small signal characteristic behaviour of a dynamic system by linearising (14) and (15) at the system equilibrium as (16) and (17) [10]

$$\Delta\dot{k}=A\Delta k+B\Delta u \tag{16}$$

$$\Delta q=C\Delta k+D\Delta u \tag{17}$$

Subsequently, the system stability subject to a small disturbance such as disturbances due to wind shear and tower shadow is based on the state matrix A

$$det(\lambda I-A)=0 \tag{18}$$

The values of λ that satisfy equation (18) are the eigenvalues of matrix A. They contain information about the response of the system to a small perturbation. The eigenvalue can be real and/or complex. The complex values appear in conjugate pairs if A is real (19).

$$\lambda_i=\sigma_i\pm j\omega_i \tag{19}$$

where σ_i is the real part of the eigenvalue and ω_i is the imaginary part. The frequency of oscillation in, Hz, and the damping ratio are given by (20) and (21):

$$f = \frac{\omega_i}{2\pi} \tag{20}$$

$$\xi = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \tag{21}$$

4. System under Study

The oscillatory modes that can trigger small signal instability when excited in power systems are the weakly damped inter area oscillatory modes. In this paper, the influence of wind shear and tower shadow on the inter-area oscillatory mode of a power system network was tested on IEEE two area network as depicted in Fig. 2. The network consists of 4 generators separated into two areas and interconnected by a tie line. The wind turbine is connected to the network at bus 130. The network was modelled using power system tool box in Matlab environment. The data of the IEEE power system as used in this paper can be found in [11] while that of the wind turbine is furnished in [3].

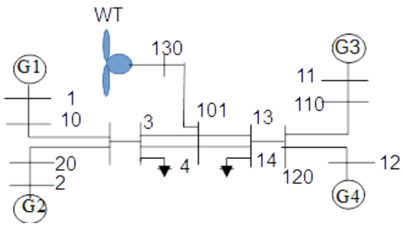

Fig. 2. IEEE two area network incorporating a wind turbine

5. Results and Discussion

This section presents the detailed discussion of the results of the study

5.1. Impact of influencing factors on wind shear and tower shadow

Parts of the factors that influence wind speed extractable by the wind turbine blades due to wind shear are hub height (*H*) and shear exponent (α). The effects of these factors on the extractible wind by the turbine blade is depicted in Fig. 3. The figure reveals that lowest wind speeds are extracted by the turbine blades when azimuthal angle is $180°$ (i.e when the blades are pointing downwards) and maximum when the angle is $0°$ (i.e when the blades are pointing upward). Fig 3(a) shows that extractible wind speed increases with the increase in turbine hub height. The shear exponent (α) depends on the terrain as indicated in Table 2 and from Fig. 3(b), the extractable wind speed decreases with increase in shear exponent.

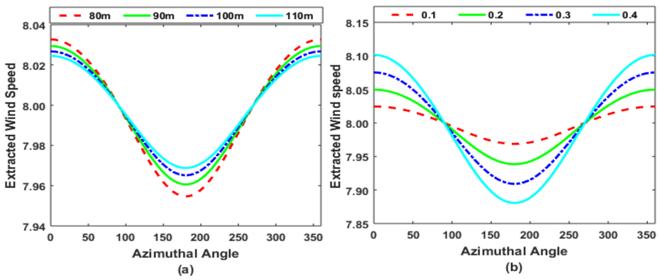

Fig.3. Effect of (a) hub height (H) and (b) shear exponent (α) on the wind speed extractible by wind turbine blades experiencing a nominal wind speed of about 8m/s

Similarly, some of the influencing factors due to tower shadow are the lateral distance of blade origin from tower (x) and the cross-sectional area of the tower hub (a). The effect of these factors on the extracted wind speed by the turbine blades are depicted in Fig.4

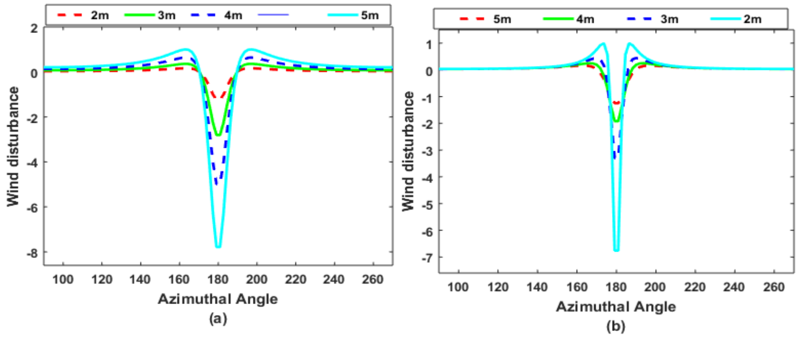

Fig. 4. Disturbance as a result of tower shadow due to (a) the cross sectional area of hub (a) and (b) the distance of blade to rotor axis(x)

5.2. Impact of wind shear and tower shadow on power output of a wind turbine

The nominal wind speed in this paper is taken as 8m/s. A reduced value is extracted by the wind turbine as a result of the disturbances due to wind shear and tower shadow. The amount of dip in wind speed due to these disturbances is depicted in Fig. 5. The figure reveals that tower shadow has much higher impact compared to the wind shear. The impact of both the wind shear and tower shadow on the power output of a wind turbine is depicted in Fig. 6. The figure reveals that 3p oscillations could result into flickering in a power system.

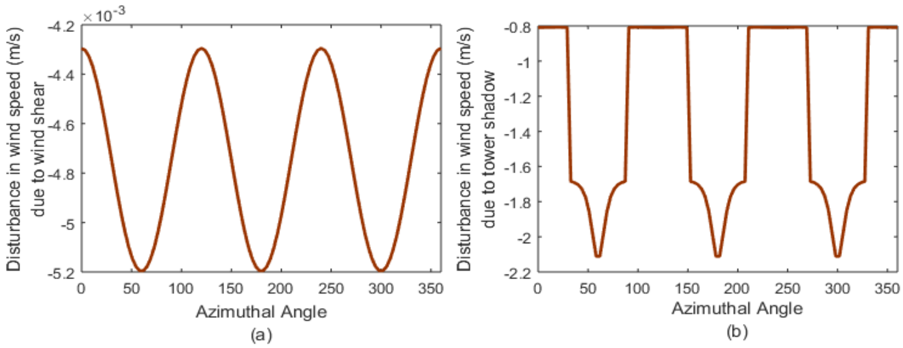

Fig. 5. Disturbance in wind speed due to (a) wind shear (b) tower shadow

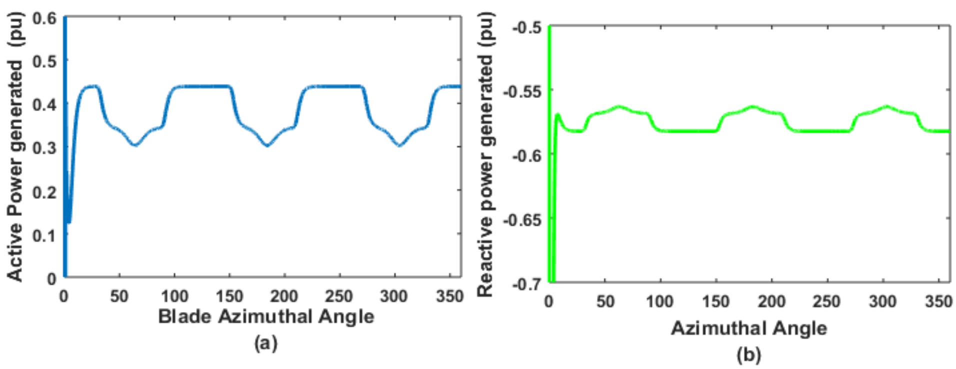

Fig. 6. (a) Real power generated (b) Reactive power generated by turbine generator from mechanical torque impacted by wind shear and tower shadow.

5.3. Influence of tower shadow and wind shear on the Small signal stability of power system

The wind turbine was connected to the IEEE two-area network at bus 101 and modal analysis was conducted using the small signal stability tool available in power system toolbox in Matlab environment. A total of 26 modes were obtained with all the modes having negative real values indicating that the system was strongly stable. Of these modes, 5 are oscillatory in nature (i.e. appear in conjugate pair). The eigenvalues, frequency and the damping ratio of the oscillatory modes are depicted in Table 4. The mode of interest is the oscillatory inter-area mode as it can trigger small signal instability in a power system. Therefore, further check was conducted to determine the inter-area mode(s) among the oscillatory modes by determining the number of state variables contributing to each of the oscillatory modes (i.e determining the participation factor). Mode 1 with eigenvalue of -0.2325 ±3.4899i, frequency of 0.5554Hz and damping ratio of 0.06646 was found to be inter area mode. It involves the rotor angle of generators 1 and 2 oscillating against the rotor angle of generators 3 and 4.

Table 4. Oscillatory modes in the power system with wind turbine connection

Oscillation Mode	Eigenvalue	Frequency (Hz)	Damping ratio
Mode 1	-0.2325 ±3.4899i	0.5554	0.06646
Mode 2	-1.2001 ±6.0282i	0.9594	0.19524
Mode 3	-0.5449 ±6.7399i	1.0726	0.08058
Mode 4	-0.5139 ±6.8109i	1.0839	0.07524
Mode 5	-4.2428 ±18.12049i	2.8839	0.22798
Mode 6	-7.0491 ±21.3782i	3.4024	0.31315

The influence of wind shear and tower shadow on the inter-area oscillatory mode (mode 1) was studied in one revolution of blade rotation. The movements of the oscillatory mode are depicted in Fig. 7. The figure reveals that the rotation of the blades causes fluctuation in both the damping and frequency of the inter-area mode, although within a small merging of 0.06646-0.06647 and 0.555434-0.55544, respectively. Hence, the wind shear and tower shadow could not result into small signal instability in a strongly damped power system although could cause flickering in a power system.

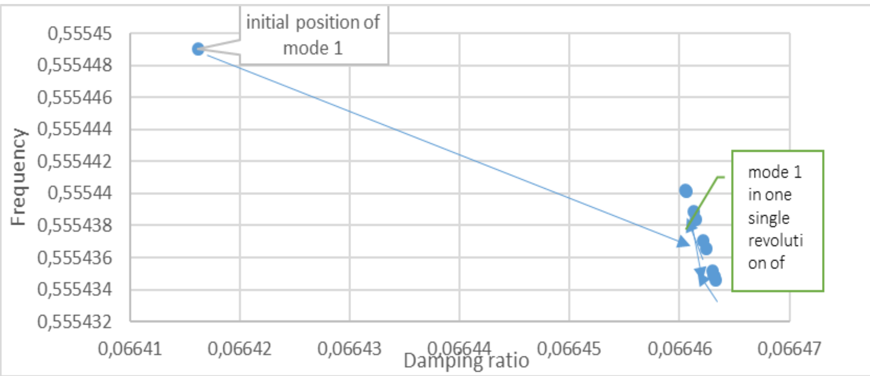

Fig. 7. Movement of the oscillatory mode 1 in one revolution of wind blade

5.4. Sensitivity analysis

The influence of change in nominal wind speed (V_h) as well as the radial distance of the rotor (r) on the damping of the inter-area oscillatory mode were studied and the results are depicted in Figs. 8 and 9, respectively. Fig. 8 reveals that when wind speed was increased from 5m/s to 7m/s, the damping of the inter-area mode was improved, however, when the wind speed was further increased, the damping of the inter area mode decreases. This indicates that there is a maximum wind speed beyond which damping of electromechanical mode decreases. It can also be deduced from Fig. 9 that an increase in the radial distance of the rotor blade would have negative influence on the small signal stability of a power system.

This is because when the length of blades is increased, the area circumvented by the 3 blades of the turbine is also increased thereby increasing the effect of tower shadow.

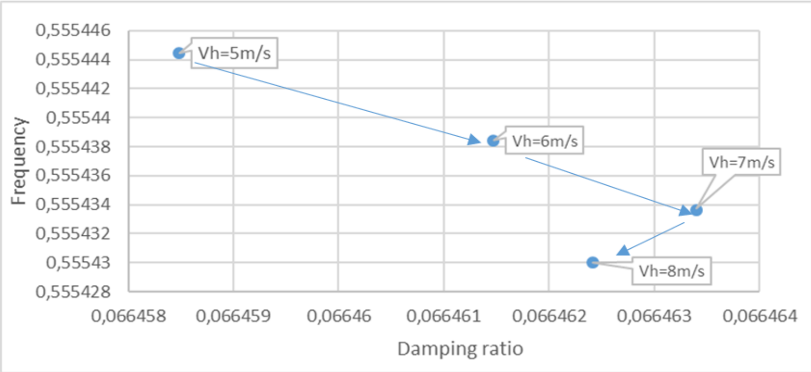

Fig. 8. Impact of nominal wind speed on the damping of electromechanical modes

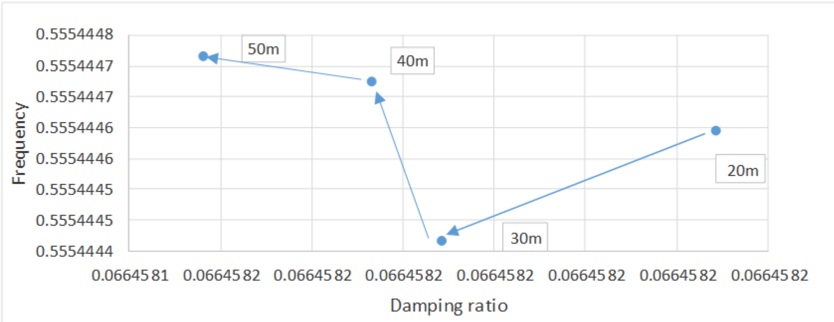

Fig. 9. Influence of wind turbine radial distance (r) on the damping of inter-area mode

6. Conclusion

The impact of 3p oscillations caused by wind shear and tower shadow on the power output of turbines made of asynchronous generators and small signal stability of a power system have been examined. From the study it can be concluded that 3p oscillations could cause flickering of electric power but may not necessarily triggered small signal instability in a power system. The length of blades (*r*) have effect on the damping of electromechanical modes. The longer the blades, the poorer the damping of electromechanical modes as a result of increased tower shadow.

Conflict of Interest

The authors declare no conflict of interest

Author Contributions

Ayodele T. R and Soile A. conducted the research; Ayodele T.R, Soile A aanalyzed the data; Ayodele T. R, Soile A. and Munda J. L wrote the paper; all authors read and approved the final version.

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