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Equilibrium optimizer-based double integral sliding mode maximum power point tracking for wind energy

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ABSTRACT

Wind energy is an effective renewable energy source. However, when it comes to harnessing its power because of its variability and nonlinearity, traditional controllers have limitations. This work proposes the design of two nonlinear maximum power point tracking (MPPT) methods to track the maximum power point for stochastic wind in the below-rated wind speed zone. These methods are the sliding mode controller (SMC) and the double integral sliding mode controller (DISMC). A benchmark model of a 4.8 MW wind turbine (WT) is subjected to random wind profiles in the MATLAB/Simulink environment. The equilibrium optimizer (EO) is used here and contrasted with particle swarm optimization (PSO) and grey wolf optimizer to achieve a good design of the controller in the sliding plane and change the switching control in sliding mode. The proposed optimization methodology and DISMC improved the smoothening of the control of angular speed, and specifically, the EO outperformed the rest of the techniques.

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NOMENCLATURE

P_{ar}	Power developed by the rotor of the turbine
λ	Tip speed ratio
β	Blade pitch angle
τ_{g_r}	Reference generator torque
S	Sliding plane

1. INTRODUCTION

The energy in the electricity and heat sector has renewable contribution doubled in the recent decade [1] worldwide when climate change has been crucial. There is a remarkable increase in installed wind harvesting capacity in India which is second to Germany recently. Wind energy is an environmentally friendly power source that generates no harmful waste, contributing positively to the United Nations' sustainable development goals (SDGs) related to climate action, health, and well-being [2]. To achieve net-zero emissions by 2050, which aligns with all 17 climate-related goals, renewable energy production needs to double from current levels by 2030 [2]-[4]. However, since wind is an intermittent resource, effectively harnessing more consistent power from large wind installations through careful design and control strategies is essential. The effective operation of wind energy conversion systems (WECS) relies on two primary control objectives: maximizing power extraction below the rated power level and maintaining a steady output when above that threshold [5]. To this effect, a variable speed wind turbine (WT) uses two main controllers, i.e., a torque controller to extract the maximum power and a pitch controller to maintain the output power level constant at the desired level [6]. WECS is a complex electro-mechanical system comprising nonlinear dynamics, disturbances, and parameter uncertainties, and has drawn significant research attention requiring advanced control.

By adjusting the maximum torque for fluctuating wind speed, power is maximized, which is zone 2 control of wind power in below-rated wind speed. This zone 2, which may provide half of the yearly energy capacity, has scope for development in energy harvesting. Generally, three types of maximum power point tracking (MPPT) methods are used, i.e., tip speed ratio (TSR) control, power signal feedback control, and hill climb searching control method [7]. The MPPT methods diverge in how the sensors are utilized, the error signals used for the MPPT control purpose from the turbine or generator, and the observer-based methods for unmeasured torque signals. Under various ambient conditions, the MPP curve varies because the aerodynamic torque varies with air density and environmental factors. However, the turbine rotor speed and aerodynamic torque of a WT system are difficult to measure.

Researchers have proposed controllers that improve the robustness of the MPPT. The observer-based sliding mode controller (SMC) for MPPT has performed robust than the proportional-integral controller with the assumption that the wind disturbance changes slowly [8]. An artificial neural network and integral SMC (ISMC) MPPT Controller has been developed [9]. The chattering reduced; however, the range of wind speed variation considered is limited. An observer with an ISMC MPPT controller is suggested for two cases of wind turbulence and sinusoidal variation to guarantee reaching the desired angular speed in a fixed time [10]. Moreover, the aforementioned controllers control the electrical signals of the generator for variable wind speed. For the sliding plane design, fractional calculus has also been incorporated [10], [11]. A DISMC MPPT is formulated using an error in load current and tested for varying load and wind [12]. Another literature report DISMC for a hybrid system for control of MPPT from electrical parameters that is robust and has better steady-state performance [13].

The following are some critical observations regarding the reviewed literature. For MPPT control in WECS, not only is power maximization important, but also power smoothing is required. Additionally, the controller needs to be resilient to changes in the nonlinear system's parameters and stand robust for random wind. A nonlinear control design approach of SMC is better suited than a linear traditional approach, as reported. However, it appears that the observer-based controller design for SMC is complex and explicit; a precise setting of design parameters is left unaddressed. Also, convergence of states and smoothing of chattering needs improvement for power smoothing for the SMC category of controllers. To control a highly nonlinear and unstable system, a comparative analysis of the model reference adaptive controller (MRAC) and the sliding mode fuzzy MRAC (SMFMRAC) is done [14]. The controller gains are tuned by using genetic algorithm and particle swarm optimization (PSO) techniques and exhibit smoother control. The multi-objective grasshopper optimization technique [15], enhanced invasive weed optimization [16], gravitational search optimization [17], hybrid mean-variance mapping optimization [18], modified PSO [19] and modified sine cosine algorithm [20], grey wolf optimization (GWO) [21] have shown significantly performing fine-tuned controller design than empirical design in such applications. In a recent work reported, on task scheduling application also GWO has outshined its rivals [22]. However, a reduced number of parameters of the optimization algorithm reduces the fitting time of the algorithm for the typical problem. Relative to its peers, it is established that the equilibrium optimizer (EO), a more recent optimizer, has the benefit of having fewer parameters and requiring less computing time to tackle multidimensional problems [23], [24]. In a similar fashion, the SMC constants should be chosen to best attract the states for smooth control, quick sliding, and quick reaching to the plane. For MPPT control, some of the control designs have been performed with different constant mean wind speeds and ramping up in steps. However, the simulation of such wind behavior is far from the real wind profile. As for MPPT control, the wind speed is not practically constant, so the steady-state chattering analysis does not have much realistic inference.

Based on the gaps of recent research works reviewed above, a DISMC controller is developed in the TSR MPPT method and compared with the SMC controller. The recognized 4.8 MW wind turbine (WT) system benchmark model is used for testing. This study's primary contributions are as follows:

- Optimize DISMC controller by EO in comparison to PSO and GWO for random wind speed,
- Use EO-tuned gain and controller constants to improve the switching process and reduce chattering in the DISMC MPPT design.

Section 2 provides a thorough description of the system, control strategy, and optimizer. Section 3 elaborates on the discussion of the simulation results. Based on the results, concluding statements are presented in section 4.

2. MATERIALS AND METHODS

The modeling and the controller formulation are implemented in the MATLAB/Simulink software. According to the Appendix's parameters, a three-bladed horizontal axis variable speed 4.8 MW wind turbine benchmark model (WTBM) is taken [25].

2.1. Simulation setup

The model comprises an aerodynamic system, pitch system, drive train, generator unit, and control system. Some measured variables used here in this model are denoted as follows: V_w is wind speed, β is blade pitch angle, β_r is reference pitch angle, τ_{ar} is aerodynamic torque, and ω_r is the angular speed of the turbine shaft. On the generator side ω_g is the speed of the shaft, τ_g is the torque, P_g is the power produced and P_r is the reference power. The power coefficient C_p is dependent on λ the TSR and β. The power developed by the rotor of the turbine P_{ar} from wind can be defined in (1):

$$P_{ar} = \frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta){V_w}^3 \quad (1)$$

and $P_{ar} = \tau_{ar}\omega_r$.
So, aerodynamic torque can be defined as (2):

$$\tau_{ar} = \frac{\rho\pi R^2 C_p(\lambda,\beta){V_w}^3(t)}{2\omega_r(t)} \quad (2)$$

Here ρ is the air thickness, R is the rotor radius, and πR^2 is the area traversed by the turning blades. Since λ is represented as (3):

$$\lambda = \frac{\omega_r R}{V_w} \quad (3)$$

Substituting λ the expression from (2) gives (4):

$$\tau_{ar} = \frac{1}{2}\rho\pi R^3 \frac{C_p(\lambda,\beta)}{\lambda}{V_w}^2 \quad (4)$$

The key intent herein is to impose the turbine to generate peak power for that wind speed. In zone 2 of the wind power curve, the generated power is maximized by increasing the C_p to its maximum (C_{p_max}) [5]. The TSR MPPT control is suitably modified to attain the optimal value of rotor speed ω_{r_opt}. With a design specification of the optimal TSR value λ_{opt}, ω_{r_opt}, at any wind speed, is obtained from (3) by:

$$\omega_{r\_opt} = \frac{\lambda_{opt}}{R}V_w \quad (5)$$

This work targets to develop a robust and stable MPPT control for the nonlinear system from Lyapunov's theory. This is achieved and tested after the implementation of the SMC and DISMC technique in the lower-than-rated wind input to trace the desirable rotor speed with the least variation in reference tracking. The DISMC technique is implemented here in zone 2 so that the system holds robustness subjected to unpredictability and internal disruptions. A schematic of the controller layout is denoted in Figure 1.

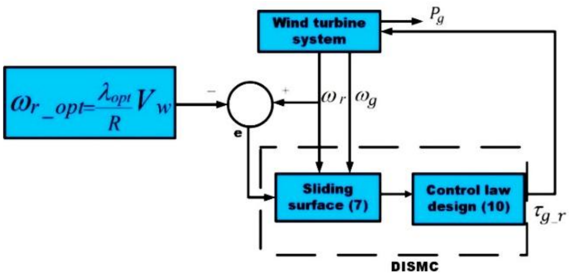

Figure 1. The DISMC scheme

2.2. Controller design

The error of the system is (6):

$$e = \omega_r - \omega_{r\_opt} \quad (6)$$

In DISMC, the sliding plane is considered as (7):

$$S = A_1 z_1 + A_2 z_2 + A_3 z_3 + A_4 z_4 \quad (7)$$

Here, A_1, A_2, A_3, and A_4 are the factors that influence the plane design to keep the error minimum and z_1, z_2, z_3, z_4 are variables derived from the error as (8):

$$\begin{aligned} z_1 &= e = \omega_r - \omega_{r\_opt} \\ z_2 &= \dot{z_1} = \dot{e} = \dot{\omega_r} - \omega_{r\_opt}^{\cdot} \\ z_3 &= \int z_1 dt = \int(\omega_r - \omega_{r\_opt})dt \\ z_4 &= \int(\int z_1 dt)\, dt = \int(\int(\omega_r - \omega_{r\_opt})dt)\, dt \end{aligned} \quad (8)$$

The control signal is founded on Lyapunov stability, i.e., the slope of the Lyapunov function V, $\frac{dV}{dt} \leq 0$.

$$V = \frac{1}{2}S^2 \quad (9)$$

The reference generator torque is calculated as (10):

$$\tau_{g\_r} = \frac{-1}{x_{12}y_{22}}\left[\widetilde{x_{11}}\omega_r + \widetilde{x_{12}}\omega_g + R_{s1} - \ddot{\omega_{r_{opt}}} + \alpha\left(\dot{\omega_r} - \dot{\omega_{r_{opt}}}\right) + K_1|S|^{\delta}\, tanh\frac{S}{\mu}\right] \quad (10)$$

R_{s1} is an estimation of unmeasured signals, K_1 is the gain, and x_{ij} are the intermediate states for i,j=1,2. The $tanh$ smoothes reaching to the equilibrium. It is to be noted that, so far as the knowledge of the authors is concerned, in the referred papers herein, no clear hint is there about choosing the values of the constants δ, μ, and R_{s1} [16].

For the optimizer, the fitness evaluation F is by mean square error percentage (MSE%) and can be represented as (11):

$$F = \frac{1}{N}\sum_{i=1}^{N}(\omega_r - \omega_{r\_opt})^2 \quad (11)$$

Here, N is the maximum count of the samples for the discrete model of WTBM. The wind dynamically changes and, so for the MPPT, MSE% is the befitting index. The *MSE*% is minimized by the EO [23] and compared with PSO [15] and GWO [21].

2.3. Equilibrium optimizer implementation

EO is established on the principle of equilibrium. The rate of change of mass is minimized in a search space to reach the equilibrium state. In the search space, the particles with their concentrations are the random solutions that strive for an equilibrium state. In cases where most of the algorithms get trapped in local optima, it is capable of escaping from local optima.

Because of the update of concentration, that is guided by two components. The generation rate controls the exploitation phase, and it is influenced by the control parameter generation probability. One of the four topmost solutions and their average are the members of the equilibrium pool, and choice from them preserves exploration. An exponential term that gradually squeezes the search region with an increase in iterations. It has proven better than PSO, GWO and salp swarm algorithm for standard test functions. The control parameters are the generation rate taken as 0.5, and two constants, a1 with a value of 2 controls exploration ability, and a2 with a value of 1 controls the exploitation ability [21]. It is computationally efficient, and the run time is less. Figure 2 demonstrates the steps of EO. After initialization, in iterations, the outputs from the EO program, the solutions of four variables within the bounds, are passed to the WTBM. The fitness, MSE% value is output from the model for the applied values of decision variables in the controller for all particles. This process goes on iteratively till all iterations. The minimum particle concentration, i.e., MSE% and corresponding controller parameters after all iterations are the final output of the algorithm. The controller competency is computed by the percent normalized sum of squared tracking error (NSSE) [5].

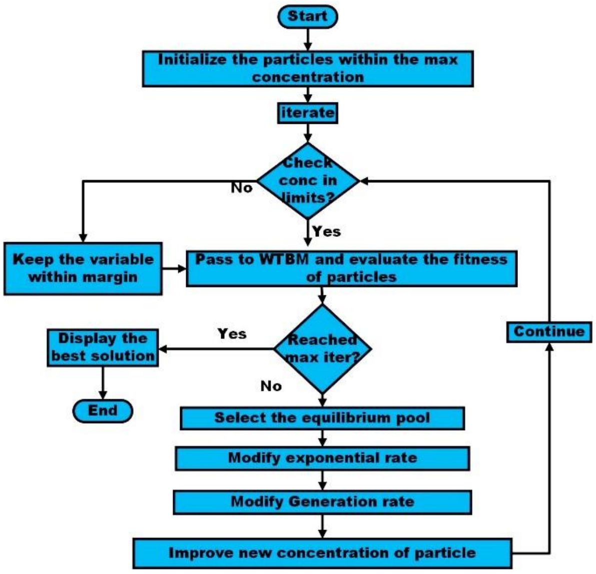

Figure 2. Flowchart of EO

3. RESULTS AND DISCUSSION

The controller is validated for the wind velocity profile given as input to the WTBM, starting from 4 m/s to 25 m/s, as in Figure 3. The wind velocity changes in altitude, and the impact on different blades is not the same at a given instant and reflects in speed. The partial load is under 160 s where the velocity is under 10 m/s. The MPPT control is active in this zone. The constants of the DISMC, namely the K_1, R_{s1}, δ, and μ, are tuned by EO with this wind input. Analogous four constants of SMC are likewise tuned. Initially, long ranges are set for all the upper and lower limits of parameters. According to the optimized values obtained from the optimization process in multiple runs, the limits are squeezed to get the best range. Regarding the agents and iterations, some tests are conducted taking the WTBM. As for particle numbers beyond 50 and iterations beyond 20, no significant improvement is observed; the maximum agents and iterations are considered 50 and 20, respectively. The algorithm was repeated for 50 runs with 20 iterations and 50 agents. The purpose is to reduce MSE in the existence of the stochasticity of the wind and find out the abovementioned four parameters for the optimal solution. The best result is shown in Table 1 as the decisive constants of the controllers.

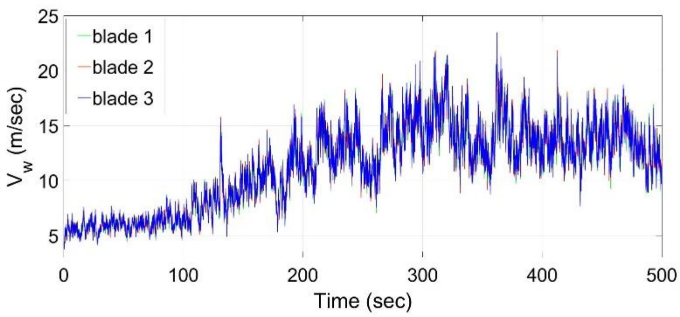

Figure 3. Wind velocity profile

Table 1. NSSE% index of the controllers

Optimizer	DISMC					
	K	R_s	δ	μ	NSSE%	F
EO	15	100	0.99	0.001	20.0952	6.7493
GWO	64.30	12.81	0.99	0.96	21.0167	6.9823
PSO	86.75	69.57	0.64	0.41	21.9538	7.0792
	SMC					
	K_1	R_{s1}	δ	μ	NSSE%	F
EO	16.93	34.5	0.99	0.001	21.5591	6.8529

The comparison of EO, GWO, and PSO has also been studied. For this number of agents, runs, and iterations are kept the same as in the previous test for a fair comparison, though for EO, 20 agents are sufficient [23]. As per big-O notation, EO is computationally similar to PSO in complexity; however, PSO is far off EO for the optimization of DISMC MPPT in the model, as seen in Table 1 from both MSE% and NSSE%. Also, as per the convergence of fitness in Figure 4, PSO converges earlier, but the final minimization is inferior to that of EO. Similarly, GWO converges to a lower value than PSO, but EO minimizes to a larger extent and proves to be the best among the three discussed here.

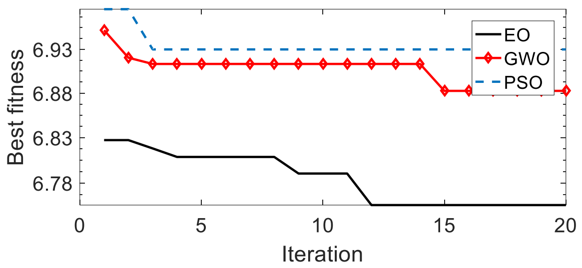

Figure 4. Convergence of algorithms in optimizing DISMC MPPT

Figure 5 shows a comparison of the generated speed tracking for SMC and DISMC. The result affirms that DISMC generates power with less fluctuation than the other controller. This is contributed by the double integral term that minimizes the area under the error and makes the control action fast. The essence of the presented optimum design of EO-DISMC for the extraction of MPPT reduces the chattering and improves the accuracy. Since a WECS delivers to the grid, the quality of power is improved. The NSSE% measure drastically reduced in DISMC in comparison to SMC and adaptive control. This will also alleviate the load on the mechanical system, such as the rotor and blades, which will reduce downtime. It is established that the contributed design approach will improve MPPT in real wind variations as considered here. Once the controller gains are tuned in simulation and set, they can be easily implemented in an embedded system for real-time testing.

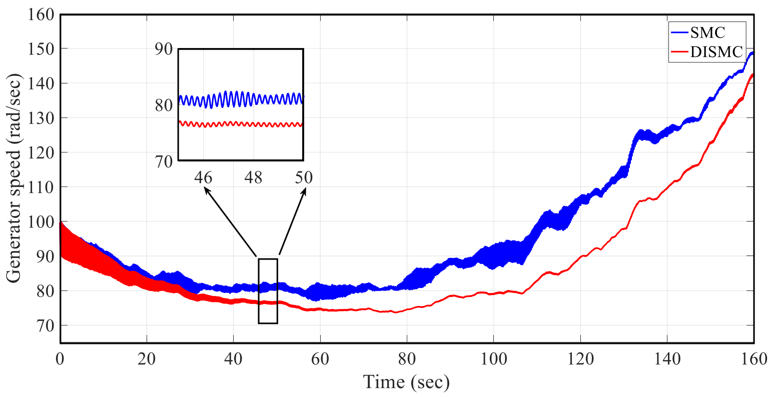

Figure 5. SMC vs DISMC for generator speed

4. CONCLUSION

Here, two nonlinear MPPT controllers are designed for the partial load operation area of a WTBM as per the TSR MPPT approach and tested for the below-rated wind speed zone of a WTBM. The controller designed handles as per the inaccuracy in the angular speed of the turbine rotor. Two robust controllers, namely SMC and DISMC, are developed, and their optimal design is demonstrated by EO, GWO, and PSO in comparison and analysis indicates EO to be the best. According to the simulations, both the SMC and DISMC have a better control impact than in unoptimized circumstances when optimized variables are taken into account. The NSSE% index is used to evaluate each controller consistently. In terms of tracking the optimal rotor speed and a smoother reaching response, it is confirmed that the proposed optimal design of DISMC performs better overall than the proposed SMC. The real-time testing of the controller in WECS hardware is a future scope. Above all, the perspectives that have been offered will be a significant method for future researchers to create reliable nonlinear controllers for enhancing wind energy capture. They may also be used for nonlinear systems in other technological domains.

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Shrabani Sahu	✓	✓	✓			✓			✓				✓	
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Nimay Chandra Giri					✓	✓				✓				
George Uwadiegwu Alaneme		✓						✓		✓				
Fathy Abdelaziz Syam						✓				✓				
Fawzan Salem					✓					✓				✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author [FS] on request.

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