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DFIG in Wind Energy Applications with High Order Sliding Mode Observer-based Fault-Tolerant Control Scheme using Sea Gull Optimization

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ABSTRACT- This paper describes a new method for maximizing power extraction from a wind energy conversion system (WECS) by using a doubly fed induction generator (DFIG) that operates below nominal wind speed. To maximize the collected power of a wind turbine (WTG) exposed to actuator failure, a fault-tolerant high-order sliding mode observer (HOSMO) and Seagull Optimization Algorithm with a model predictive controller (MPC) technique is proposed. Evaluate both the real state and the sensor error simultaneously using a higher-order sliding-mode observer. Active fault tolerant controllers are designed to regulate wind turbine rotor speed and power in the presence of actuator defects and uncertainty. With the growing interest in employing wind turbines (WTGs) as the primary generators of electrical energy, fault tolerance has been seen as essential to improving efficiency and reliability. This research focuses on optimal fault-tolerant pitch control, which is used to modify the pitch angle of wind turbine blades in the event of sensor, actuator, and system failures. A Seagull Optimization Algorithm (SOA) is proposed to tune controller parameters to improve the performance of WT. The proposed method has achieved 92% of power tracking performance when compared to existing method.

Keywords: High Order Sliding Mode Observer (HOSMO), Seagull Optimization algorithm (SOA), Doubly-fed induction generator (DFIG).

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1. INTRODUCTION

Wind turbines are among the cleanest natural energy sources since they harness the kinetic energy of the wind. A doubly fed induction generator is the basis of variable speed wind energy systems (DFIG).The advantages of DFIG include the capacity to manage torque, operate at varied speeds, have a cheap cost for the inverter, and be flexible when it comes to active and reactive power regulation [1].Additionally, within the presence of model uncertainties, a better-order sliding-mode control technique is used to preserve stability in each domains and to enhance the optimum feedback manipulate solution [2]. The rotor current sensor is tampered with, and a model-based fault-tolerant rotor current estimation technique based on measured stator current and voltage is presented. Under normal operating conditions, numerical results show that a baseline fractional-order control method outperforms a standard sliding-mode control system [3-5].

A sensor error observer (SEO) is presented to provide exact estimations of sensor error components. In the event of a fault, the current observer's error estimate is used to correct for the fault signal, allowing system reconstruction from the DFIG without the requirement for fault diagnostics [6]. A wind turbine (WT) design with fault tolerant control (FTC) that operates at high wind speeds. By controlling generator power to its nominal value and reducing pitch actuator disturbances, its purpose is to alleviate mechanical stress at high wind speeds [7, 8]. In the presence of unknown disturbances, faults in the WECS are recognised and determined, if the transmission element of the system is set up and an adaptive disturbance observer is raised. The error observer is then used to create an active-tolerant controller to ensure the WECS transmission component's fault-tolerant stability [9-11].

An AFTC regulation contains a first-order integration mechanism to smooth the output signal and improve tracking accuracy throughout generation [12]. A novel modified development stage location search formula is aimed to assist the search process by introducing a velocity operator and inertia weight. Then, based on the cosine function, a nonlinear parameter E of the escape energy is introduced in order to accomplish a smooth transition from the exploration to the utilisation stages [13-15]. Defective sensors and actuators have the potential to disrupt the closed-loop system. As a target controller for tracking maximum power, a model predictive controller (MPC) is constructed [16]. The theory of variable structure control is frequently employed in both linear and nonlinear systems. The classical Sliding Mode Control (SMC) approach is resilient against system uncertainties with established upper bounds, but its major limitations include high frequency chattering and implementation incompatibility [17-20].

The major contributions of the proposed research work are listed below,
To maximize wind power generation, the work presented here uses the Seagull optimization algorithm with a Higher Order Sliding Mode (HOSMO) control scheme based on MPC controller to control the WT speed. The HOSMO was developed to track high wind power as a nominal controller, whereas the Model Predictive Controller was developed to display actual states and sensor faults. A Seagull optimization is proposed for fixing characteristic optimization, feature selection and fault tolerant of wind turbine and this technique able to mitigating pitch actuator faults. A simulation results are demonstrating the suggested Seagull Optimization Algorithm based on the MPC controller with High Order Sliding Mode effective performance.

The fault-tolerant control mechanism based on a sliding mode observer and HOSMO will be discussed briefly in *Section 1*. *Section 2* discusses the proposed technique and system modelling for wind turbines and actuator faults. The innovative Seagull Optimization Algorithm is explained in *Section 3*. *Section 4* contains the findings of the simulation. *Section 5* contains the paper's conclusion.

2. METHODOLOGY

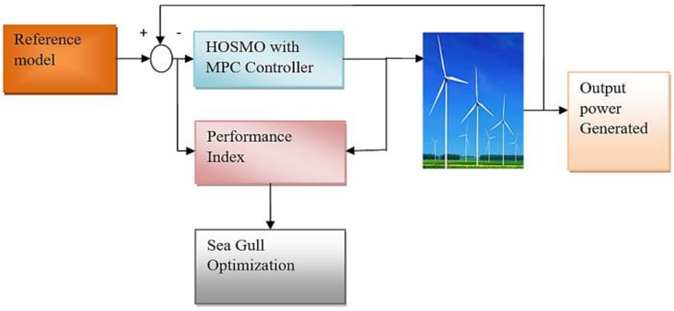


Figure 1. Block diagram of proposed fault tolerant control

Wind turbine systems strive to convert as much wind energy as possible into mechanical energy. Electricity is produced by mechanical energy. Ordinary feedback controllers benefit from supervisory levels provided by error-tolerant control circuits. When no problems occur, the system reverts to its nominal behavior, and the nominal controller dampens disturbances while maintaining acceptable standards and other closed-loop system needs. A suggested fault tolerant controller is depicted in *figure 1* as a block diagram. A diagnostic block detects faults, and a control change block modifies the control to accommodate the new set of control parameters. After that, the modified system continues to achieve the control objectives.

2.1 Wind Turbine System Modelling

The generator and gearbox are kept within the nacelle, that's on top of the tower shape. The blades are connected to the rotor, which is connected to the generator with the aid of a gearbox. A motor inside the nacelle directs the blades into the wind. Large utility generators are frequently variable velocity, with systems to exchange the angle of attack of the blades and wind raise. The generator torque load can be used to calculate the amount of power absorbed by way of the mechanical device, as well as to behave as a brake mechanism to restriction rotor acceleration. From analysis and control design through real world implementation, system design demands an accurate global mathematical model of turbine dynamics.

According to Bates theory, wind turbine aerodynamic power can be stated as

$$\rho_a = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda, \beta) \tag{1}$$

Where, ρ is density of air and λ is denoted tip speed ratio

$$\lambda = \frac{R\omega_r}{v} \tag{2}$$

Aerodynamic torque T_a can be expressed as

$$T_a = \frac{p_a}{\omega_r} \tag{3}$$

By applying Eqn. (1) and (2) in to *equation (3)*

$$T_a = k_a \omega r^2 \tag{4}$$

$$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_1} - C_3\beta - C_4\right)\exp\left(\frac{-C_5}{\lambda_1}\right) + C_6\boldsymbol{\lambda} \tag{5}$$

Consequently, a wind power controller that maintains the turbine's optimal angle speed ωr* while varying the angular speed ωr in response to wind speed v is required, which can be calculated as

$$\omega_r{}^* = \frac{\lambda_{opt} v}{R} \tag{6}$$

Table 1. Parameters of a wind power system.

Parameters	**Values**
Blade radius	21.64m
Optimal blade tip ratio	8.1
Air density	1.293kg/m^3
Maximum power coefficient	0.38
Wind turbine rotor inertia	325000kg/m^3
Generator rotor inertia	34.4kgm^3
Wind turbine rated torque	200kN^{-m}

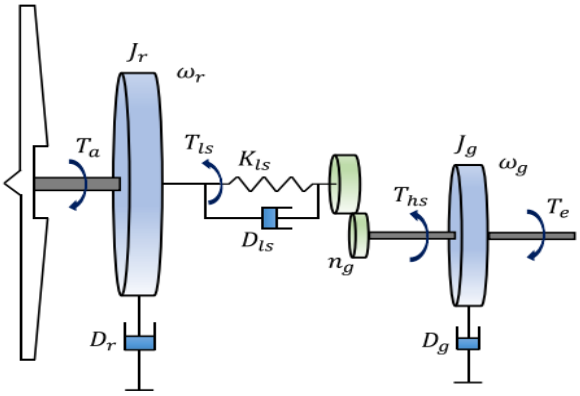


Figure 2. Schematic of the two-mass model

The model with two masses, as shown in *figure 2*, describes the drive train structure of the wind energy system that is the subject of this paper. A turbine rotor is driven by an aerodynamic torque Ta at speed ωr. The torque produced by a slow rotating shaft Tls functions as a braking torque for the rotor of a wind turbine. A generator rotor is braked by an electromagnetic torque called Tem and driven at speed by a rapid torque called Ths. The gearbox transmits speed and torque in accordance with the gearbox ratio ng. *Table 2* shows the results of numerical simulations performed on a 2-mass wind turbine.

Table 2. Parameters of a two-mass wind turbine

Parameters	Values	Unit
R	21.65	M
J_r	3.25×10^5	Kgm^2
D_r	27.36	Nms/rad
D_{ls}	2.691×10^5	Nms/rad
J_g	34.4	Kg/m2

2.2 Fault Tolerant MPC with HOSMO Fault Estimation

The system dynamics are formulated as follows to simulate the actuator fault:

$$x(k+1) = f\big(x(k), \alpha(k)u(k)\big) \qquad (7)$$

For a healthy system α I and for total actuator ineffectiveness α = 0. For partial loss of actuator i: 0 < α_i<1. The purpose of fault identification is constantly evaluating the fault parameter matrixα.

$$J^{ID}(\Gamma_k,)\alpha_k(.)) = \textstyle\sum_{p=0}^{N_I-1}\big[\big\|x(p+1) - f\big(x(p), \alpha_k(p)u(p)\big)\big\|\big] \qquad (8)$$

The moving horizon estimation formulation should be formulated to reduce online computation time. After removing the state estimation function, the cost function is just a function of the error parameters and input/output data.

$$J^{ID*}(\Gamma_k) = Min_{\alpha_k(k-1)J^{ID}}\big(\Gamma_k, \alpha_k(.)\big) \qquad (9)$$

Using the MPC control method, a HOSMO is presented to the pitch actuator under damped systems with an extended settling periods, maximum overshoots, and unacceptable dynamic errors. Let the pitch actuator system as

$$G(s) = \frac{Y(s)}{U(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} = \frac{N}{D} \qquad (10)$$

3. SEA GULL OPTIMIZATION

By analysing the biological features of seagulls, a new form of bio-inspired optimization algorithm, the seagull optimization method was developed. Seagulls hunt and attack prey in flocks, using their wits. Seagulls' most notable qualities are mobility and aggressive behaviour. Using HOSMO-based MPC control, the proposed SOA approach maximises power extraction from wind energy conversion systems (WECS) operating at or below the rated wind speed. Due to nonlinearities associated with the dynamics of WECSs, the stochastic nature of wind, and the inevitable presence of faults in practice, developing reliable fault-tolerant control strategies to guarantee maximum power production of WECSs has always been considered important. The SOA algorithm has the advantages of solving large-scale constrained problems, low computational cost, and fast convergence speed. Compared with other optimization algorithms, it has strong advantages. A function that can target the process stage of seagull flock reconnaissance and maximize the power extraction and algorithmic accuracy of the WECS.

$$A = f_c \times \frac{1}{e^{4\left[{}^{t}/_{Maxiteration}\right]^4}} \qquad (11)$$

Seagulls must fulfil the following three requirements in order to migrate:

- Avoid collision: The variable, A is used to determine the new position of searching gull in order to prevent collisions with other birds.

$$C_s(t) = A \times P(t) \qquad (12)$$

Ps(t) is denoted by current location of the search log,
t is representing current iteration

$$A = f_c - (t \times {}^{f_c}/_{Max_{iteration}})) \qquad (13)$$

- Best position: Seagulls move to the best location to avoid overlap with other birds.

$$M_s(t) = B \times \big(p_{bs}(t) - P_s(t)\big) \qquad (14)$$

- Seagulls near the best search areas: A seagull moves to the best location to reach its new location after moving to a location where it does not collide with other seagulls.

$$D_s(t) = |C_s(t) + M_s(t)| \qquad (15)$$

The proposed SOA's specific implementation procedures are listed below.

Step 1: Determine the A, B, and SOA initial parameters,

$Max_{iteration}$, fc = 2, u = 1and v = 1.
Step 2: Start a seagull population.
Step 3: A fitness value of each log can be calculated using the calculated fitness function, and the best log location can be selected at the moment.
Step 4: Upgrade the migration and attack stations of seagulls by employing various tactics.
Step 5: Steps 3 and 4 should be repeated as many times as necessary to update the protocol's optimal location and value.
Step 6: Get the best possible fitness value and log.

4. SIMULATION RESULT AND DISCUSSION

In this section, we evaluate the energy extraction performance of the proposed SOA method. *Table 1* displays the results of numerical simulations on 2-mass wind turbine. The characteristics apply to a 36-meter-high, two-bladed, speed-controlled Advanced Research Turbine. A pitch actuator system is described by a higher-order system. In fact, the reaction is determined by whether the high-order sliding-mode observer system is over damped, severely damped, or underdamped. Moreover, noise and fault might unbalance the system.

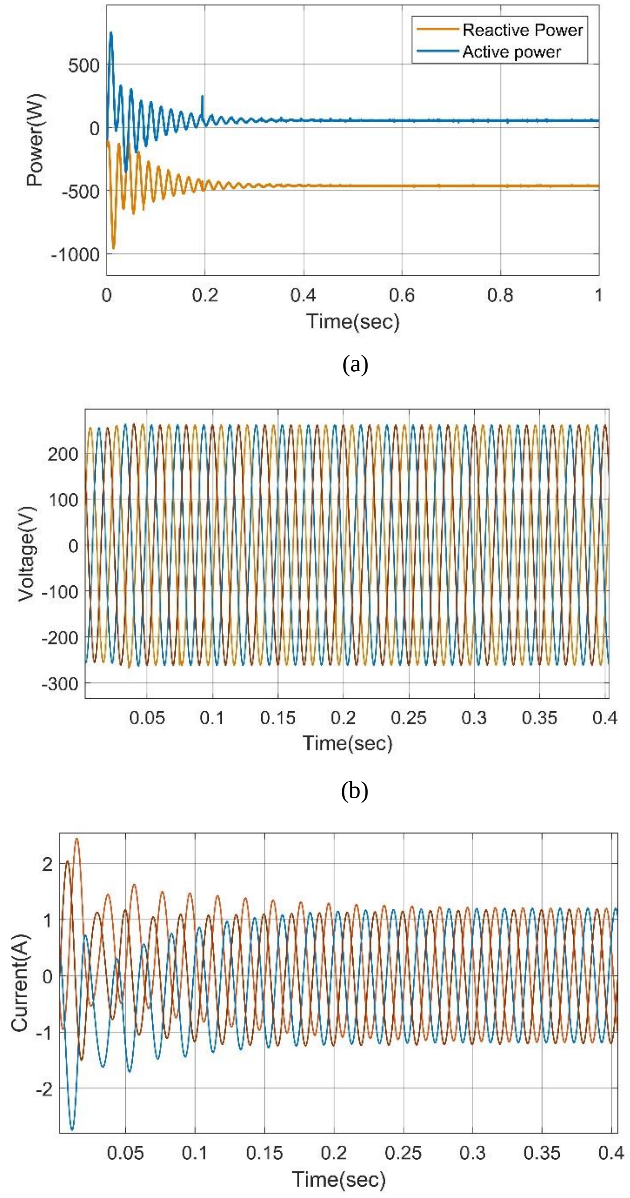
4.1 Faulty actuator

Only minor variations are noticeable when errors occur and are eliminated. The generator power, voltage and current are shown in Figure 3. The MPC process function of HOSMO is used to set the generator output to the nominal value. Despite the existence of multiple pitch actuator faults and turbulence, the performance dynamics are rather smooth. When mistakes are introduced and eliminated using the HOSMO technique, noticeable spikes and large output swings are noticed. As a result, the sensor error related to active current is expected to occur between 0.1 and 0.2 seconds, and the two faults related to reactive current are assumed to occur between 0.13 and 0.19 seconds. Additionally, the system is supposed to be affected by an overall uncertainty of d = 50% f + 50% hu.

With fewer fluctuations and loads, the rotor speed, generator speed, drive train helix angle, and power output respond reliably. *Figure 3* depicts this degradation. HOSMO tolerates actuator defects quite well, with no notable changes or fluctuations. Figure 3 depicts the generator tracking, voltage, and current in the defective circuit simulation. At constant wind speed, a sudden normal failure of the actuator occurs. As a result, the wind profile is applied to the system without actuator error for the first 0.2 seconds. At time t = 0.4 s, the actuator fails with a partial linear loss of actuator force and develops to a nonlinear condition at time t = 0.5 s.

4.2 Healthy actuator

By applying the wind profile to the turbine, the recommended SOA based on the HOSMO controller performance was established without error or ambiguity. *Figure 4* depicts the generator tracking, voltage, and current for a standard actuator simulation. Performance of reconstruction in the presence of uncertainty and failing sensors.

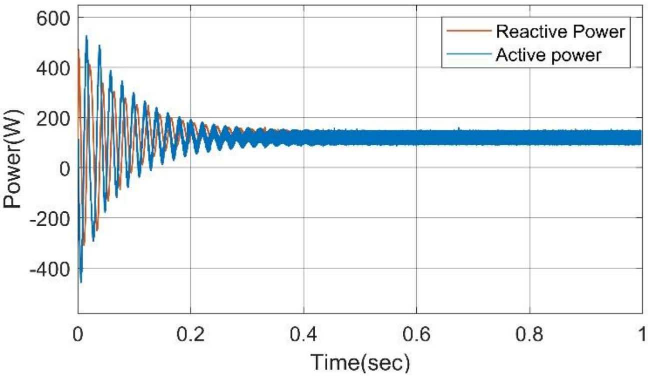


(a)

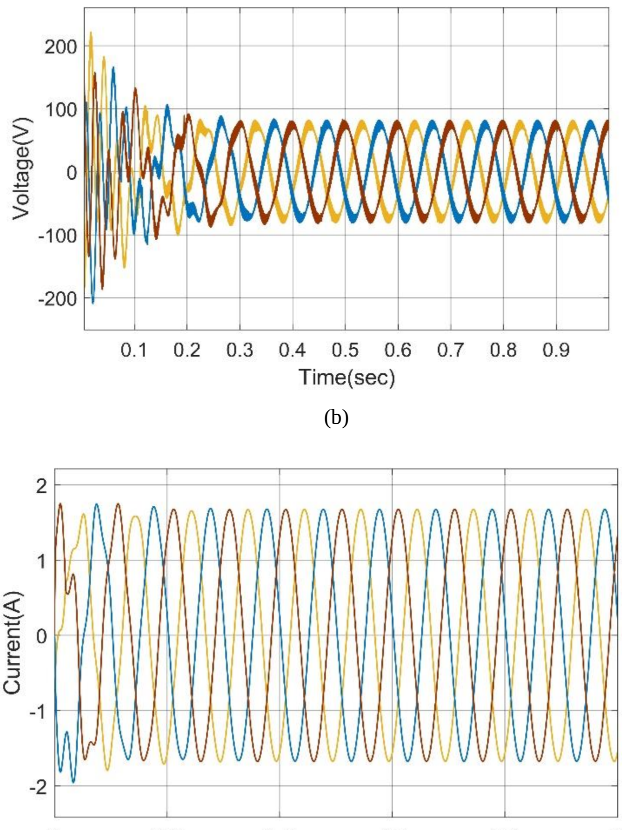
(b)

(c)

Figure 3. Dynamics of the wind turbine system at Faulty actuator a) Power b) Voltage c) Current



(a)



(b)

(c)

Figure 4. Dynamics of the wind turbine system at Faulty actuator a) power b) Voltage c) Current at healthy

As a result, the turbine is subjected to a constant wind speed (V = 7 m/s), which increases to V = 13 m/s at t = 1.2 s. Furthermore, a 35% increase in both stator and rotor resistance was examined at t = 1.8 s. The estimations were clearly met swiftly and with little mistake, showcasing its remarkable performance.

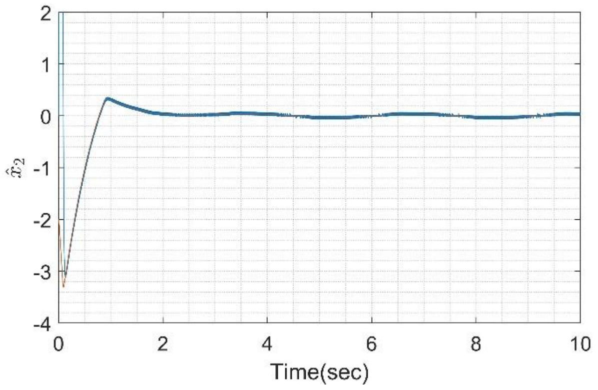


Figure 5. Plant state based on High Order Sliding Mode Observer

The response curve of a plant state estimation (x_2)ˆis depicted in *figure 5*. It is obvious that the predicted variable quickly converges to x2 = 0.72 as the system boots up. The estimated variables gradually rise to bm = 10.6 after the fault, achieving greater stability. The suggested controller maintains its own robustness and self-adaptation to changes in the system and faults by not relying on system model parameters or external fault detection to identify actuator failure information. It has strong convergence stability and flexibility to system state changes, and it can quickly estimate general disturbance limits.

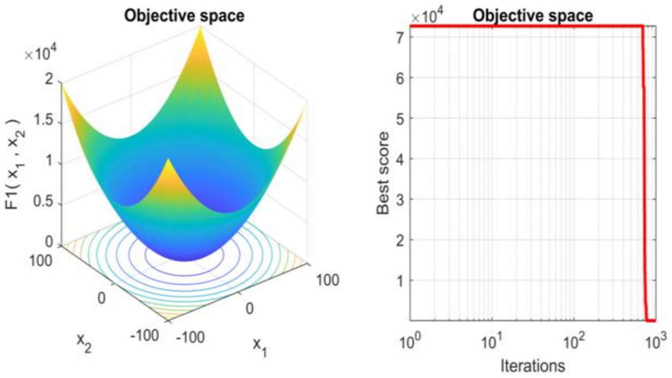


Figure 6. Fitness value of Seagull optimization

Random particle groupings (collections) are produced and placed in motion at first. All particles evaluate their fitness (objective function value) at the conclusion of each iteration (generation) and relocate to better spots. The velocity of each particle, as shown in *figure 7*, is a random variable that can change based on its distance from the optimal position. As a result, the local and global search algorithms are used to their maximum potential. Using traditional approaches, a velocity (u) and position (s) of single particle in the iterations are calculated. A power coefficient function is the fitness function.

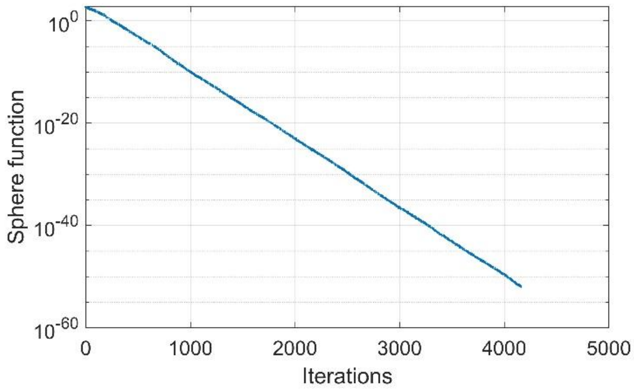


Figure 7. Iterative curve of proposed method

As a result, the rotor speed, tip speed ratio and blade pitch parameters are determined to achieve the maximum coefficient of performance. A hyperspace in question is determined by the spherical distribution's form and scale characteristics, as well as the decision variable (x), as shown in *figure 6*. The shape and scale parameters of the spherical distribution are given as stochastic parameters of the control issue in this paper because the wind speed distribution changes the maximum power point. According to the simulated waveforms, the proposed SOA with HOSMO can efficiently regulate the turbine power coefficient and tip speed ratio at maximum and optimal levels regardless of actuator fault operation. SOA has the best wind power absorption performance when compared to PSO and HHO.

Table 3. This is a table. Tables should be placed in the main text near to the first time they are cited

Author and Year	Optimization Method	Power tracking performance	Fault duration (s)
Wen Longet.al., (2022)	Harris Hawks Optimization Algorithm	87%	1.8
Yassine Fadiliet.al., (2020)	Particle Swarm Optimization Algorithm	82%	2.2
Proposed	Seagull Optimization Algorithm	92%	0.45

The proposed method Seagull Optimization Algorithm was compared to the Harris Hawks Optimization Algorithm and Particle Swarm Optimization Algorithm methods. When compared to the existing methods, the fault duration time is reduced and also performance is increased are shown in table in table 3. Higher desirable chattering mitigation performs better than the suggested SOA. The aforementioned results indicate that the proposed fault tolerant control technique describes rotor currents as well as how superior it is at tracking speed and power.

5. CONCLUSION

This paper proposed a fault-tolerant control system for wind turbines functioning at high wind speeds in order to limit generator output to its rated value and reduce pitch actuator difficulties. The purpose of control is to discover the largest power consider request to enhance energy production. The highest power factor value is considered to correspond with the highest wind speed and maximum power. In fixed speed operation, the control strategy is to determine the optimum rotor speed. The control technique in variable speed operation is to determine the optimal speed ratio and pitch angle. It is suggested that SOA can effectively address the wind turbine control problem, particularly when the wind speed distribution is uncertain. When applied to a 5 MW variable speed WT subjected to pitch actuator malfunctions and turbulent wind conditions, the proposed SOA with HOSMO approach demonstrated good dynamic performance and uncertainties while ensuring system stability and finite time convergence.

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