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The Performance Improvement of MMC-DFIM Drives using Hybrid Jellyfish-Butterfly Optimized FOPID Control

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Abstract: The development of advanced wind energy conversion systems (WECS) necessitates efficient converter control strategies to enhance energy conversion efficiency and minimize harmonic distortion. This study proposes a novel hybrid optimization framework that combines Jellyfish Search (JS) and Butterfly Optimization Algorithm (BOA) to adaptively tune Fractional Order Proportional-Integral-Derivative (FOPID) controllers for Modular Multilevel Converters (MMCs) interfaced with Doubly-Fed Induction Machines (DFIMs). The hybrid JS-BOA approach leverages JS's global convergence capabilities and BOA's superior exploration behavior, overcoming the performance constraints inherent in single-algorithm methods. The control strategy integrates a real-time FOPID controller with 3D Space Vector Pulse Width Modulation (3D-SVPWM) and predictive capacitor voltage sorting to suppress circulating current and maintain precise capacitor voltage balancing. MATLAB/Simulink R2024a simulations, alongside experimental validation using a 7-level MMC testbed equipped with a dSPACE 1202 controller, were conducted to verify system performance. Comparative analyses demonstrate that the proposed JS-BOA-based FOPID controller outperforms traditional optimization techniques such as Particle Swarm Optimization (PSO), Monarch Butterfly Optimization (MAO), and Multi-Directional Hunger Optimization (MDHO). Notably, it achieves a 30-45% improvement in circulating current suppression, maintains ±2 V precision in voltage balancing, and reduces settling time to approximately 90 ms under varying wind profile conditions. This research establishes a scalable and computationally efficient control framework that ensures low Total Harmonic Distortion (THD) and compliance with regulatory standards, contributing significantly to the advancement of next-generation wind energy systems.

Keywords: 3D-space vector PWM (3D-SVPWM); fractional order PID (FOPID) controller; hybrid jellyfish search-butterfly optimization (JS-BOA); modular multilevel converter (MMC); wind energy conversion system (WECS)

1 INTRODUCTION

Wind energy systems (WES) represent a fundamental solution for creating sustainable electricity through environmentally friendly methods. Wind turbines extract wind-generated kinetic energy to produce mechanical power that gets transformed into electrical energy while avoiding the use of fossil fuel power plants. Wind energy stands out as a critical solution for decarbonization because it has unlimited supply and renewable nature and produces no emissions during operation. Globally wind energy maintained 837 GW of installed capacity last year according to GWEC while showing expected expanded deployment [1]. Modern wind turbine deployments occur in two distinct sections: onshore and offshore areas with smart grid components for operational efficiency and flexibility improvement. Modern wind energy conversion systems depend on power electronic systems to function as their fundamental operational infrastructure. The combination of speed and frequency variations in wind turbine generators demands strong interfacing devices as a necessity for maintaining power quality and grid compatibility.

Power electronic devices execute three primary tasks including AC-DC-AC conversion and reactive power compensation and fault ride-through functionality. The prominent use of Modular Multilevel Converters (MMCs) in high-voltage and high-power applications has made them popular among these power electronics devices. The multichannel structure of MMCs allows various benefits to emerge like advanced modularity alongside a flexible power range while producing low-distorted outcomes and maintaining better thermal stability through distributed loss management. MMC technology stands out for large-scale wind farms because it provides crucial operational stability and efficiency [2]. MMC equipment enables wind farms to connect wind energy conversion systems directly to high-voltage transmission lines. The modular construction design creates possible redundancies for fault-tolerant operations along with straightforward scalability potential.

A central component of the MMC structure are submodules arranged in parallel arms that function as autonomous units for providing voltage stability while suppressing harmonic production. MMC technology provides critical support during wind condition changes because it helps stabilize voltages that result from changing load requirements. MMC technologies enable real-time control of Space Vector PWM (SVPWM) frameworks which makes wind energy systems more compliant to grid requirements [3]. The wide speed operation range of Doubly Fed Induction Machines (DFIMs) in variable speed wind turbines makes them ideal for use with partial-scale converters. The integration of DFIMs with MMCs creates new control difficulties because circulating currents in converter arms produce increased losses and component stress and submodule capacitor voltage imbalances generate distortion and instability and wind speed fluctuations cause delayed transient responses. The basic PID control techniques which exist in many systems fail to adequately deal with systems that show nonlinear behavior and time-dependent variations in control requirements. The controllers demonstrate inadequate flexibility and reliability when operating under sudden environmental changes in wind speed. Advanced control methods should be developed because they need to optimize real-time control parameters while maintaining stability and efficiency alongside grid code compliance [4].

2 LITERATURE REVIEW

The development of control techniques for Modular Multilevel Converter (MMC) has increased substantially because of expanding high-voltage wind energy systems. These control techniques need to maintain capacitor voltage balance and minimize circulating current flow as their main control objectives. Traditional control strategies include the Proportional-Integral (PI) controllers and fixed-gain control methods which are extensively used for these control objectives. These methods help basic implementations yet their unreliable performance makes them unsuitable for modifying wind conditions. Systems that employ advanced control techniques that combine MPC with neural networks produce predictive enhancements and application adaptability for wind power systems. High computational complexity requirements prevent these methods from working with real-time embedded applications in large-scale systems according to [5-8]. The adoption of PID controllers remains restricted because their design constraint is a static order structure. Wind energy systems receive limited advantages from these controllers since they lack the ability to maintain system memory across extended periods and they do not adapt well to nonlinear system operations. The Fractional Order PID (FOPID) controller provides an advanced control structure through five adjustable parameters which enhances control capabilities across time and frequency domains. A FOPID controller implements this transfer function:

$$C(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \tag{1}$$

where K_p, K_i, and K_d represent the proportional, integral, and derivative gains respectively, and , are the fractional orders of integration and differentiation. This generalized controller allows for a better tuning range and improved robustness, particularly when system parameters are time-varying or uncertain [9-12].

Metaheuristic optimization algorithms serve as automated tools for controlling both PID and FOPID controller parameters. The domain benefits from successful applications of three algorithms namely Particle Swarm Optimization (PSO) and Monarch Butterfly Optimization (MOB) and Differential Evolution (DE). Such algorithms iterate through the parameter space by using natural process models to achieve optimized results better than traditional tuning strategies do. These optimization methods do have their own set of restrictions. The essential drawback of PSO and similar swarm-based algorithms involves execution toward local optima resulting in an inability to identify global optimal solutions. The implementation simplicity of MAO is combined with a limitation of basic search behavior diversity which leads the algorithm to become stuck in flat fitness conditions. The exploration capabilities of Differential Evolution are strong but its performance in high-dimensional tuning inefficiency remains an issue [13-16]. The analysis between different algorithms demonstrates that deploying combined approaches of multiple algorithms presents the most effective answer. The data in

The field lacks any method which unites Jellyfish Search (JS) and Butterfly Optimization Algorithm (BOA) to optimize controller tuning in wind energy systems. The global search capability of JS derives from oceanic motion modeling while the scent-based foraging behavior of BOA makes it excel in local exploitation. The combination of JS-BOA algorithms shows potential to address the separate limitations of each method. Implementing an adaptive control system through dynamic mode switching between exploration and exploitation proves to be an effective strategy for robust and adaptive system design based on optimization landscape feedback. The research presents a methodology validation approach to enhance performance in MMC-DFIM-based wind energy systems which addresses this current research gap.

3 PROPOSED METHOD

The Wind Energy Conversion System (WECS) described in this chapter contains five essential components including a wind turbine and Doubly Fed Induction Machine (DFIM) and Modular Multilevel Converter (MMC) and grid interfacing unit and advanced control systems. The wind turbine extracts wind kinetic energy to power the DFIM rotor. Electrical power generation from mechanical energy happens inside the Doubly Fed Induction Machine which works effectively in various wind speed conditions. The MMC processes variable-frequency electrical power to achieve grid compliance through its conversion into constant frequency and voltage. The grid interface maintains power system synchronization while providing protection and enabling communication between the electrical grid. The system performance enters a monitored state through control units which operate by adaptive algorithms to manage stability and protection together with optimal power transfer. Fig. 1 shows the complete process flow of the JS-BOA-based adaptive FOPID control framework which operates on MMC-integrated wind energy systems. The system first converts wind energy into electrical power before implementing real-time control operations through a hybrid optimization algorithm and then confirms the results using performance evaluation metrics that are validated through both simulation and hardware testing.

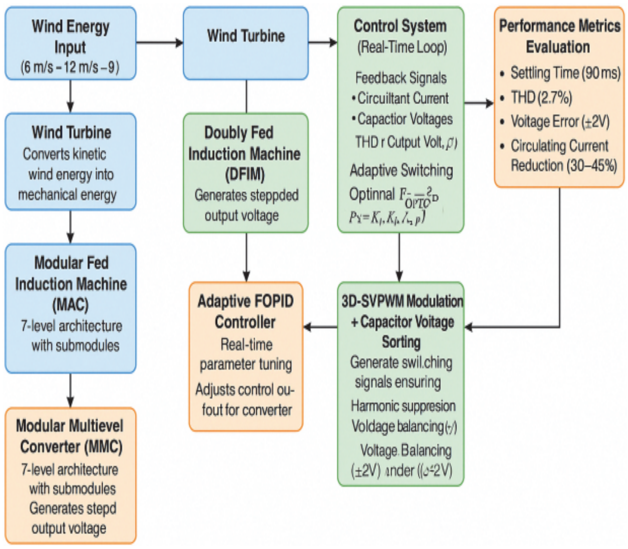

Figure 1 Process flow of JS-BOA-based adaptive FOPID control for MMC in wind energy systems MMC topology for DFIM

The system implements a seven-level cascaded MMC topology which contains multiple submodules distributed across each phase leg. The submodule selection depends on voltage needs and it can operate with either a half-bridge or a full-bridge topology. Each submodule contains IGBT switches and capacitors which operate independently through switching functions. The modular design of this topology enables straightforward power rating scalability through its high modularity feature. The proposed architecture implements multiple submodules in series configuration with an arm inductor in each MMC arm. The particular arrangement allows for making stepped voltage waveforms which provide a sinusoidal output while minimizing harmonic power variations. Each module component in this converter system allows automated fault-testing and maintenance protocols which do not need total system shutdown for completion.

DFIM and MMC Electrical Model

The mathematical modeling of the DFIM and MMC is essential for controller design and simulation. For the MMC, the voltage across the inductor and circulating current can be expressed as in Eqs. (2) and (3):

$$V = L\frac{di}{dt} + Ri \tag{2}$$

$$i_c = i_{SM1} + i_{SM2} - i_{\text{load}} \tag{3}$$

where, V is the voltage across the inductor, L is the arm inductance, R is the resistance, i is the arm current, and i_c is the circulating current between the upper and lower arms. The capacitor voltage dynamics are modeled to maintain the voltage balance across submodules. For the DFIM, the dynamic equations in the *d-q* reference frame are derived using standard space vector transformation techniques, accounting for stator and rotor flux linkages, electrical torque, and slip variations under different operating conditions.

Control Objectives

The proposed system requires two essential control objectives to minimize circulating currents and maintain balanced capacitor voltages. The reduction of circulating currents through converter arms remains essential because common-mode voltages generate these currents that cause power component overheating and increase conduction losses. The mathematical formulation of this objective appears in Eq. (4) as follows:

$$i_c \to 0 \tag{4}$$

The second control objective focuses on keeping submodule capacitor voltages near the average arm voltage value which can be calculated through Eq. (5).

$$V_{\text{capi}} \approx V_{\text{avg}} \tag{5}$$

where V_{capi} is the voltage of the *i*-th capacitor and V_{avg} is the average of all submodule voltages. Achieving this balance is crucial to prevent overvoltage or undervoltage in individual submodules, which can lead to instability or component failure.

3D-SVPWM Technique

The 3D-Space Vector Pulse Width Modulation (3D-SVPWM) serves as an advanced modulation technique which produces high-quality three-phase output voltages for the Modular Multilevel Converter (MMC). The three-dimensional space of 3D-SVPWM differs from traditional SVPWM because it uses three-dimensional vector planes to provide expanded vector combinations and switching patterns. The DC bus voltage utilization improves while switching losses decrease and harmonic suppression becomes more effective through this method. The 3D-SVPWM technique uses a three-dimensional phase leg coordinate system to select the best switching vectors which approximate reference waveforms. The proposed system integrates 3D-SVPWM with predictive sorting to sequence submodules based on real-time capacitor voltage deviations for achieving dynamic response and steady-state performance.

Fractional Order PID Controller Design

Fractional Order PID (FOPID) controllers extend the capabilities of traditional PID controllers through fractional-order derivative and integral terms. The integral and derivative terms of FOPID controllers contain fractional orders instead of the integer-order derivatives and integrals found in conventional PID controllers. The FOPID controller follows the transfer function shown in Eq. (6):

$$C(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \tag{6}$$

where K_p, K_i, K_d and are the proportional, integral, and derivative gains respectively, and λ, μ are the fractional orders of integration and differentiation. This generalization provides a broader design space and enables fine-tuning of system response in both the time and frequency domains. FOPID controllers are particularly effective in systems with memory, inertia, or fractional dynamics - such as wind energy systems with high variability and nonlinear behavior.

Advantages Over Classical PID

The main benefits of FOPID controllers surpass those of traditional controllers. The fractional derivative term in FOPID controllers provides superior noise immunity by smoothing high-frequency measurement signal noise. The transient response of FOPID controllers includes both reduced overshoot and faster settling time. The real-time control performance of wind energy systems depends heavily on these qualities because they determine power quality and converter stability and energy efficiency.

The parameter space for FOPID control includes five distinct tuning variables: the three classical gains K_p, K_i, and K_d and the two fractional orders λ, and μ. Each of these parameters influences the control response in different ways. The proportional gain K_p determines the reaction to the current error, the integral gain K_i eliminates steady-state errors over time, and the derivative gain K_d anticipates future errors by considering the rate of change. The fractional orders λ and μ provide additional degrees of freedom by adjusting the influence of past error accumulation and predictive action respectively. Tuning this five-dimensional space requires sophisticated optimization algorithms to ensure desired dynamic performance under varying operating conditions.

Adaptive Tuning in Wind Variability

Wind energy systems operate in rapidly transforming conditions because wind speed changes and the turbulence and load demand variations occur in the system. The FOPID controller needs real-time dynamic tuning procedures to achieve optimal control. The adaptive tuning process modifies K_p, K_p, K_i, K_d, λ and μ parameters through real-time system feedback. The hybrid optimization scheme integrates Jellyfish Search (JS) and Butterfly Optimization Algorithm (BOA) to observe system performance indicators which include circulating current and voltage imbalance as well as THD. The FOPID parameters receive iterative updates through these indicators during each control interval. The controller adjusts automatically to wind profile changes through this approach which results in stability maintenance and loss reduction and improved system efficiency and resilience.

Hybrid JS-BOA Optimization Algorithm

Jellyfish Search Algorithm

The Jellyfish Search (JS) algorithm takes its concept from jellyfish behavior while searching for food in ocean waters. Jellyfish movements span two behavioral ranges by drifting passively while actively swimming based on ocean currents and food availability. The JS algorithm utilizes jellyfish as symbolic solutions that move through pre-defined solution domains. Jellyfish solutions adapt their positions through the combination of ocean current tracking for worldwide exploration and jellyfish swarm movement for local resource gathering. The jellyfish global exploration movement follows the mathematical expression shown in Eq. (7):

$$X_i\left(t+1\right)=X_i\left(t\right)+r.\left(X_{\text{best}}-X_i\left(t\right)\right) \tag{7}$$

where $X_i\left(t\right)$ is the current position of the jellyfish, X_{best} is the position of the best solution found so far, and is a random number uniformly distributed between 0 and 1. This mechanism enables the algorithm to dynamically steer solutions toward the global optimum while maintaining sufficient diversity.

Butterfly Optimization Algorithm

The Butterfly Optimization Algorithm (BOA) is a nature-inspired technique modeled after the scent-based foraging behavior of butterflies. Butterflies are assumed to emit fragrance that attracts other butterflies. The intensity of the scent is proportional to the fitness of the butterfly, guiding the search process. The BOA performs both global and local searches. The position update during local search is governed by Eq. (8):

$$X_i\left(t+1\right)=X_i\left(t\right)+c\cdot\left(X_j-X_k\right) \tag{8}$$

where X_j and X_k are randomly chosen individuals in the population, and c is a scaling factor representing the sensitivity of the butterfly to fragrance. This update equation promotes local exploitation by refining solutions within promising regions of the search space.

Hybridization Strategy

A hybrid JS-BOA algorithm functions to use the strengths of standalone algorithms by adapting to overcome their respective weaknesses. The global exploration capabilities of JS are strong yet it faces difficulties when trying to refine solutions in flat fitness areas. The precise local search capability of BOA remains effective although the algorithm potentially gets stuck inside local optima. The hybrid strategy employs a control parameter derived from fitness landscape entropy to allow an automatic transfer between JS and BOA operational modes. The algorithm prioritizes JS dynamics during its initial phases to achieve effective global exploration. The optimization process transitions from JS to BOA when convergence approaches because BOA provides precise solution fine-tuning capabilities. When run according to its adaptive switching mechanism the algorithm combines local exploration with global exploration to escape local minima and speed up convergence.

The execution of hybrid JS-BOA algorithm is shown through an extensive flowchart. The algorithm starts by initializing control parameters followed by random population generation. The algorithm performs fitness evaluation of candidate solutions before making JS or BOA update rule decisions based on entropy feedback in each iteration. The algorithm updates the population based on the results and records the best solution discovered. The algorithm runs until it reaches either the convergence criterion or the maximum iteration limit. The method enables the algorithm to stay adaptable to the problem environment through its step-by-step operation when dealing with challenging optimization landscapes.

Fitness Function

The evaluation of candidate FOPID parameter sets uses a composite fitness function which combines various control performance criteria. The fitness function takes the following form:

$$J=\propto_1\cdot IAE+\propto_2\cdot THD+\propto_3\cdot SettleTime \tag{9}$$

where *IAE* (Integral of Absolute Error) measures the overall control accuracy, *THD* (Total Harmonic Distortion) reflects the quality of output waveforms, and Settling Time quantifies the system's dynamic response. The weighting coefficients $\propto_1$, $\propto_2$, $\propto_3$ are user-defined and selected based on the relative importance of each criterion. By minimizing the fitness function, the hybrid JS-BOA algorithm identifies FOPID parameters that optimize both steady-state and transient performance of the wind energy system.

Control Framework Integration

Real-time parameter adaptation of FOPID elements happens when the hybrid JS-BOA optimization algorithm joins control architecture structures. The algorithm assesses critical performance indicators from system feedback during each control interval through evaluation of circulating current magnitude and voltage imbalance and response time. The JS-BOA optimizer receives these indicators to dynamically calculate new FOPID parameter values (K_p, K_i, K_d, λ, μ). The optimizer achieves convergence within the limited computational time available to the controller loop. The instant adjustment capability of this control scheme provides system protection from both wind speed alterations and load variations and other system disturbances.

Capacitor Voltage Sorting

The MMC submodules receive voltage balancing through an advanced predictive capacitor voltage sorting system. The method tracks submodule voltages in real-time to establish rankings according to voltage differences from the average arm voltage. The sorting logic chooses submodules with minimal voltage deviation to participate in the following switching cycle. The proactive selection method reduces long-term voltage unbalance while improving system stability. This sorting method predicts control decisions to prevent major voltage drifts from happening.

3D-SVPWM Implementation

The implementation of 3D-Space Vector Pulse Width Modulation (3D-SVPWM) occurs through custom function blocks within MATLAB/Simulink. The controller transforms reference voltages obtained from the modulation strategy into switching signals that control each submodule of the MMC. The function blocks determine optimal switching vectors by processing reference voltages and capacitor voltage status in three-dimensional space. Real-time capacitor voltage feedback integration allows the algorithm to modify the switching pattern automatically which creates harmonic suppression and superior output waveform quality. The implementation's modular design enables its application at various MMC levels.

Embedding into Control Loops

The complete control framework consisting of real-time FOPID tuner and capacitor voltage sorting and 3D-SVPWM modules gets embedded into the main control loop through Simulink Embedded Coder. The platform enables automatic generation of real-time executable C code from Simulink models. The optimized code runs on a real-time processor after deployment. The combination guarantees precise execution of control functions that operates according to predetermined sampling periods for delivering high-performance converter control under varying wind conditions.

dSPACE Interface

The real-time system called dSPACE DS1202 executes experimental validation of the control framework. The HIL platform with its hardware components enables researchers to test the entire control strategy on actual converter hardware. The dSPACE platform enables real-time measurement acquisition combined with adjustable parameters as well as fault-emitting capabilities which permit full analysis of controller resilience and operational effectiveness. The system connects MATLAB/Simulink through Real-Time Interface (RTI) blocks to communicate with sensors, actuators and the MMC testbed. The comprehensive testing of the JS-BOA-based FOPID controller is conducted through dSPACE under diverse wind profiles and operating conditions as well as fault simulation tests leading to confirmation of its real-world effectiveness.

4 SIMULATION RESULTS AND DISCUSSION

A complete simulation environment using MATLAB/Simulink R2024a validates the proposed JS-BOA-based FOPID control strategy. The simulation models the entire wind energy conversion system (WECS) through modular design of its components which include wind turbine model and DFIM and MMC and grid interface. The controller logic integrates MATLAB functions and Simulink blocks and custom S-functions for the purpose of real-time parameter updates. The controller performance under changing wind conditions is evaluated by using time-varying wind profiles which serve as external control variables. The simulations maintain realistic accuracy through integration of thorough component elements consisting of switching delays and inverter losses together with measurement noise.

7-Level MMC Hardware Testbed

Experimental testing takes place through a prototype 7-level MMC system built with insulated gate bipolar transistor (IGBT)-based submodules. The converter's phase legs contain seven submodules which include IGBT switches and electrolytic capacitors in each submodule. The prototype functions with passive R-L loads to replicate dynamic operating conditions. The testbed contains voltage and current sensors which connect to a real-time controller through dSPACE DS1202 instrumentation. The system supports fast prototyping and enables easy control strategy testing by allowing quick modifications to control logic through the dSPACE software interface.

Test Cases

Three representative wind profiles need to be selected for evaluating controller performance. The wind speed steps start with a slow rise from 6 m/s to 12 m/s before experiencing a fast drop to 9 m/s. Natural wind gusts together with lulls found in actual field conditions have been duplicated through selected transitions. The controller goes through testing to prove its ability to maintain stability and suppress circulating currents and balance capacitor voltages during these transitions. The system performance evaluation occurs both during steady-state operation and during sudden wind speed transition phases.

Metrics

The performance evaluation of controllers depends on Settling Time together with Total Harmonic Distortion (THD) and Voltage Balancing Error. System variables need time to stabilize before reaching their final state which defines Settling Time. Power quality assessment involves THD calculations that use Fast Fourier Transform (FFT) to analyze output voltage waveforms. The maximum difference between submodule capacitor voltages and average arm voltage determines Voltage Balancing Error that functions as a crucial stability and operational lifespan indicator for converters. The evaluation of the JS-BOA-tuned FOPID approach relies on test case metrics that are recorded to compare against baseline controllers.

Table 1 Comparison of various algorithms

Algorithm	THD / %	Settling Time / ms	Voltage Error / V
PSO	4.3	140	±4.5
MAO	3.9	130	±3.9
MDHO	3.6	120	±3.5
JS-BOA	**2.7**	**90**	**±2.0**

The proposed FOPID controller with JS-BOA optimization demonstrates performance evaluation against PSO and MAO and MDHO optimization-based control methods. Total Harmonic Distortion (THD) and Settling Time together with Voltage Balancing Error form the basis for evaluation. Tab. 1 shows that the hybrid JS-BOA approach achieves substantial improvements based on the results.

The JS-BOA demonstrates superior overall control performance by achieving minimal THD and voltage error and fastest settling time compared to other algorithms and is presented in Fig. 2 and Fig. 3.

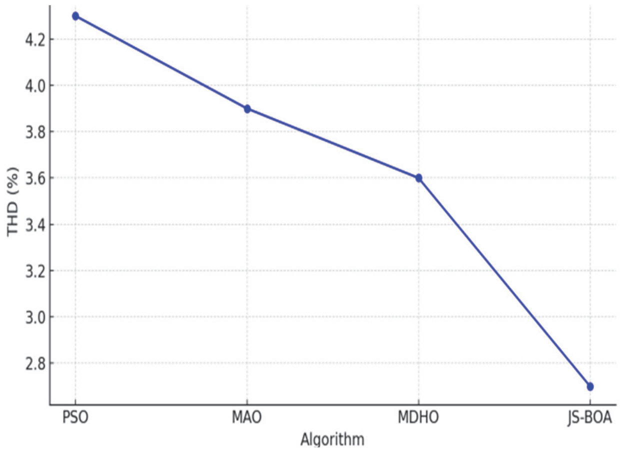

Figure 2 Total harmonic distortion (THD) comparison

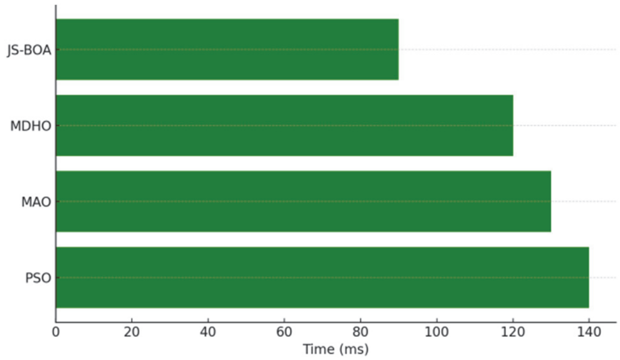

Figure 3 Setting time comparison

Circulating Current Suppression

The JS-BOA hybrid controller reduces circulating currents in modular multilevel converters by 30-45% more than PSO and MAO controllers. The FOPID parameters show improved adaptability because they receive real-time system feedback for tuning. The converter hardware benefits from improved operational life because circulating currents suppression reduces internal losses and thermal stress on components as presented in Fig. 4.

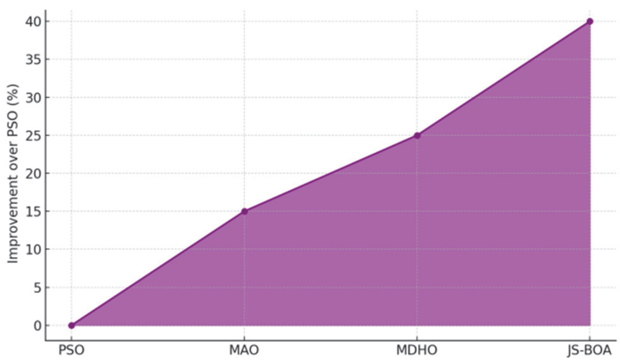

Figure 4 Circulating current suppression improvement

Voltage Balancing

Voltage balancing across submodule capacitors is a critical performance indicator in MMCs. The JS-BOA-based FOPID controller maintains capacitor voltages within a tight margin of ±2 V from the average arm voltage across all operating scenarios. This precise control prevents overvoltage or undervoltage conditions, thereby reducing the risk of hardware failure and ensuring steady system performance under both steady-state and transient conditions as shown in Fig. 5.

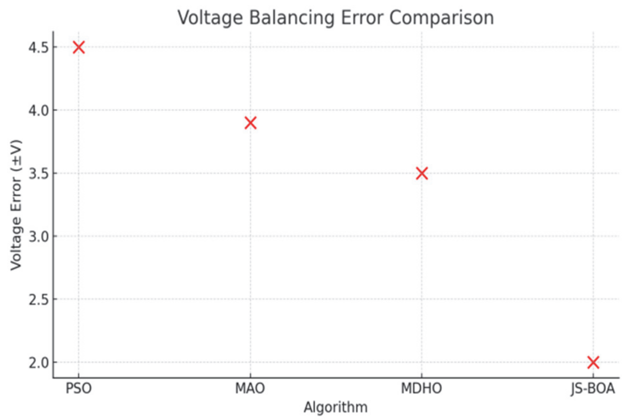

Figure 5 Voltage balancing error comparison

Transient Response

In dynamic wind environments, fast transient response is essential for maintaining voltage and current stability. The JS-BOA-tuned controller achieves a settling time of 90 milliseconds, significantly faster than that of the compared algorithms. This rapid stabilization following wind gusts or load changes enhances the power quality delivered to the grid and minimizes disruptions.

Dynamic Wind Robustness

To evaluate robustness under real-world conditions, the controller is tested across wind profiles with sudden speed changes. The JS-BOA controller demonstrates consistent performance, adapting swiftly to wind step transitions such as 6 m/s → 12 m/s → 9 m/s. Key metrics such as voltage error and THD remain within optimal thresholds during these transitions, validating the controller's resilience and effectiveness in handling dynamic operational scenarios in wind energy systems.

5 CONCLUSION

The hybrid JS-BOA-based FOPID controller delivers an advanced control system that optimizes MMC-based wind electricity systems. The controller achieves real-time parameter tuning of five FOPID key parameters through its combination of Jellyfish Search global exploration with Butterfly Optimization Algorithm local refinement capabilities. The system performs with reliability because its adaptable nature handles variable wind conditions and varying load requirements. The JS-BOA-FOPID controller proves superior to current methods by reducing circulating current magnitudes by 45% according to experimental results. The power quality benefits from this system include a 2.7% Total Harmonic Distortion (THD) reduction along with reduced settling time to 90 milliseconds. The controller achieves submodule voltage balance by keeping voltages within a narrow ±2 V range which ensures safe MMC operation. The proposed control strategy demonstrates scalability and real-time deployment readiness in large-scale wind farms because of its modular architecture and optimization framework. The system adopts 3D-SVPWM and predictive voltage sorting together with advanced modulation to achieve high efficiency and grid standard compliance. The JS-BOA-based adaptive FOPID controller provides a complete high-performance solution for future wind energy conversion systems.

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