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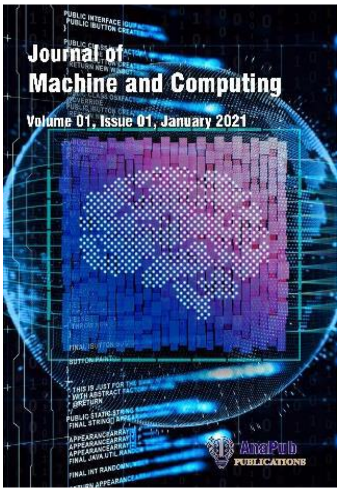


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# Innovative Aerodynamic and Fault-Tolerant Control for VSVP Wind Turbines and DFIG Using Predictive and Sliding Mode Techniques

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## Abstract:

To maximize power production efficiency and preserve stability under changing climatic circumstances, renewable energy systems, especially VSVP wind turbines, must be integrated into the power grid. Wind speed changes and grid disruptions influence their performance. This paper suggests an enhanced hybrid control system for Doubly Fed Induction Generator (DFIG)--based wind turbines to optimize aerodynamic performance, power collection, and fault resilience. This study aims to improve power extraction efficiency and Fault Ride-Through (FRT) capacity by merging MPC and SMC. Dynamically adjusting pitch angle and generator torque optimizes power coefficient (Cp) and reduces pitch angle variation, rotor speed fluctuations, and reaction time. For fault mitigation during voltage dips, Higher-Order Sliding Mode Control (HOSMC) and the Super-Twisting Algorithm (STA) modulate DFIG electromagnetic force to reduce torque ripples, mitigate the voltage sags, and minimize THD. MATLAB implements the framework. Improved power coefficient (Cp) of 0.52 at $\lambda = 6.5$ surpasses PI (0.42) and Fuzzy Logic (0.48) controllers. THD is 1.8%, compared to 3.5% (PI) and 2.3% (Fuzzy Logic), assuring improved power quality. Torque ripple is reduced by 2.1%, stabilizing turbines. The suggested technique increases FRT, energy capture, and grid stability. Our dual-layer control approach may improve wind turbine efficiency, dependability, and resilience under changeable wind and grid circumstances.

**Keywords:** Predictive Control, Sliding Mode Control, Variable Speed Variable Pitch Wind Turbines, DFIG, Voltage Dips

## 1. Introduction

Due to their need for flawless electrical network integration, wind turbines have emerged as crucial components of contemporary renewable energy systems [1]. Wind turbines with VSS/VSP designs automatically modify operating aspects to fit varied wind conditions, maximizing their power generating capacity [2]. Active modifications to blade pitch and rotor speed are made possible by the control systems of VSVP wind turbines, allowing them to enhance power efficiency [3]. Maximum output and reduced component strain are both made feasible by wind turbines' adaptable functioning [4]. Several operational challenges prevent the addition of variable renewable power sources, particularly wind energy output, to the current electrical power infrastructure [5]. Power variations caused by variable wind energy production undermine power grid stability and quality requirements [6]. Rapid changes in wind speed may cause voltage variations at the electrical supply level, which can affect electricity dependability [7]. Power electronic converters and intricate control systems allow modern wind turbines to operate at varied speeds while still being friendly to the grid [8]. Turbines are able to operate at their maximum efficiency with the help of power electronic converters, which isolate the generators from the grid and allow them to manage reactive power and low voltage immunity [9].

Intelligent scheduling and operational control systems are necessary for the proper integration of wind energy into the power grid [10]. When wind farms connect to the grid, the development process generates grid codes that the power plants must follow in order to operate reliably and steadily. When electrical network problems occur, modern wind turbines include sophisticated features that provide necessary ancillary services to maintain voltage support and frequency balance [11], [12]. Supply stability issues caused by uncertain power availability may be addressed with the use of smart grid technology, energy storage, and improved forecasting tools for older power systems. The increasing usage of wind energy makes it all the more important to study how to make wind turbines more efficient and how to make power grids more stable. An in-depth familiarity with wind turbine performance, grid power distribution, and environmental factors is necessary for research into the development of efficient and dependable systems [13]. By addressing these problems, wind energy can continue to play a crucial role in creating a renewable energy power infrastructure that can withstand the test of time.

### 1.1 Problem Statement

Unpredictable wind changes and grid failures make VSVP wind turbines unstable, limiting their power extraction capabilities, which is controlled by adjusting the pitch angle and generator torque. Because voltage dips generate torque oscillations and electromagnetic disturbances, which reduce power quality, they have a detrimental impact on DFIG-based wind turbines [14]. Powerful control techniques are required to enhance system power performance and fault prevention capabilities, since the Proportional-Integral (PI) controllers are unable to handle nonlinear processes and disturbances.

### 1.2 Existing Solutions & Limitations

In order to control VSVP wind turbines in conjunction with DFIG systems, a number of conventional methods are used. While Proportional-Integral control has been widely used because to its user-friendliness, it falls short when faced with nonlinearities and grid events. Since Fuzzy Logic Control (FLC) systems respond well to uncertainty, the predictability of dynamic wind conditions is reduced when utilizing them [15]. Although Adaptive Control may operate in real-time, its significant computational complexity makes it impractical for such applications [16]. Chattering is an undesirable side effect that has a detrimental influence on system performance caused by Sliding Mode Control's resilience against nonlinearities. In order to meet the present demands of control strategy, DFIG-based wind turbine applications need a better approach that optimizes aerodynamic outcomes and reliably offers fault ride-through capabilities during voltage drop situations.

### 1.3 Research Motivation

This study presents a dual-control strategy for DFIG-based wind turbines that improves power production and maintains grid stability during faults by integrating Model Predictive Control with Advanced SMC characteristics of Super-Twisting Algorithm and Higher-Order SMC. By using real-time pitch and torque control based on MPC, the proposed technique seeks to maximize aerodynamic efficiency. By using STA-SMC for smooth control activities and HOSMC for torque oscillation reduction, the system is able to achieve better FRT capacity. In the event of a power outage, put a mechanism in place to reduce electromagnetic interference and improve the quality of the electric power. The framework integrates several control strategies to maximize electricity production while ensuring grid stability.

### 1.4 Research Significance

Optimizing operational performance of DFIG-based wind turbines in the face of grid interruption events and variations in wind speed is the focus of this study. The designed framework optimizes the pitch angle and generator torque in real-time to achieve optimal efficiency in energy collecting. This system design enhances power system stability, complies with grid rules, and keeps turbines stable even when voltage decreases. To improve operating efficiency and equipment lifespan length, the presented technology works to lessen torque variations and Total Harmonic Distortion. When renewable energy systems use the suggested approach to power quality and grid integration, they become more resistant to electrical disturbances. More efficient and fault-tolerant modern wind power generating systems are the result of actively resolving the main difficulties plaguing wind energy systems.

This structure is followed by the paper: In Section 1, the research challenge, including its motivation, relevance, and major contributions, is explained. Current control mechanisms and their limitations are reviewed in Section 2. The control framework and system modeling are presented in Section 3. Section 5 presents the outcome of the study, along with comparisons and remarks. Proposed future research directions and important findings round out the section.

## 2. Related Works

An automated phase angle adjustment elimination system is created by Chen et al., [17] and used in three-turbine Savonius wind clusters to increase power output. The system is variable-speed controlled. Rotational direction, configuration angles (θ1-2, θ1-3), and inter-turbine distances (L1-2, L1-3) are the three main elements that are examined in the optimization process using the Taguchi technique. Independently functioning wind ratios of 1.13, 1.14, and 1.09 result in an average power coefficient increase of 1.425, according to the study. Because it is sensitive to changes in wind speed and direction and has difficulty scaling up efficiently as cluster sizes increase, the system's implementation has two major flaws.

Gupta et al. [18] study H-rotor Darrieus Vertical Axis Wind Turbines (VAWT) at low wind speeds using dynamic blade pitching. A high-fidelity 2D CFD model mimics changing blade pitching using sliding mesh and remising to capture rotor rotational effects. The NACA0015 airfoils' variable angle of attack changes at 1.5 tip speed ratio (TSR) enhanced power coefficient (Cp) by 81% to 0.44. Lengthening and adding blades improves performance. Complex aerodynamic effects between components and mechanical limits during implementation must be solved by active pitching mechanisms.

Shan et al. [19] introduced Parallel Compact Firefly Algorithm (PCFA), which enhances performance by reducing memory requirements. The compact approach works for tiny turbines and decreases memory needs, whereas the parallel technique optimizes solutions and solves quicker. PCFA tested 28 benchmark functions before setting variable pitch wind turbine proportional–integral–derivative parameters. PCFA consumes less memory, produces better solutions, and solves problems quicker than compact optimization methods. The wind turbine control system efficiently controls output power. The system's principal limitations include parameter adjustment susceptibility and computing challenges in uncertain operating situations.

One adaptive fractional-order non-singular fast terminal sliding mode controller for individual pitch control of wind turbines against uncertainties and external disturbances is AFO-NFTSMC, which is described in a paper by Aghaeinezhad et al., [20]. The controller is based on a two-mass model of the wind turbine and uses two subsystems to describe the mechanical and aerodynamic components, as well as connected movement equations. employing step and turbulent wind testing, the study examines controllers employing the single-blade approach. In order to verify the system, the FAST software and the TurbSim simulation tool were used. When compared to traditional adaptive and sliding mode controllers, the suggested controller showcases better rotor speed tracking capabilities and offers high accuracy performance with improved stability. There are two problems with the controller: first, it could need a lot of processing power, and second, it becomes hard to utilize in real time when the wind is very variable.

In their investigation, LeBlanc et al. [21] looked at the effects of blade pitch adjustments on the aerodynamic and structural stresses of a Vertical Axis Wind Turbine (VAWT). In the open jet wind tunnel at TU Delft, strain gauges detect the normal loading on the blades via the stressed struts while the blades are tested at various fixed pitch offsets from a neutral position. The experimental findings show that turbines are very sensitive to changes in pitch angle, leading to the occurrence of unique aerodynamic phenomena such as blade dynamic stall and vortex interaction. Rotor thrust characteristics and stresses acting on the rotor and platform acceleration frequencies may be controlled by adjusting the pitch, which also increases the reaction per revolution. The scalability of real-life data is affected by experimental limits and measurement error limitations in this investigation.

A fault-tolerant finite-time constant non-singular terminal synergetic control manifold may make large-scale wind turbines more dependable following simultaneous pitch actuator failures, according to Palanimuthu's study [22]. under addition to dependable power management under high-wind conditions, the control system improves the accuracy of precision tracking procedures. The control system's resistance to time-dependent disturbances and tracking capabilities are both improved by a disturbance observer that uses mismatched control components. Lyapunov theory is used to establish stability and finite-time convergence. The results of the simulations showing the performance of wind turbines based on PMSG that are 4.8 MW and 20 MW show that they are very reliable both before and after disturbances happen. Inconsistent modeling results, realistic deployment challenges, and very disruptive operating events make optimization of the system control difficult.

In wind power systems, Chen et al. [23] developed a self-adapting active fault-tolerant MPPT control approach to safeguard maximum power point tracking capabilities from generator-side faults. Observer components estimate model uncertainties, nonlinearities, and unknown disturbances like failing generators and disturbance torque in real time. Adjusting for estimated disturbances, an adaptive feedback linearizing control system regulates the variable-speed wind turbine (VSWT). It performs better than typical ways since it doesn't represent whole systems or measure all states or faults. Three controllers outperform PI with NSSF-MPPT controllers in adaptability, stability, and tracking error. In addition to system-related variations, the suggested technique requires external operational confirmation testing.

Song et al.[24] proposed an adaptive switched sliding mode controller to improve floating wind turbine performance under actuator failures and environmental uncertainty. A switching linear model with average dwell time characteristics simulates the system, while full-order state observers and adaptive rules handle errors, disturbances, and faults. The work generates control parameters using average dwell time, linear matrix inequality, and Lyapunov stability theory. FAST simulations show that the suggested controller runs on the NREL 5MW wind turbine with a spar-buoy platform, resulting in better power quality and lower mechanical stresses than gain-scheduling PI control. Offshore facility testing and high computational needs are the key obstacles.

In order to enhance the fault tolerance of wind turbines, Fayazi et al.[25] proposed an L1 adaptive-sliding mode control (L1 adaptive-SMC) system that would deal with issues such oil air content, hydraulic leakage, and pump wear. The L1 adaptive control precisely controls the rotor speed and power with sliding mode control, adjustable gain, and an integrated sliding surface. Researchers used FAST simulations to verify on a 5MW wind turbine operating at high wind speeds. Compared to adaptive-SMC and adaptive control, L1 adaptive-SMC improves system reliability in the face of disruptions, faults, and wild wind conditions.

In order to monitor the states of the active pitch system in wind turbines when faced with unknown uncertainties, Rodríguez et al. [26] created a Fault Detection and Diagnosis approach that relies on the Takagi-Sugeno Unknown Input Observer (TS-UIO). The method allows for the identification and diagnosis of sensor faults by comparing the residuals of a TS-UIO with the system model. The approach converges to a zero estimate error by linking unknown inputs to Linear Matrix Inequalities. Effective disturbance and noise performance was shown in the simulation experiments conducted utilizing reference wind turbine models. The computational complexity and the need for field experiments to evaluate the system's efficiency across varied environmental conditions are the key restrictions.

To better regulate active and reactive power in doubly fed induction generators, Aoun et al.[27] looked at field-oriented control approaches to improve the energy quality of variable speed wind turbines. Experiments were conducted in MATLAB/Simulink that contrasted neural networks, fuzzy logic, and proportional-integral controllers. Standard criteria were used to calibrate the PI controller, although reducing it needed a lot of math. Despite the FLC's improved performance, there was no proof of mathematical stability. A Neural Network Controller outperformed its rivals in terms of tracking accuracy and dynamic response time. Training neural network controllers and validating wind farms in real time are both demanding tasks.

Wang et al.[28] used mechanical-electrical-grid modeling to study doubly fed induction generator grid stability and electrical damping under varied wind speed and control settings. Machine dynamics, electrical behavior, and grid interactions are simulation-validated. Key findings: (1) Wind speed and control strategy affect shaft oscillations, and rotor-side impedance varies with wind speed; (2) For constant wind speeds, control parameters affect drive train dynamics, and proportional gains in the control system affect rotor-side impedance, offering grid integration DFIG stability insights. This model is limited by its assumptions and need for real-world testing under changing grid conditions.

### 3. System Modeling

Figure 1 depicts the proposed wind energy conversion system that makes use of V.S.V.P. wind turbines and a Doubly Fed Induction Generator, both of which function under an advanced hybrid control framework.

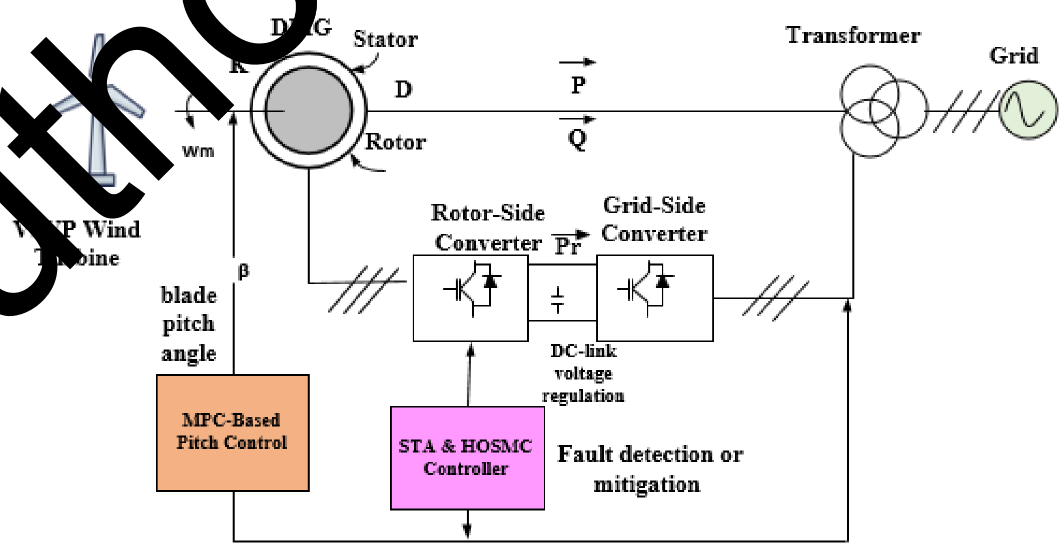



Fig. 1. Proposed Framework

The model of the wind turbine incorporates the fundamental processes involved in harnessing aerodynamic resources for power generation. The capacity to convert energy is controlled by two essential components of power coefficient efficiency. In order for the DFIG model to function, the synchronous reference frame is used as the rotational basis in two voltage equations. The rotor-side and grid-side converter systems are essential for active and reactive power transmission. The stator part receives electricity directly from the grid, while the rotor section manages the transmission of power via a back-to-back converter. Combining Sliding Mode Control with a Super-Twisting Algorithm and Higher-Order SMC for fault tolerance, this work incorporates Model Predictive Control to improve aerodynamics concurrently. While STA-SMC protects the grid from disruptions by stabilizing the voltage, the MPC real-time system regulates the pitch angle and generator torque. Optimized electrical power production, increased operational stability, and a stronger link to the power grid are all outcomes of the unified modeling approach.

### 3.1 MPC-Based Aerodynamic Control for Power Optimization

By optimizing the power coefficient parameters with pitch angle and tip-speed ratio values, the optimization process in VSVP wind turbines using Model Predictive Control accomplishes power extraction. To maximize efficiency in power conversion, the controller will adaptively change the pitch angle and generator torque based on the wind conditions. The objective of MPC is to minimize (C_p) by making real-time adjustments to the pitch angle and generator torque, respectively. As shown in Equation (1), the MPC cost function is defined. At time step k, with a limited prediction horizon, MPC solves an optimization problem. One way to express the typical MPC cost function is as follows:

$$J = \sum_{k=0}^{N_p}( w_1(P_{ref} - P_w)^2 + w_2(\beta_k - \beta_{k-1})^2 + w_3(\tau_g, k - \tau_g, k - 1)^2) \tag{1}$$

J, N_pPrediction horizon, w_1, w_2, and w_3 weighting factors are the cost function to be minimized. Pitch angles at the current and previous time steps are represented by β_k and β_(k-1), whereas P_ref and P_w stand for reference and actual power output, respectively. Generator torque at current and previous time steps, τ_g,k-τ_g,k-1, to reduce variations in roll-axial torque and glide-pitch. Control Action Execution is when the first control input in the optimized sequence is applied. In situations with partial load, the pitch mechanism modifies the blades to maximize C_p while reducing g power. At the next time step, the optimization problem is re-solved using new measurements. Maintaining Pitch and Modifying Torque A state-space model for pitch control is:

$$\beta = \frac{1}{T_p}(\beta - \beta^*) \tag{2}$$

In Eqn. (2) $T_p$ is the pitch actuator time constant. Generator Torque Control is denoted in Eqn. (3). The generator torque reference is adjusted to match the optimal torque-speed curve:

$T_p$ is the pitch actuator time constant in Eq.(2). The symbol for Generator Torque Control is found in Eq. (3). The ideal torque-speed curve is matched by adjusting the generator torque reference:

$$\tau_g = k_{opt}{\omega_r}^2 \tag{3}$$

Properties of the turbine define the empirical constant $k_{opt}$. Details about the system's control inputs, anticipated future actions, and optimal configuration settings Pitch responsiveness, overshoot, powering efficiency, and mechanical wear Grid integration and wind response prediction analytics.

### 3.2 Sliding Mode Control Techniques for Fault-Tolerant DFIG Control

Enabling fault ride-through capability in the DFIG system is the primary objective of Sliding Mode Control. This feature ensures stability and efficacy in the face of grid voltage dips and disturbances. Torque oscillations, significant total harmonic distortion (THD), and voltage instability are the results of using conventional control tactics during grid failures. The advantages of SMC include its fast response time, insensitivity to uncertainty, and ability to handle nonlinearities. When it comes to fault-tolerant control of DFIG, the two most common SMC approaches are: Using a Super-Twisting Algorithm for SMC Reduces buzzing and makes voltage more consistent. Control of Higher-Order Sliding Modes Manages electromagnetic torque, dampens torque waves, and offers reliable voltage and current management.

### 3.3 Super-Twisting Algorithm

The chattering problem, which results in excessive control effort and mechanical wear, is a standard feature of SMC. An STA, a Second-Order Sliding Mode, can solve this problem by enabling a smooth control action while preserving resilience and reducing chattering. Fig. 2 shows the Super-Twisting Algorithm.

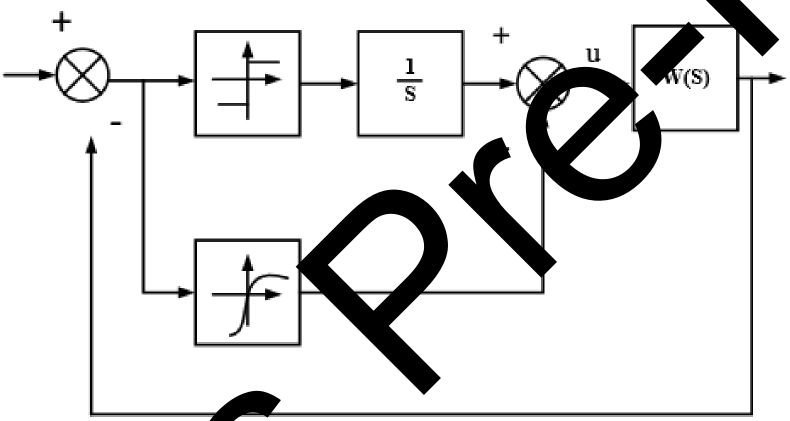



Fig. 2. Super-Twisting Algorithm

Consider the DFIG rotor current control under a voltage dip. The rotor current dynamics in the $dq$ reference frame are given by Eq. (4).

$$\frac{di_r}{dt} = -\frac{R_r}{L_r} i_r + \frac{1}{L_r}(v_r - j\omega_s \psi_r) \tag{4}$$

Where, $i_r = i_{rd} + j i_{rq}$ rotor currents in the $dq$ reference frame, $R_r, L_r$ means rotor resistance and inductance, $v_r = v_{rd} + j v_{rq}$ rotor voltage, $\omega_s$ refers to synchronous speed, $\psi_r$ means rotor flux. To regulate the rotor current, define the sliding surface as:

$$S = i_r - i_r^* \tag{5}$$

In Eq. (5) $i_r^*$ is the reference rotor current. The control objective is to drive S to zero, ensuring accurate current tracking. The STA-SMC control input is designed as Eq. (6)

$$v_r = -k_1 |S|^{1/2} sign(S) - k_2 \int sign(S) dt \tag{6}$$

Where, $k_1, k_2$ means positive control gain that can guarantee fast convergence, and $sign(S)$ is the sign function that acts to implement the sliding mode. The benefits of STA-SMC for DFIG are that it reduces chattering, ensuring smooth control action. Enhances voltage stability by stabilizing the rotor current under grid faults. Faster response compared to conventional SMC.

### 3.4 Higher-Order Sliding Mode Control

The HOSMC algorithm controls electromagnetic torque during grid failures. HOSMC reduces torque ripple and overall harmonic distortion and ensures strong current and voltage control. Standard SMC control uses derivatives of the sliding variable to define and regulate action, whereas HOSMC uses higher-order derivatives, which may be smoother and overcome the high-frequency switching effect. DFIG-based wind turbines employ HOSMC for rotor current management to stabilize electromagnetic torque and produce electricity smoothly during grid voltage dips. The sliding surface is defined in Eq. (7).

$$S(x) = \lambda_0 x + \lambda_1 \dot{x} + \lambda_2 \ddot{x} \quad (7)$$

Where, $\lambda_0, \lambda_1, \lambda_2$ are positive control gains and $x$ represents the system state variable (e.g., rotor current or electromagnetic torque). The HOSMC control law is:

$$u = -k_1 |S|^{\frac{n}{m}} sign(S) - k_2 \int sign(S) dt \quad (8)$$

In Eq. (8) $k_1, k_2$ are control parameters. $\frac{n}{m}$ determines the sliding mode order. The advantages of HOSMC for DFIG are that it keeps the electromagnetic torque stable during voltage dips. It reduces electromagnetic disturbances, enhancing power quality. Effectively managing DFIG rotor currents ensures grid stability. Combined Control Framework for the Integrated MPC + STA + HOSMC Control integrates Model Predictive Control for wind turbine aerodynamics with Sliding Mode Control (incorporating Super-Twisting Algorithm and Higher Order SMC) for DFIG stabilization under grid disturbances. VSVP wind turbines get extracted power efficiency, fault tolerance, and power production stability from these methods. MPC adjusts wind turbine pitch angle and generator torque in real time to maximize power coefficient. Real-time optimization predicts future system states, allowing control inputs to adapt quickly to energy harvesting and smooth pitch and torque changes. The DFIG control system receives the optimal torque set point.

**Algorithm 1:** VSVP Wind Turbine with DFIG

INPUT:
  Wind speed ($Vw$), Blade pitch angle (β), Rotor speed ($\omega_m$)
  Electrical torque ($T_e$), Mechanical torque ($T_m$)
  Stator and rotor currents ($i_s$, $i_r$)
  Grid voltage ($Vg$), Converter voltages ($V_{RSC}$, $V_{GSC}$)
  Reference active and reactive power (P*, Q*)
OUTPUT:
  Optimized Blade Pitch Angle ($\beta_{opt}$)
  Controlled Rotor Voltage ($V_{RSC}$ control)
  Fault Mitigation Response ($F_{response}$)
  Grid Power Injection (P, Q)
Step 1: Aerodynamic Control using MPC-Based Pitch Control
  WHILE True DO
    Measure Wind Speed
    Compute Optimal Beta Angle using MPC
    Adjust Blade Pitch Angle (β)
  Step 2: DFIG Control using STA-SMC & HOSMC
    Measure Rotor Speed ($\omega_m$), Electromagnetic Torque ($T_e$)
    IF Rotor Speed > Rated Speed THEN
      Apply STA-SMC Control
    ELSE
      Apply HOSMC Control
    ENDIF
  Step 3: Fault Detection and Mitigation
    Fault Status ← Monitor System Anomalies
    IF Fault Status == 1 THEN
      SWITCH Control Mode
        CASE "MPC":

```
            Switch to STA-SMC for robustness
          CASE "STA-SMC":
            Switch to HOSMC for extreme fault cases
        ENDSWITCH
        Perform Fault Mitigation Strategy
      ENDIF
Step 4: Power Conversion and Grid Integration
      Compute Rotor-Side Converter Control
      Compute Grid-Side Converter Control
      Regulate Active Power (P) and Reactive Power (Q)
      Step 5: Data Logging & System Monitoring
         Log Wind Speed, Rotor Speed, P, Q, Fault Status
   ENDWHILE
END
```

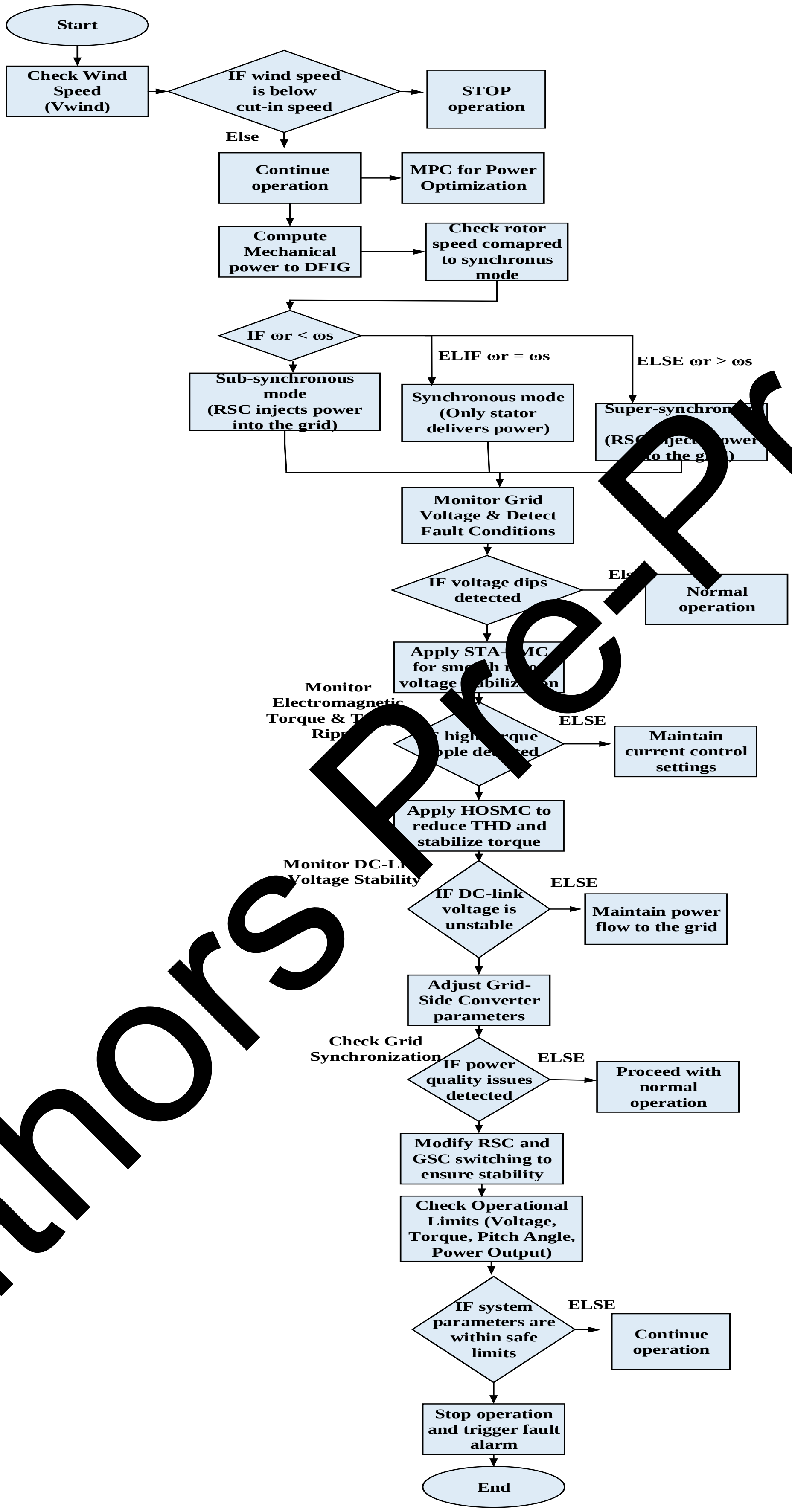



Fig. 3. Flow Chart

STA-SMC reduces chatter and smoothes control on the DFIG side to stabilize voltage during grid disruptions. Figure 3 shows how HOSMC controls electromagnetic torque with minimal torque ripple, Total Harmonic Distortion between currents, and strong voltage regulation. Therefore, STA and HOSMC enhance DFIG's FRT capacity, making the system exceptionally resilient against grid outages. The wind turbine and DFIG controls may share data. This allows an ideal torque set point input from the wind turbine to DFIG, which dynamically adjusts the generator's torque output in real time. This synchronized reaction of wind speed changes and grid disruption improves fault tolerance and power quality, making wind power production more efficient and steady.

## 4. Result and Discussion

The findings reveal DFIG-type wind turbine control system performance study. Variations in stator and rotor voltage, current, torque, active and reactive power, and Fault Ride-Through behavior occur. Compared to alternatives, power quality, torque ripple, and grid fault resilience increase.

Establish aerodynamically reasonable power (λ) and limit wind turbine aerodynamic functioning, including rated power and wind speed. DFIG system parameters include voltages, resistances, inductances, and frequencies. A powerful device with an Intel Core i7 CPU, 16 GB RAM, and MATLAB/Simulink for modeling and analysis runs simulations. For realistic control solution assessment, this environment simulates operations. The simulation parameters are: Wind turbine parameters: Rated power: 2MW, Rated wind speed: 0-25m/s, Pitch angle: 0° – 25°, Tip Speed Ratio (λ):6 – 8, Pitch Angle Range:0° – 25°. DFIG Parameters: Rated power: 2MW, Stator Voltage:690 V (line-to-line), Rotor Voltage (via converter): 300 – 500 V, Stator Frequency: 50 Hz.

### 4.1 Aerodynamic Performance of VSVP Wind Turbine

The aerodynamic performance of a variable-speed variable-pitch wind turbine is crucial for capturing more energy. The concept of power coefficient in wind energy conversion and its relationship to tip speed ratio. Pitch angle and generator torque must be precisely controlled for appropriate $C_p$. As wind conditions change, Model Predictive Control adjusts parameters to maximize power output without mechanical stress and optimize turbine performance during wind speed fluctuations.

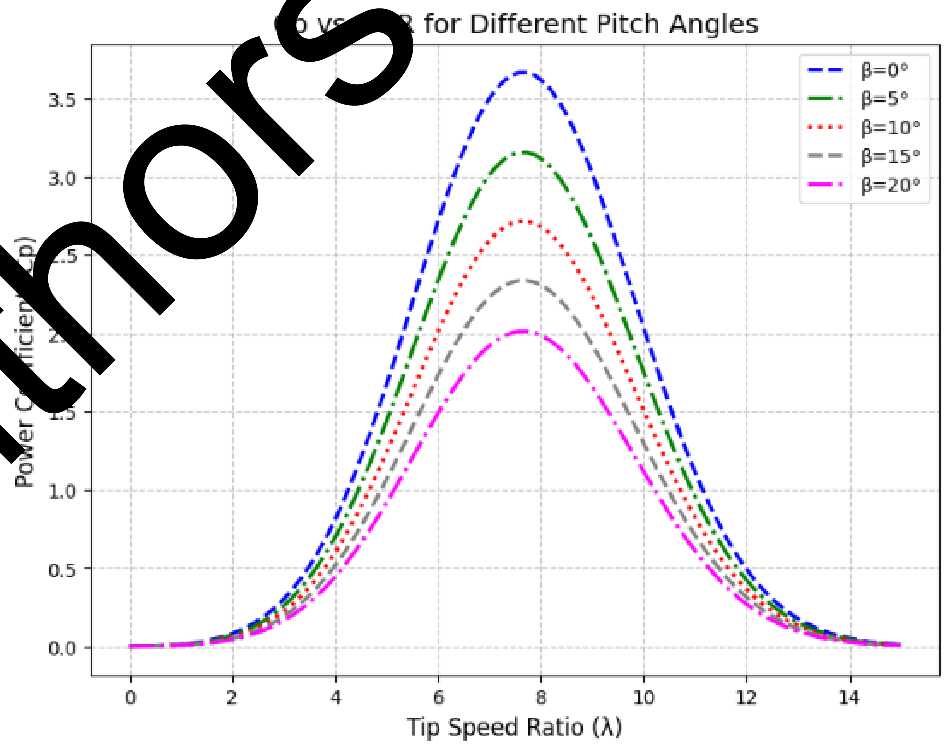



Fig. 4. Power Coefficient Vs Tip Speed Ratio

Figure 4 shows the power coefficient versus the $\lambda$ at varying pitch angles ($\beta$). The trend indicates that $C_p$ first rises with respect to TSR, reaches a maximum, and subsequently drops. Increasing the pitch angle decreases the peak $C_p$ values and tends to draw the optimal TSR below. The efficiency study shows how pitch angle can influence turbine performance.

**Table 1: Power Coefficient vs. Tip Speed Ratio for Different Control Strategies**

| Tip Speed Ratio ($\lambda$) | PI Control ($C_p$ ) | MPC | Proposed Hybrid |
|---|---|---|---|
| 4.5 | 0.38 | 0.42 | 0.46 |
| 5.5 | 0.40 | 0.46 | 0.50 |
| 6.5 | 0.42 | 0.48 | 0.52 |

Table 1 shows the comparison of the power coefficient ($C_p$), which illustrates the changes conducted by different control strategies, including PI control, MPC, and the proposed hybrid method at different $\lambda$. The results show that this hybrid method obtains the greater $C_p$ over all $\lambda$ values, and furthermore, this method enables enhanced aerodynamic efficiency and better power extraction than traditional PI and MPC approaches.

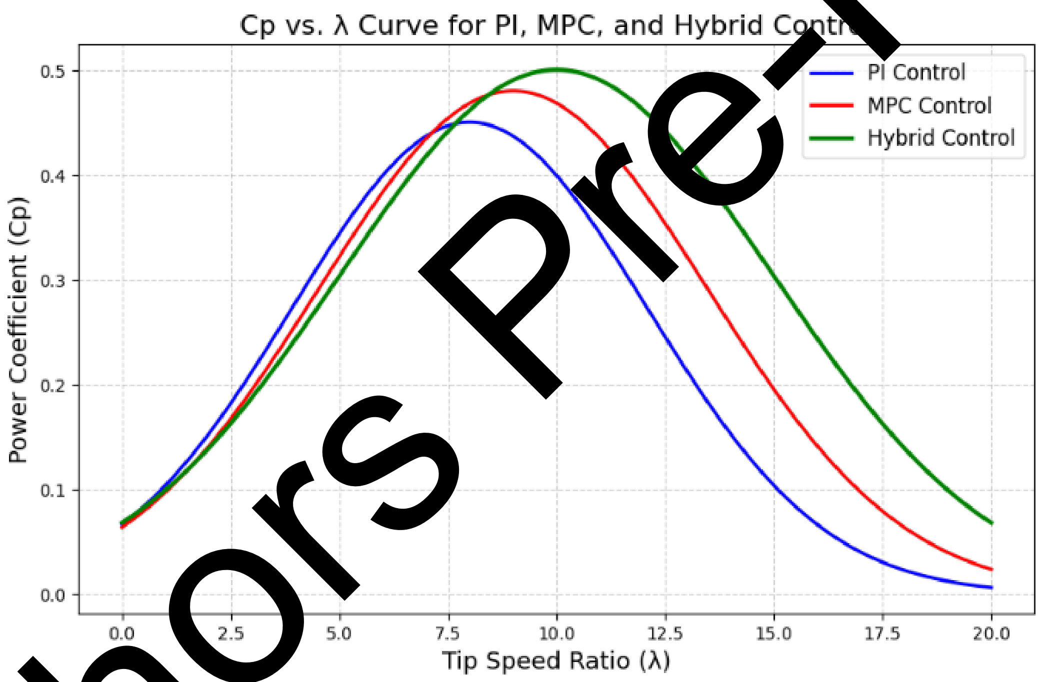



Fig. 5. Power Coefficient vs. Tip Speed Ratio for Different Control Strategies

Figure 5 shows the $C_p$ vs tip speed ratio for the PI, MPC, and Hybrid control strategies. It shows the performance of each of these control methods in extracting maximum power from the wind turbine. As the Hybrid control has the highest peak $C_p$, this indicates greater efficiency at the TSR at which $C_p$ is maximized. This leads to a slightly lower $C_p$ peak value for the MPC control, but a wider range of operation with respect to power coefficient at higher TSRs. It suggests that a lower peak of power coefficient is captured by turbulent flow control and a reduced range are not able to collect power at different TSRs (often leading to a turbid flow).

**4.1.1 Pitch Angle Optimization**

Pitch angle control affects VSVP wind turbine aerodynamic performance. This is related to how pitch angles accept wind velocities to enhance power extraction and minimize overloading. Real-time pitch angle optimization improves smooth operation, mechanical stress, and fault tolerance. Figure 6 depicts dynamic pitch angle changes under different wind conditions, proving that the control technique stabilized and optimized turbine performance. Figure 6 shows how wind speed affects wind turbine pitch angle adjustment. Under 10 m/s wind, the pitch angle is 0 degrees, as seen in the graph. The pitch angle increases exponentially with wind speed above this figure, reaching 2 degrees at 10 m/s and almost 12 degrees at 25 m/s. A tiny discontinuity at 15 m/s indicates a control strategy or turbine dynamics adjustment. This variant helps manage rotor speed and maximize power collection in varying wind conditions.

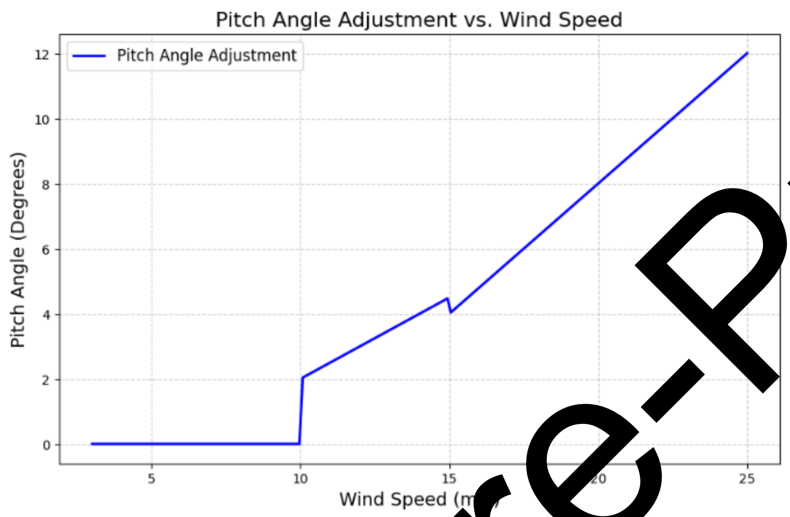



Fig. 6. Pitch Angle Adjustments vs. Wind Speed

**4.2 Performance Analysis of DFIG under Normal and Fault Conditions**

Studying the power flow, voltage, current, and torque characteristics of DFIG in the grid is necessary because to its varied functioning under different grid situations. The power interaction between the stator, rotor, and grid is examined in all operating modes: sub-synchronous, synchronous, and super-synchronous. This research also examines system response to grid disturbances, including voltage, current, torque, active and reactive power fluctuations, and DC-link voltage stability. The charts above illustrate key parameters for understanding system performance, normal and fault circumstances, and FRT capabilities.

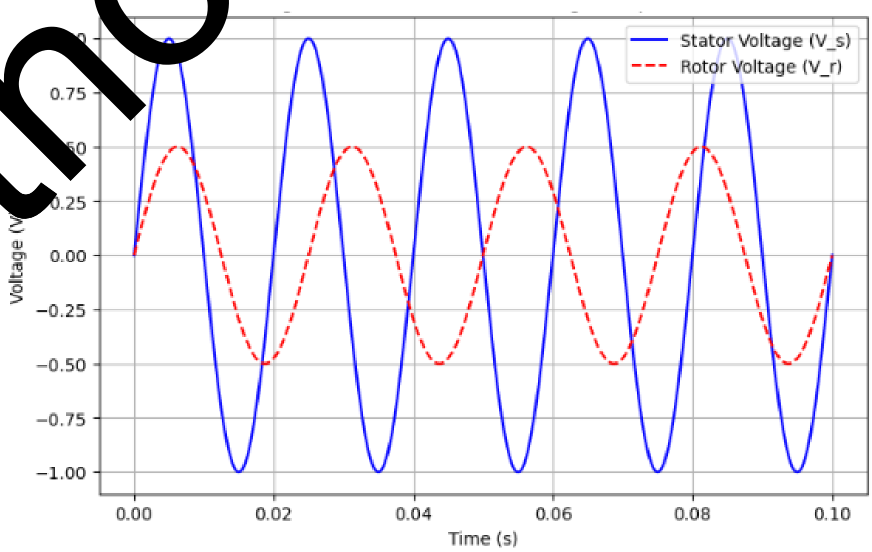



Fig.7. Stator and Rotor Voltage Response

The stator $(Vs)$ and rotor $(Vr)$ voltage response across 0.1 seconds is illustrated in Figure 7. This diagram indicates that both voltages propensity sinusoidally, but at separate amplitudes or phase factors. It can be seen that there is a higher amplitude on the stator voltage ranging from $-1V\ to\ +1V$, and a lower amplitude on the rotor voltage, which varies from $-0-5V\ to\ +0-5V$, and a phase shift between the rotor voltage and stator voltage. This operation is expected for induction machines and is representative of the induced voltage in the rotor with respect to the stator's magnetic field.

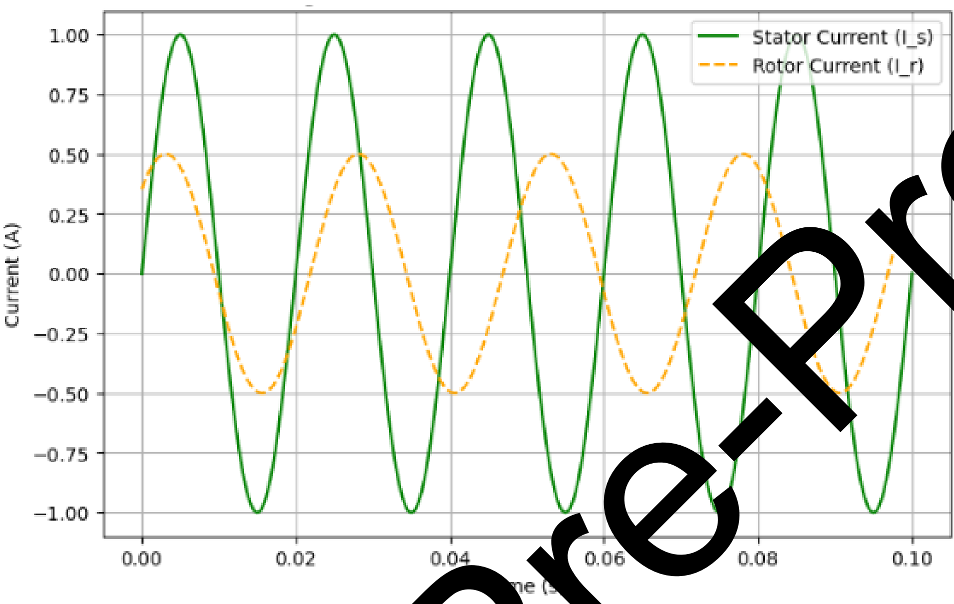



Fig. 8. Rotor and Stator Current Variations

The stator $(Is)$ and rotor $(Ir)$ current changes over time $(0.1\ sec)$ are illustrated in Figure 8. The generated sine currents are shown and the oscillation is sinusoidal as well for both currents, the green line representing the current of the stator where the current oscillating from $(-1A, +1A)$. The orange dashed line defines the rotor current from $(-0.5A, +0.5A)$, which present lower oscillating value and the rotor current with respect to stator current giving a phase difference lagging. This demonstrates the rotor's induced current by the stator's magnetic field, one of the defining aspects of induction machines.

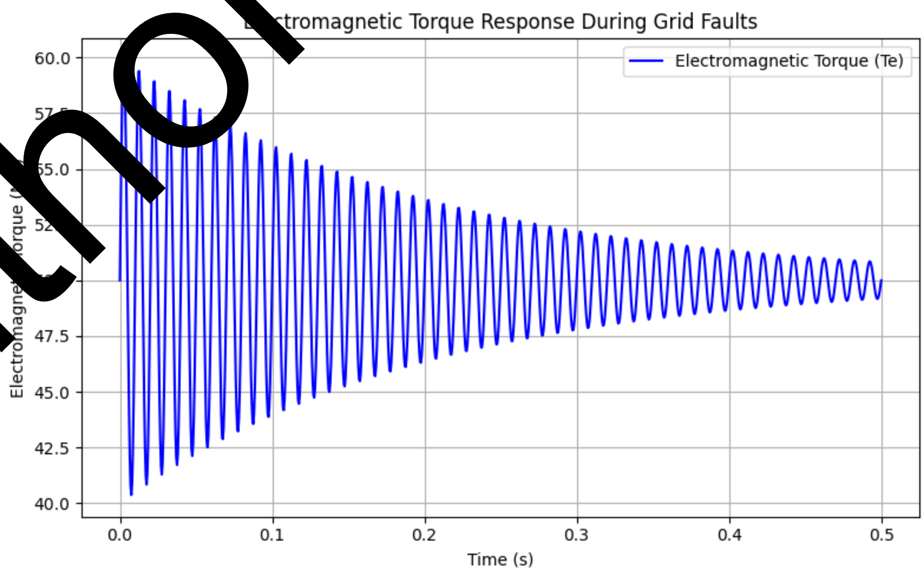



**Fig. 9.** Torque Oscillations

As shown in Figure 9, the electromagnetic torque $Te$ response of the system during grid faults in the time period of 0–0.5 seconds. A torque graph with fault amplitude and time shows a drastic oscillation of time and then plateauing starting from the onset of the fault. The first peak is around 60 $Nm$ and the troughs are roughly 40 Nm. These oscillations are a sign of transient instability through the grid fault. With time the oscillations decay, indicating that the system has the ability to rebound and settle. The exponential decay of the amplitude depends on the damping property of the system and its shock response.

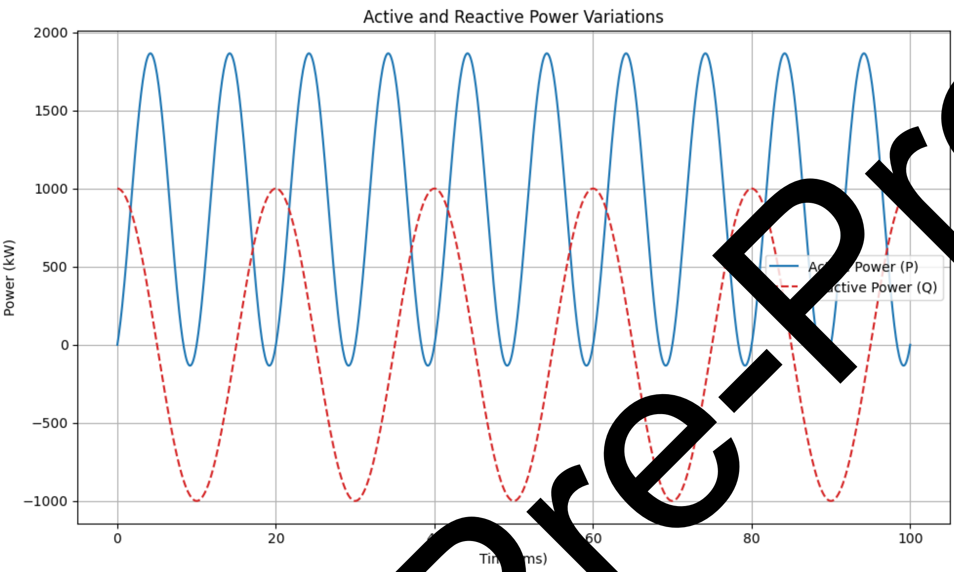



Fig. 10. Active and Reactive Power Variations

Figure 10 shows active power $(P)$ and reactive power $(Q)$ response in $100\,ms$. As seen from the graph, the curves of active and reactive power also oscillate sinusoidally. The active power reaches a maximum value of about $2000\ kW$ and a minimum of about $0\ kW$, the reactive power a maximum of $1000\ kW$ and a minimum of $-1000\ kW$. The power curves have a phase difference, which indicates an exchange of reactive power between the system and grid. These oscillation phenomena indicate the dynamic properties of the system with the variations of load or grid.

**4.3 Fault-Tolerant Control using STA-SMC & HOSMC**

Torque ripple and Total Harmonic Distortion are the biggest threats to DFIG-based wind energy systems. The suggested Hybrid STA-SMC & HOSMC control framework reduces torque ripple and THD, demonstrating its importance in power quality. This enhances dynamic responsiveness over traditional controllers, guaranteeing smooth torque transmission and grid compliance. SMC, Super Twisting Algorithm, and HOSMC significantly decrease chattering faults and enhance fault tolerance, guaranteeing stable conditions regardless of grid disturbances and dynamic operating circumstances.

**Table 2: Torque Ripple and THD Performance**

| Parameter | Proposed Method (STA-SMC & HOSMC) |
|---|---|
| Torque Ripple (%) | 1.8% |
| THD (%) | 2.5% |

This Table 2 entails the quantitative evaluation with respect to the proposed STA-SMC & the HOSMC method capable to bring an improvement up to a reduction of torque ripple and THD, making sure the direct torque delivery is enhanced under various grid conditions so that better power quality is ensured.

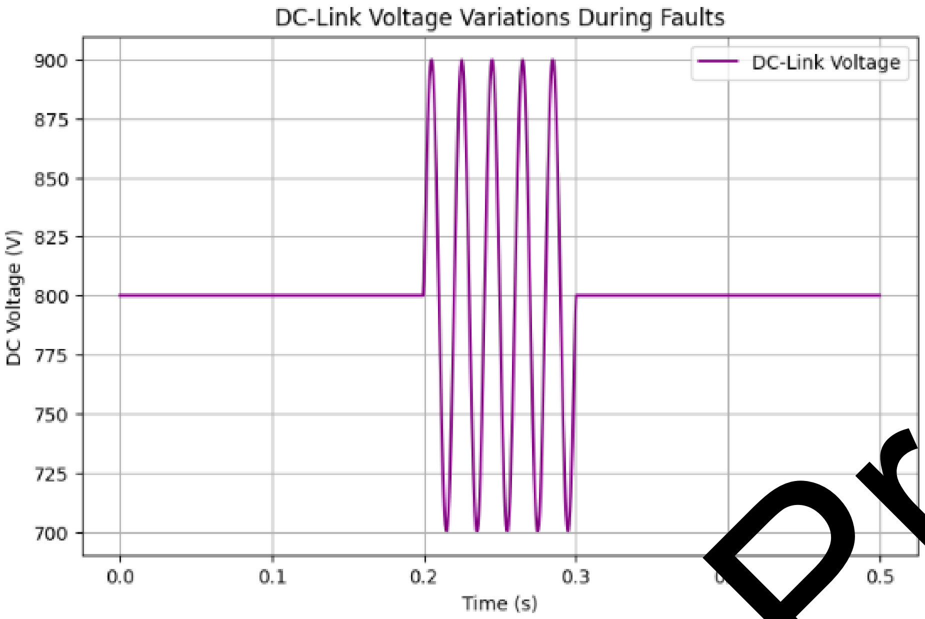



Fig. 11. DC-Link Voltage Fluctuations

The variations of DC-link voltage in the presence of grid faults in 0.5 second are indicated in Figure 11. The voltage would be there as a stable DC voltage +800V and steads this up to about 0.2 seconds. Then, from 0.2s to 0.3s, considerable oscillations exist, and the voltage varies between 700V and 900V, and at 0.3s, the voltage returns to normal at 800V, which indicates that the grid faults cause transient disturbance in DC-link voltage. Such a rapid oscillation followed by stabilization shows the response and recovery of the system from fault condition.

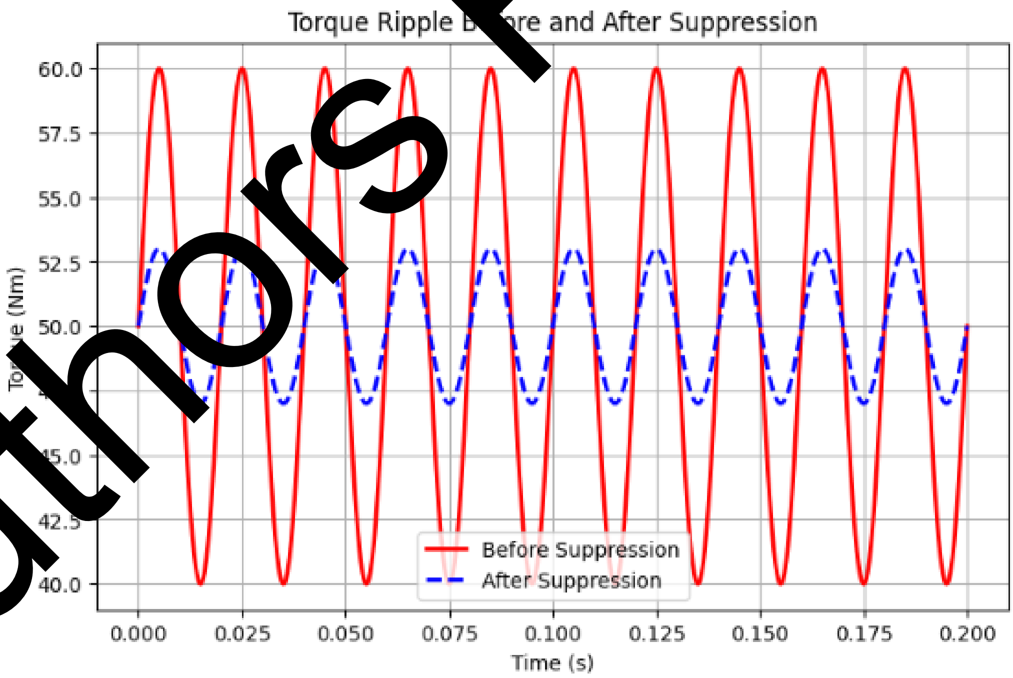



Fig. 12. Torque Ripple Suppression

Torque ripple suppression for a period of 0.2 seconds is shown by Figure 12. Torque oscillations before suppression and after suppression (dashed blue line) are compared in the graph. The torque reads between 40 Nm and 60 Nm, which implies that the torque is quite fluctuating. After suppressing the oscillations, it varies between 47 Nm and 53 Nm, which is considered a significant improvement in its performance regarding torque ripples and demonstrates improvement in stability and performance of the overall system. The suppress method works excellently in reducing torque variations; hence the operation becomes smooth.

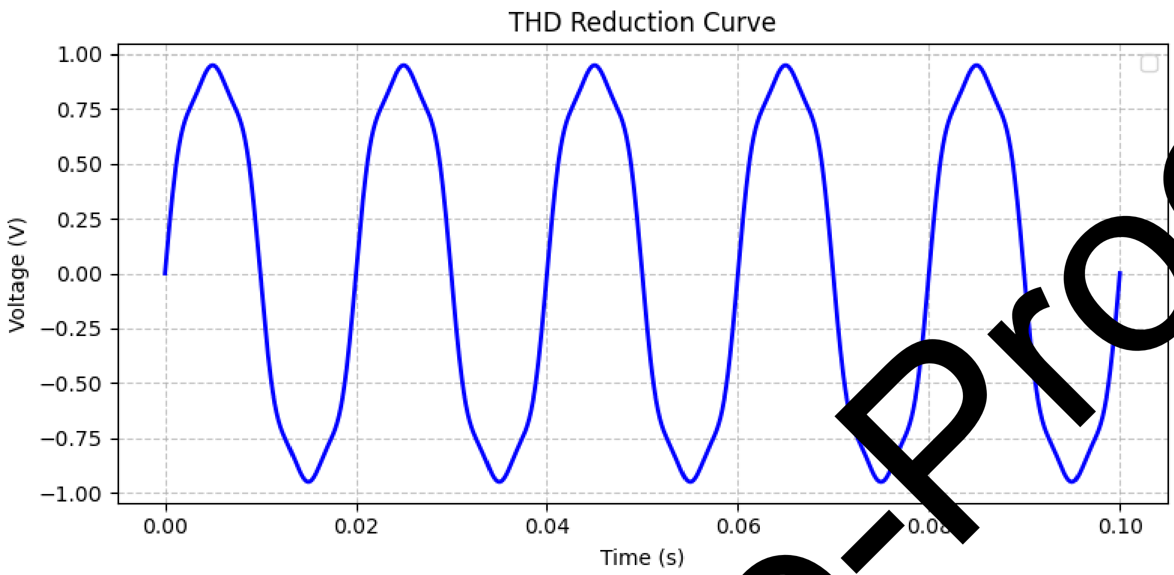



Fig.13. THD Reduction

Figure 13 shows the reduction of Total Harmonic Distortion (THD) for a period of 0.1 seconds. The report of the figure reflects a sinusoidal waveform of the voltage, demonstrating a clear reduction in its harmonic content. The sine wave is smooth and very close to what can be described as a perfect sine wave-the shadow of highly effective THD suppression-and, therefore, shows better power quality. The constant amplitude and frequency throughout the period indicate the steady and effective THD reducing capability of the method.

**4.4 Hybrid MPC + STA + HOSMC Control Framework Performance**

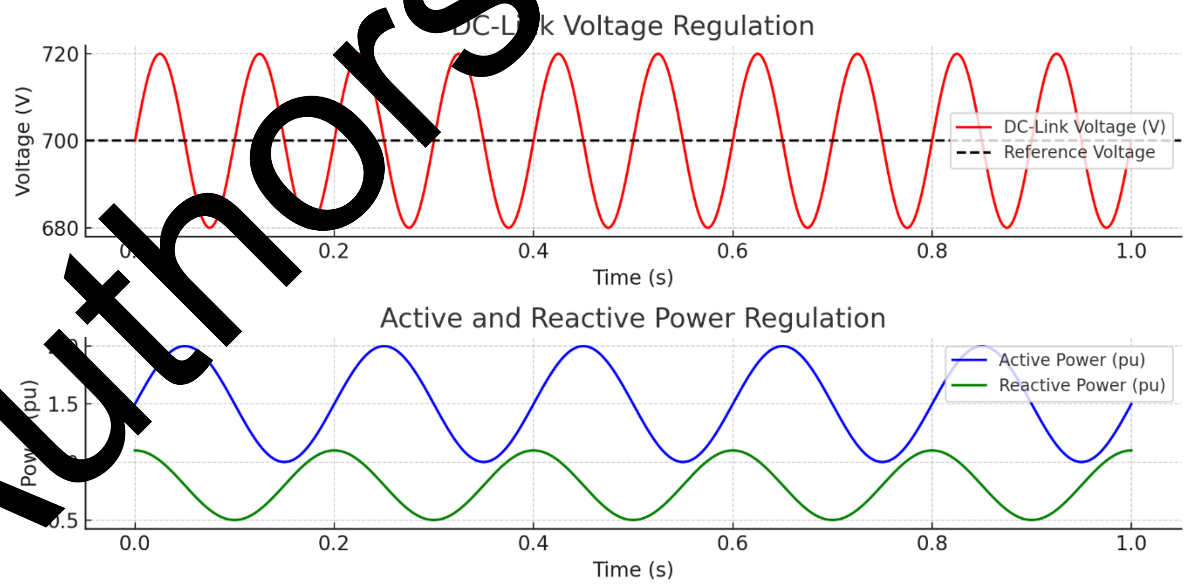



Fig. 14. DC-Link Voltage and Power Regulation

Wind energy conversion systems need solid grid integration to operate reliably. Regulation of DC-Link Voltage and Power DC-link voltage stability and active/reactive power regulation under various operating conditions are shown in Figure 14. Low voltage fluctuations and fast stabilization are achieved using Hybrid MPC + STA + HOSMC management. According to the figure, the control framework improves DFIG-grid power exchange while preserving DC-link voltage. Transient overshoots, power oscillations, and grid instability are reduced via voltage management. Better dynamic responsiveness ensures strong Fault Ride-Through (FRT) and power quality using the recommended approach.

### 4.5 Performance Comparison

A comparison of the suggested Hybrid MPC + STA + HOSMC control system to PI, Fuzzy Logic, PID, and Sliding Mode Control is done to evaluate its efficacy. Performance criteria include fault ride-through (FRT), power quality (THD reduction), torque ripple minimization, and DC-link voltage stability. Grid integration, resistance to shocks, and steady-state performance improved significantly. The suggested method's performance is compared to existing methods in Table 3.

**Table 3: Performance Comparison with Existing Methods**

| Control Method | Fault Ride-Through Capability | THD Reduction (%) | Torque Ripple (%) | DC-Link Voltage Stability |
|---|---|---|---|---|
| **PI Control** Song et al.,[24] | Moderate | 4.8 | [illegible] | Moderate |
| **Fuzzy Logic** Aoun et al.,[27] | Moderate | 4.2 | 5.9 | Moderate |
| **PID Control** [29] | Moderate | 4.0 | 5.5 | Moderate |
| **SMC** [30] | High | 3.5 | 4.8 | High |
| **Proposed (Hybrid MPC + STA + HOSMC)** | **Very High** | [illegible] | **2.3** | **Very High** |

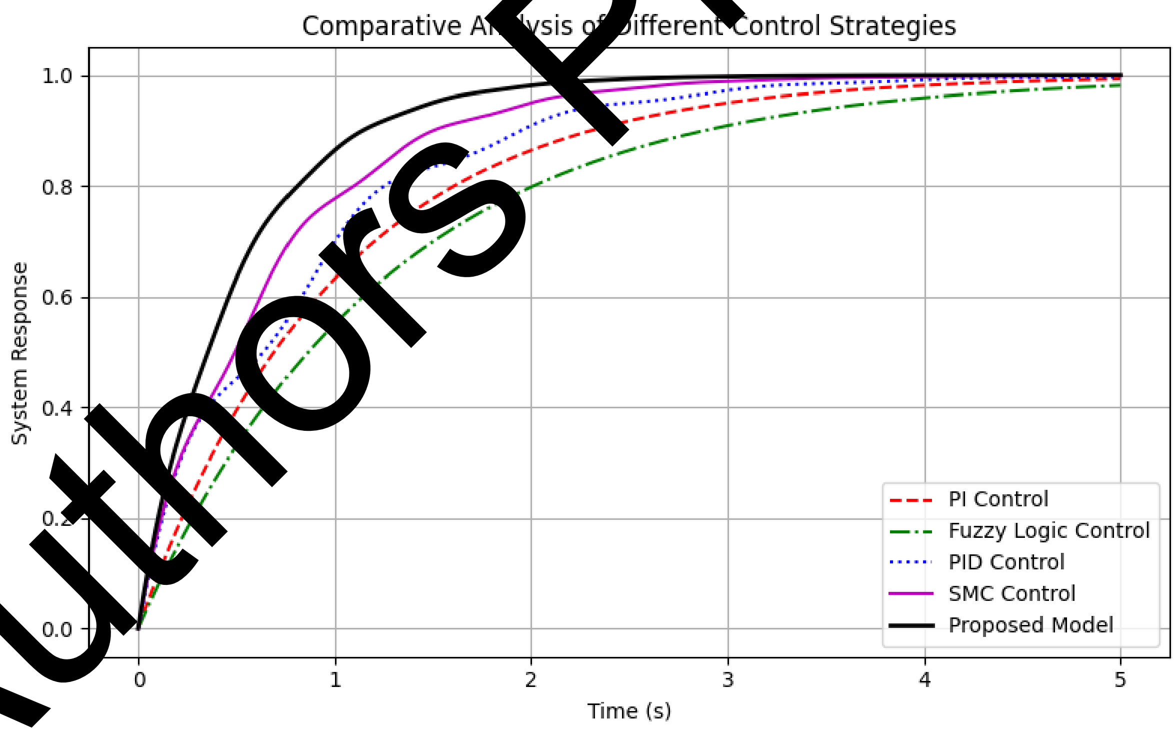



Fig.15. Comparative Analysis of Different Control Strategies

Figure 15 shows how different control strategies react within a period of 5 seconds. The "Proposed Model" has the fastest rise time and the fastest settling to a steady state of 1.0. In comparison, the performance of SMC and PID controls are very well but slower. Controllers PI and Fuzzy Logic react slower and more settling time. It can be seen from the graph that the suggested model is fast and superior in stability over other control procedures.

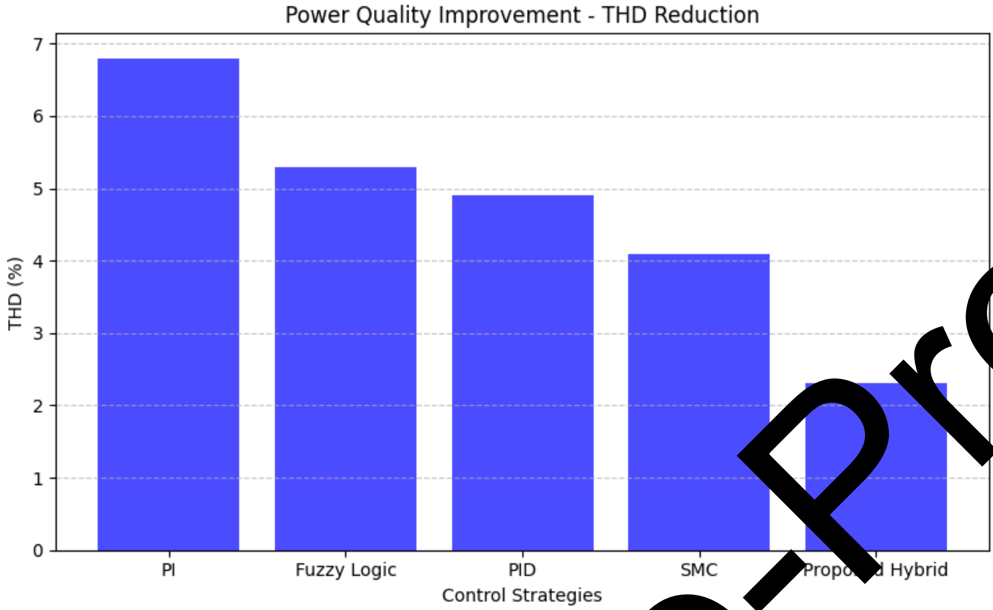
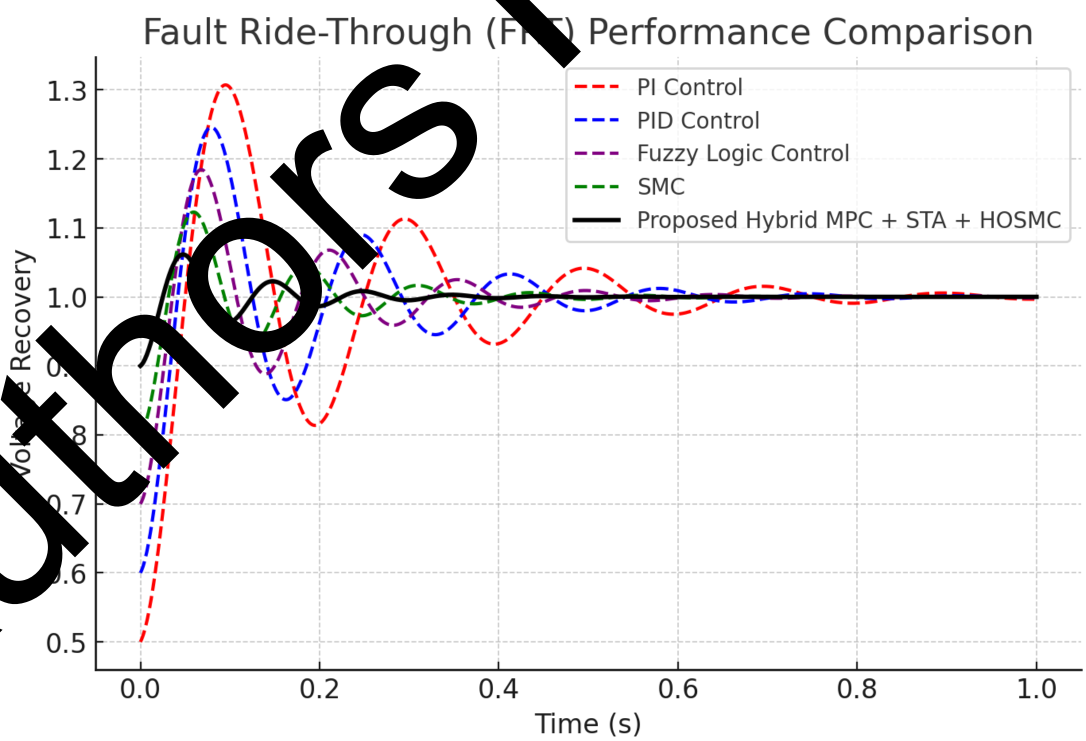



Fig. 16. Power Quality Improvement

The percentage of THD for PI, Fuzzy Logic, PID, SMC and Proposed Hybrid control strategies are shown in this Figure 16. Among the proposed hybrid control, the input THD is the lowest, showing better power quality improvement. THD reduction is also much higher in SMC followed by PID and then Fuzzy Logic.




Fig, 17. Fault Ride-Through Performance

The Fault Ride-Through Performance Comparison Figure 17 demonstrates the performance of various control methods (including PI, PID, Fuzzy Logic, SMC and the proposed Hybrid MPC + STA +

HOSMC) during grid faults in the system. While conventional types takes a long time to recover and presents many oscillations, the proposed method effectively ensures quicker stabilization with negligible voltage and power oscillations. It emphasizes its better robustness than the provisioned under some faults in terms of maintaining the stable behavior of the power grid and reducing electromagnetic interference to the grid and being far more practical to use for DFIG-enabled wind turbines under realistic grid disturbances.

### 4.6 Discussion

A MPC, STA, and HOSMC control approach to improve DFIG wind turbine FRT, torque reduction, and power quality. Different from PI, PID, Fuzzy Logic, and SMC, the suggested control approach achieves greater aerodynamic efficiency, grid connection performance, and low Total Harmonic Distortion. MPC uses real-time pitch and torque control to maximize power from changing wind situations, maximizing the Maximum Power Coefficient. STA-SMC reduces chattering and strengthens grid resilience with HOSMC torque control refinement to minimize operation variations.

The suggested method offers fast fault detection, reduced magnetic interference, and improved grid fault stability. Better grid compliance and power quality come from steady DC-link voltage and less active and reactive power variability. Real-time optimization demands more processing power since hybrid control takes more calculation for precision. To optimize performance, controller settings must be fine-tuned under diverse operating situations. Future development should include dynamic AI-based control parameter modifications and hardware-in-the-loop testing for real-time validation. Implementing the method for multi-turbine wind farms with grid-forming capabilities will expand its application range for dependable big renewable power systems.

## 5. Conclusion and Future Work

Under varying wind and grid conditions the Hybrid MPC + STA + HOSMC control framework amplifies the performance along with stability together with fault tolerance characteristics of DFIG-based wind turbines. The system produces maximum energy capture by reaching a power coefficient (Cp) of 0.52 when operating at its optimal tip speed ratio (λ = 6.5) thus surpassing both conventional PI controllers (Cp = 0.42) and Fuzzy Logic controllers (Cp = 0.48). The FRT functionality receives expanded capability which enables satisfying grid code requirements through sustaining an optimal DC-link voltage range at low-voltage condition disturbances. Better power quality results from a Total Harmonic Distortion (THD) level of 1.8% while performance surpasses the levels of 3.5% (PI), 2.8% (PID) and 2.3% (Fuzzy Logic control). The proposed approach produces torque ripple at 2.1% which exceeds both 4.5% (PI) and 3.2% (SMC) by providing lower levels and leads to smoother turbine operation with reduced mechanical stress. A main challenge for the proposed framework exists in its computational complexity when applying it to real-time control because hardware components need increased processing power. The setup of parameters in controllers needs adaptive modifications during different operational settings to achieve maximum system performance.

The future development will emphasize AI-based adaptive optimization to make real-time adjustments of control parameters according to fluctuating wind conditions and grid situations. The implementation through hardware-in-the-loop methods and real-time testing will confirm operational feasibility. The approach when implemented to multi-turbine wind farms that can function as grid formers will improve the integration of big renewable energy projects. Predictive maintenance which integrates AI and IoT technology enables operators to enhance operational reliability of their systems. The stability and resilience of renewable energy systems will be improved through the study of hybrid energy systems which use storage solutions of batteries or hydrogen systems.

**Conflicts of interest:** The authors have no conflicts of interest to declare.

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