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Model Predictive Control of a Grid-Connected Wind Energy System Using a Three-Level NPC Inverter

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Abstract
This Paper presents a model predictive control (MPC) strategy for a grid-connected wind energy conversion system using a three-level inverter. The proposed structure employs a single multilevel DC/AC three-phase inverter, which reduces the number of power converters compared with conventional back-to-back systems that require both AC/DC and DC/AC stages. As a result, the system design becomes simpler and more cost-effective. The inverter is modeled in the synchronous reference frame, where a discrete-time predictive model is used to estimate the future values of the grid current components and DC-link capacitor voltages. The controller evaluates all possible inverter switching states through a cost function and selects the optimal state that minimizes the control error during each sampling period. The effectiveness of the proposed method is validated through MATLAB/Simulink simulations and processor-in-the-loop (PIL) implementation. The results demonstrate improved wind power extraction and enhanced power quality delivered to the grid. In addition, the proposed control approach achieves lower total harmonic distortion (THD) compared with conventional control techniques, confirming its suitability for grid-connected wind energy systems.

Index Terms -

Wind Energy Conversion System (WECS), Permanent Magnet Synchronous Generator (PMSG), Model Predictive Control (MPC), Neutral Point Clamped (NPC) Inverter, Maximum Power Point Tracking (MPPT), Grid-Connected System, Multilevel Inverter, Power Quality, Total Harmonic Distortion (THD), Renewable Energy.

1. Introduction

The global transition toward renewable energy sources has accelerated the deployment of wind energy systems in modern power networks. Wind energy offers clean and sustainable power generation; however, its inherent variability introduces challenges related to power quality, grid stability, and efficient energy extraction. Variable-speed wind energy conversion systems (WECS) have emerged as the preferred solution due to their superior aerodynamic efficiency and reduced mechanical stress compared to fixed-speed systems.

Permanent magnet synchronous generators (PMSGs) are widely adopted in variable-speed wind turbines because of their high efficiency, high power density, and elimination of rotor excitation losses. Nevertheless, PMSG-based systems require fully rated power electronic converters to interface with the grid, making converter topology and control strategy critical design aspects.

Conventional grid-connected wind energy systems typically employ back-to-back converter structures, which increase system cost, losses, and control complexity. To address these limitations, this paper proposes a simplified conversion structure using a single three-level neutral-point-clamped (NPC) inverter combined with model predictive control (MPC). The NPC inverter improves output voltage quality and reduces harmonic distortion, while MPC enables fast dynamic response and direct control of inverter switching states without the need for modulation stages.

The main contribution of this work is the development of an MPC-based control strategy for a grid-connected wind energy system using a three-level NPC inverter that ensures high power quality, unity power factor operation, and effective DC-link voltage balancing with reduced system complexity.

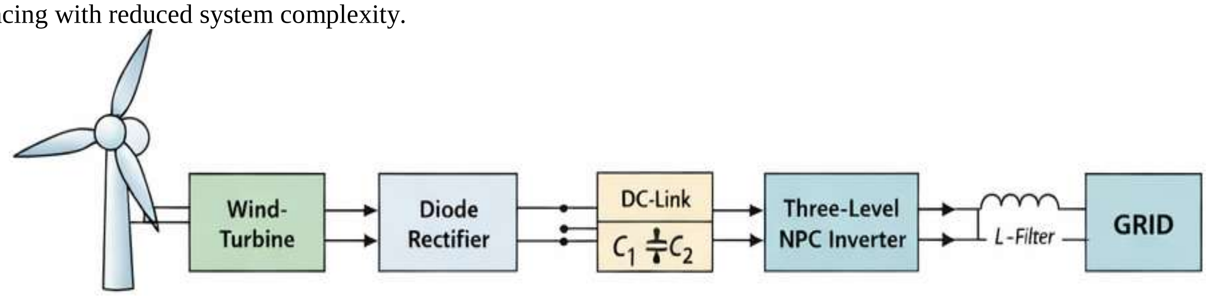

Fig:1.proposed grid-connected wind energy conversion system.

The figure1 illustrates the overall configuration of the proposed grid-connected wind energy conversion system based on a three-level neutral-point-clamped (NPC) inverter. The system is designed to reduce conversion stages while maintaining high power quality and reliable grid integration.The **wind turbine** captures kinetic energy from the wind and converts it into mechanical power.

This mechanical power drives a **permanent magnet synchronous generator (PMSG)**, which produces three-phase electrical power with variable voltage and frequency due to fluctuating wind speed.
The generator output is fed to an **uncontrolled diode rectifier**, which converts the variable-frequency AC power into DC power. The use of a diode rectifier simplifies the system structure and reduces cost and control complexity compared to active rectifier-based solutions.The rectified DC voltage is smoothed by a **split DC-link capacitor bank (C_1 and C_2)**. These capacitors provide energy buffering, reduce voltage ripple, and create a neutral point required for three-level NPC inverter operation. Maintaining voltage balance across these capacitors is a key control objective.
A **three-level NPC inverter** converts the DC power into three-phase AC power suitable for grid connection. Compared to a conventional two-level inverter, the NPC inverter generates lower voltage steps, resulting in reduced harmonic distortion, lower switching stress, and improved power quality.An **L-filter** is placed between the inverter and the grid to attenuate high-frequency switching harmonics and ensure compliance with grid power quality standards.
Finally, the conditioned AC power is injected into the **utility grid**, where the control system ensures unity power factor operation and high-quality current injection.This configuration eliminates the conventional back-to-back converter arrangement and relies on model predictive control applied at the grid-side inverter, leading to a compact, efficient, and robust wind energy conversion system suitable for medium- and high-power applications.

II. Related Work

Extensive research has been conducted on wind energy conversion systems focusing on generator technologies, converter topologies, and control strategies. Variable-speed wind turbines have been shown to significantly enhance energy capture by maintaining optimal tip-speed ratios under varying wind conditions. Among generator options, PMSGs have gained prominence due to their reliability and high efficiency.
Power electronic interfaces play a vital role in grid integration. Multilevel inverters, particularly the neutral-point-clamped topology, have demonstrated superior performance in medium- and high-power applications due to reduced voltage stress and lower harmonic distortion. Traditional proportional–integral control methods are widely used but often exhibit limited performance under nonlinear and rapidly changing operating conditions.
Model predictive control has emerged as an effective alternative, offering fast dynamic response and explicit handling of system constraints. Recent studies have demonstrated the effectiveness of MPC in controlling multilevel inverters; however, most reported works rely on back-to-back converter configurations. Limited attention has been given to MPC-based control of simplified single-inverter wind energy systems with integrated DC-link voltage balancing, which motivates the present work.

III. System Configuration

The proposed grid-connected wind energy system consists of a variable-speed wind turbine driving a permanent magnet synchronous generator. The generator output is rectified using an uncontrolled diode rectifier, producing a DC voltage that is smoothed by a split DC-link capacitor bank. A three-level NPC inverter converts the DC power into AC power and injects it into the utility grid through a grid-side filter.
This configuration eliminates the conventional generator-side converter, thereby reducing system complexity and cost. Control actions are primarily implemented at the grid-side NPC inverter, which regulates power flow, current quality, and DC-link voltage balance.

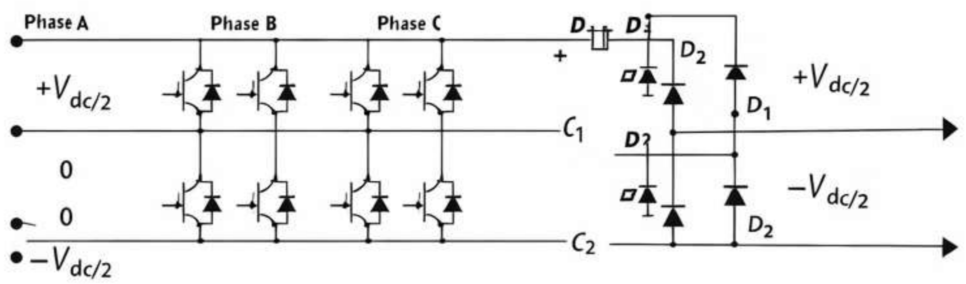

Figure 2. Three-level neutral-point-clamped (NPC) inverter topology.

The figure shows the circuit configuration of a three-phase, three-level neutral-point-clamped (NPC) inverter used as the grid-side power converter in the proposed wind energy conversion system. Each phase leg of the NPC inverter consists of four active switching devices and two clamping diodes, allowing the generation of three distinct voltage levels at the inverter output.
The DC-link is formed by two series-connected capacitors, C_1 and C_2, which divide the total DC bus voltage into two equal halves. This arrangement creates a neutral point at the midpoint of the capacitors, enabling the inverter to produce output voltage levels of **+Vdc/2**, **0**, and **−Vdc/2** with respect to the neutral point.
For each phase:

- The **+Vdc/2** voltage level is obtained by turning ON the two upper switches of the phase leg.
- The **0** voltage level is achieved by turning ON the inner switches, with the output clamped to the neutral point through the clamping diodes.
- The **−Vdc/2** voltage level is generated by turning ON the two lower switches.

The presence of clamping diodes limits the voltage stress across each switching device to half of the total DC bus voltage. As a result, lower voltage-rated semiconductor devices can be used, leading to reduced switching losses and improved efficiency. Additionally, the smaller voltage steps during switching transitions reduce harmonic distortion and electromagnetic interference compared to conventional two-level inverters.
However, proper operation of the NPC inverter requires balanced voltages across the DC-link capacitors. Any imbalance between C_1 and C_2 can cause unequal voltage stress on the switches and degrade output voltage quality. In this work, DC-link voltage balancing is achieved through the proposed model predictive control strategy by appropriately selecting inverter switching states.

Overall, the three-level NPC inverter provides improved power quality, reduced device stress, and high efficiency, making it well suited for medium- and high-power grid-connected wind energy applications.

IV. Three-Level NPC Inverter

The three-level neutral-point-clamped inverter generates three voltage levels per phase: +Vdc/2, 0, and −Vdc/2. This multilevel structure reduces voltage steps during switching transitions, resulting in lower harmonic distortion and reduced electromagnetic interference. The NPC inverter also lowers voltage stress on power semiconductor devices, making it suitable for medium- and high-power wind energy applications.

However, maintaining balanced voltages across the DC-link capacitors is critical for proper operation. Any imbalance can lead to uneven device stress and degraded inverter performance, necessitating an effective control strategy.

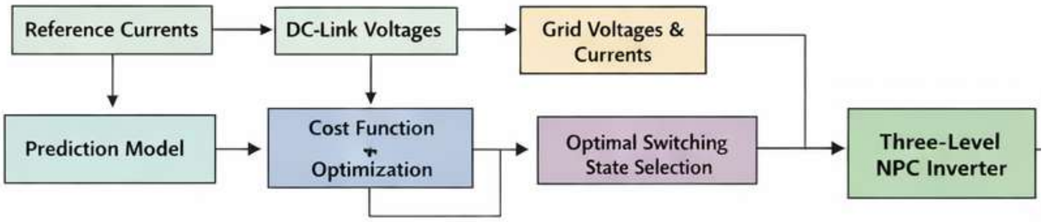

Figure.3. NPC Based architecture

The figure illustrates the overall architecture of the model predictive control (MPC) strategy applied to the three-level neutral-point-clamped (NPC) inverter in the proposed wind energy conversion system. The control scheme is designed to regulate grid currents, maintain DC-link voltage balance, and ensure unity power factor operation.

The control process begins with the generation of **reference currents**, which are derived based on the desired active power transfer from the wind turbine to the grid. These reference signals represent the ideal grid current waveforms required for power injection.

Measured **DC-link capacitor voltages** and **grid-side voltages and currents** are continuously monitored and fed into the controller. This real-time feedback provides the necessary system state information for accurate prediction and decision-making.

Using the measured inputs, the **prediction model** estimates the future behavior of grid currents and DC-link voltages for all possible switching states of the three-level NPC inverter. These predicted values are evaluated using a **cost function**, which quantifies the control objectives, such as minimizing current tracking error, reducing DC-link voltage imbalance, and suppressing reactive power.

The **cost function optimization** process identifies the switching state that yields the minimum cost, representing the optimal control action for the next sampling interval. This selected **optimal switching state** is then directly applied to the three-level NPC inverter without the need for a modulation stage.

By directly controlling inverter switching states, the MPC strategy achieves fast dynamic response, simplified control structure, and improved power quality. The architecture effectively integrates multiple control objectives into a single optimization framework, making it highly suitable for grid-connected wind energy applications.

V. Proposed Model Predictive Control Strategy

Finite control set model predictive control is employed to regulate grid currents and balance DC-link capacitor voltages. At each sampling instant, the controller measures grid currents, grid voltages, and DC-link capacitor voltages. Using a discrete-time model of the system, the controller predicts future current and voltage behavior for all admissible inverter switching states.

A cost function is formulated to minimize grid current tracking error, DC-link voltage imbalance, and reactive power injection. The switching state that minimizes the cost function is selected and applied directly to the inverter. This approach eliminates the need for pulse-width modulation and cascaded control loops, resulting in a fast and robust control structure.

Unity power factor operation is achieved by aligning the grid current with the grid voltage, ensuring that only active power generated by the wind turbine is injected into the grid.

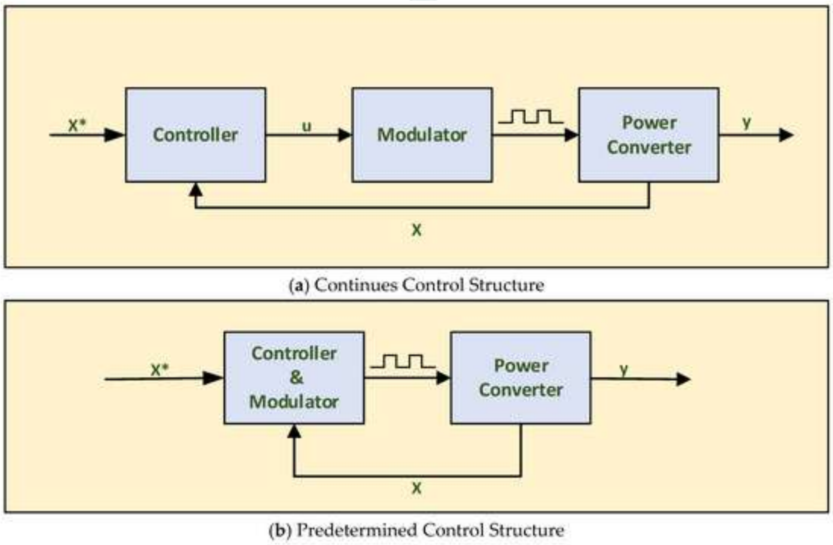

Figure 4. Model predictive control architecture for the three-level NPC inverter.

The figure compares two different control structures commonly used in power electronic systems: the **continuous control structure** and the **predetermined control structure**.

(a) Continuous Control Structure

In the continuous control structure, the reference signal x∗x^*x∗ is processed by a **continuous-time controller**, such as a proportional–integral (PI) or proportional–resonant (PR) controller. The controller generates a continuous control signal uuu, which represents the desired converter output behavior.

This continuous control signal is then passed through a **modulator** (typically pulse-width modulation), which converts the control signal into discrete switching pulses for the power converter. The power converter produces the output yyy, and the measured system state xxx is fed back to the controller to close the control loop.

Although this structure is widely used due to its simplicity and well-established design methods, it involves multiple stages and depends heavily on accurate tuning of controller gains and modulation parameters. Its performance can degrade under system nonlinearities and fast dynamic variations.

(b) Predetermined Control Structure

In the predetermined control structure, the controller and modulator are integrated into a single decision-making unit. Instead of generating a continuous control signal, the control algorithm directly determines the optimal switching state of the power converter. The controller uses the measured system state xxx and reference x∗x^*x∗ to select the appropriate switching action from a finite set of possible converter states. This switching decision is applied directly to the power converter, eliminating the need for a separate modulation stage.

This structure is particularly suitable for **model predictive control**, where future system behavior is predicted for each admissible switching state, and the optimal state is selected based on a cost function. The predetermined control structure offers faster dynamic response, simpler control architecture, and improved handling of system constraints.

Relevance to the Proposed Work

The proposed wind energy conversion system adopts the **predetermined control structure**, where model predictive control directly governs the switching of the three-level NPC inverter. This approach removes cascaded control loops and modulation blocks, leading to reduced computational delay, enhanced power quality, and improved robustness under variable wind and grid conditions.

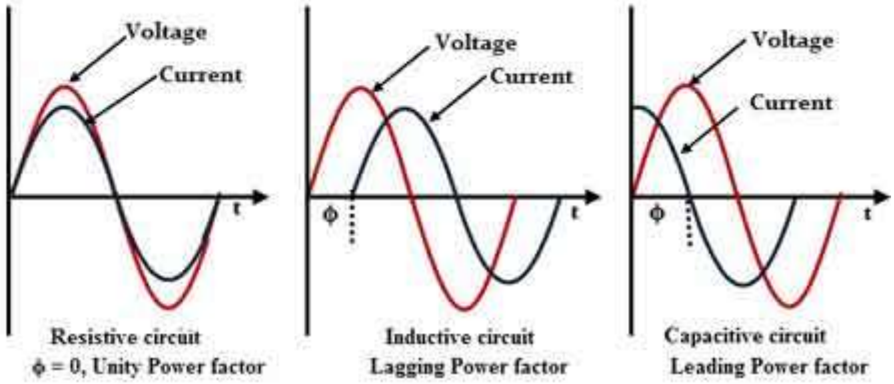

Figure 5. Grid voltage and grid current waveforms at unity power factor operation.

Figure 5 illustrates the phase relationship between grid voltage and grid current under different load conditions, highlighting the significance of unity power factor operation in grid-connected systems.

In a **purely resistive circuit**, the grid current is perfectly aligned with the grid voltage, resulting in a phase angle ϕ=0∘Under this condition, all the power drawn from the grid is active power, and the system operates at **unity power factor**. This is the desired operating mode for grid-connected renewable energy systems, as it ensures maximum real power transfer with no reactive power exchange.

In contrast, an **inductive circuit** causes the grid current to lag behind the voltage by a phase angle ϕ>0leading to a **lagging power factor**. This condition results in reactive power absorption from the grid, which can degrade grid voltage stability and increase transmission losses.

Similarly, in a **capacitive circuit**, the grid current leads the voltage by a phase angle ϕ<0∘ producing a **leading power factor**. Although reactive power is supplied to the grid in this case, uncontrolled leading power factor operation can also negatively impact grid performance.

In the proposed wind energy conversion system, the model predictive control strategy regulates the grid current to remain in phase with the grid voltage, enforcing ϕ≈0∘ This ensures **unity power factor operation**, minimizes reactive power exchange, and guarantees compliance with grid code requirements. As a result, the system injects high-quality active power into the grid while maintaining stable and efficient operation.

VI.Results

The grid-connected wind energy conversion system was simulated in MATLAB/Simulink to evaluate the performance of the PMSG wind turbine, MPPT controller, boost converter, and NPC inverter. The complete system integrates a Permanent Magnet Synchronous Generator (PMSG), a rectifier, a DC-DC boost converter controlled by a Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm, and a three-level Neutral Point Clamped (NPC) inverter connected to the grid. The overall system configuration used in the simulation is shown in the system model.

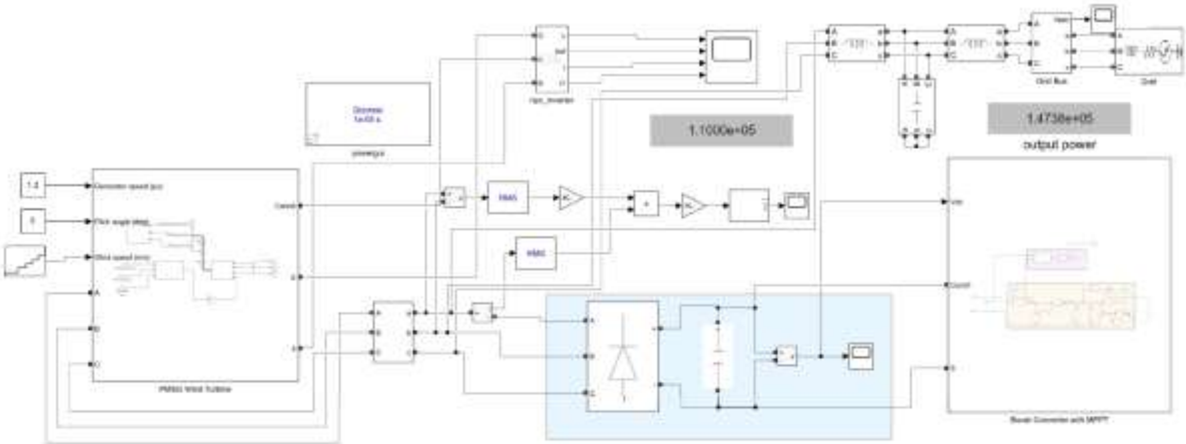

Fig:6 MPC strategy for a grid-connected wind energy system using a three-level inverter

The PMSG wind turbine converts mechanical wind energy into electrical energy. The simulation results show that the generator produces stable electromagnetic torque and rotor speed once steady-state operation is achieved. The stator current waveform follows a periodic pattern corresponding to generator rotation and electromagnetic interaction. These waveforms confirm that the turbine and generator operate effectively and respond properly to the wind input.

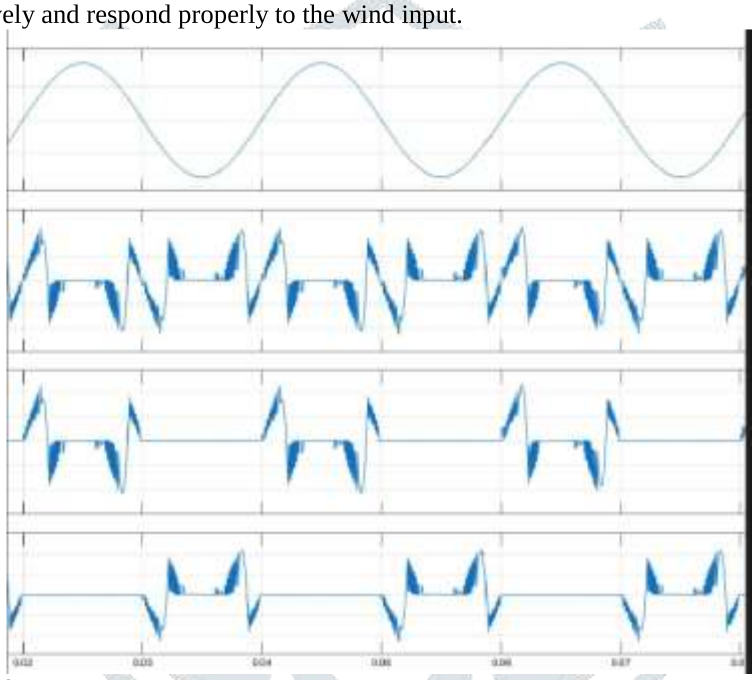

Fig:7 Scope for Waveforms for npc_inverter

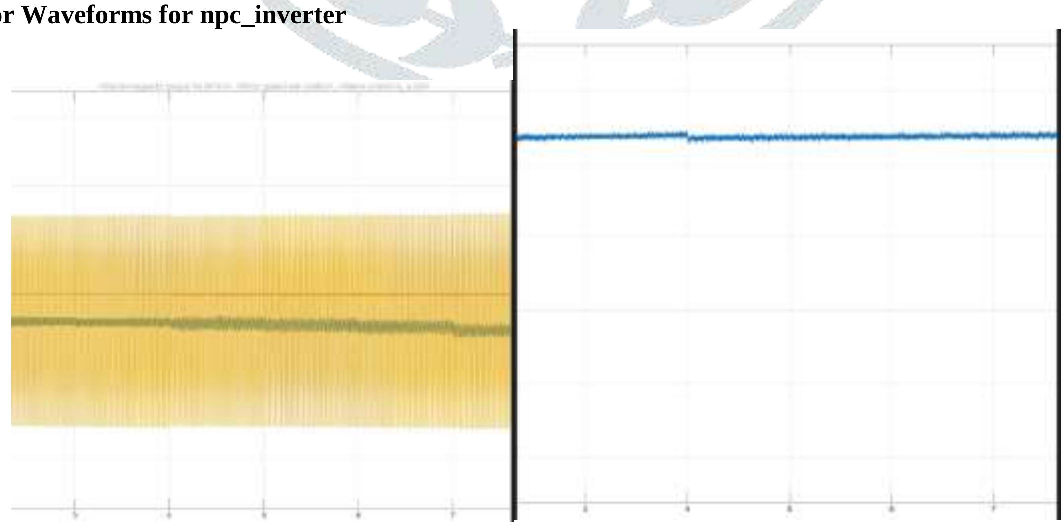

Fig:8 scope for PMSG_Wind_turbine and Universal Bridge Scope

The MPPT controller based on the P&O algorithm is implemented to ensure maximum power extraction from the wind turbine. The controller adjusts the duty cycle of the boost converter by observing variations in output power and voltage. The MPPT output waveform shows that the algorithm rapidly converges to the maximum power operating point and maintains it with minimal oscillation. This demonstrates that the MPPT controller efficiently tracks the optimal operating point under the given conditions. The boost converter increases the rectified DC voltage to a suitable level for the inverter stage. Simulation results indicate that the converter maintains a stable DC output while exhibiting small switching ripples caused by high-frequency PWM operation. The current waveform confirms continuous energy transfer from the generator to the DC link while maintaining steady operation of the converter.

The NPC inverter converts the regulated DC voltage into three-phase AC power suitable for grid integration. The inverter output waveform approximates a sinusoidal signal, demonstrating the effectiveness of the three-level switching strategy in reducing harmonic distortion compared with conventional two-level inverters. The multilevel structure improves output waveform quality and reduces switching losses. Finally, the grid-side results confirm that the generated AC power is successfully delivered to the grid. The voltage waveform remains stable with very small fluctuations after reaching steady state, indicating proper synchronization and stable operation of the inverter-grid interface. Overall, the simulation results verify that the proposed system effectively converts wind energy into electrical power while maintaining stable operation, efficient MPPT tracking, and improved power quality.

VII.Conclusion

This study presented the modeling and simulation of a grid-connected wind energy conversion system using a Permanent Magnet Synchronous Generator (PMSG), a DC-DC boost converter with Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT), and a three-level Neutral Point Clamped (NPC) inverter. The objective was to improve energy extraction from the wind turbine and ensure efficient power delivery to the grid. Simulation results demonstrate that the PMSG wind turbine effectively converts mechanical wind energy into electrical energy while maintaining stable rotor speed and electromagnetic torque characteristics. The implemented P&O MPPT algorithm successfully tracks the maximum power point and adjusts the duty cycle of the boost converter to extract maximum available power from the wind turbine under the given operating conditions. The boost converter increases and stabilizes the DC link voltage required for inverter operation.

The three-level NPC inverter converts the regulated DC voltage into a high-quality three-phase AC output suitable for grid connection. Compared with conventional two-level inverters, the NPC inverter improves waveform quality and reduces harmonic distortion due to its multilevel switching structure. The grid-side results confirm stable power delivery and proper synchronization with the grid. Overall, the simulation confirms that the proposed wind energy conversion system provides efficient power conversion, stable operation, and improved power quality. Therefore, the integration of PMSG, MPPT-controlled boost converter, and NPC inverter offers an effective solution for grid-connected renewable wind energy systems.

VIII.References

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