Modeling a Simplified Wind Power System with Wireless Data Transmission

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Abstract

This paper presents a low-fidelity model of a wind power system using a Simplified Generator block, designed for planning and pitch control studies. The model integrates renewable energy generation with an air interface-based wireless network to enable efficient data communication. QPSK, known for its high spectral efficiency, low latency, and flexible frequency bands, transmits key operational data such as power output, wind speed, and system diagnostics. The physical layer of the network, including free space path loss, limited bandwidth, RF receiver dynamics, and demodulation, is simulated using MATLAB and Simulink. The study explores the impact of wireless communication on transmitted signals, analyzing the effects of channel characteristics and system design on data integrity and performance. Results demonstrate the viability of using QPSK networks for real-time monitoring and control in wind power systems, offering insights into the efficient integration of wireless technology for renewable energy applications.

Introduction

Over the past two decades, wireless communication services have witnessed remarkable global growth. Transitioning from analog to modern digital cellular services, wireless technologies have significantly outpaced fixed-line telephony in terms of availability and subscriber numbers. In Pakistan, for instance, wireless communication has achieved penetration rates approximately four times higher than those of fixed-line systems.

Globally, the number of mobile subscribers has surged to nearly one billion users in less than 20 years. Research analysis highlights the impact of these factors on network throughput. Moreover, the adoption of efficient scheduling algorithms plays a crucial role in enhancing network efficiency.

The findings from this research demonstrate that inter-site distances significantly influence signal strength within the coverage area. The mobile industry increasingly demands higher data download speeds and reduced latency to support various applications, including VoIP, online gaming, and interactive data usage. Furthermore, optimizing spectrum utilization has become a critical priority. The growing demand for renewable energy sources has led to significant advancements in wind power systems. Wind energy, as a clean and sustainable alternative, plays a crucial role in reducing dependency on fossil fuels and minimizing environmental impacts. However, integrating wind power systems into the electrical grid poses several challenges, including effective monitoring, real-time control, and seamless data communication. Addressing these challenges requires the adoption of efficient modeling techniques and modern communication technologies.

This paper presents a low-fidelity model of a wind power system using a Simplified Generator block, focusing on planning and pitch control studies [1]. Low-fidelity models are essential for analyzing system behavior without the computational complexity of high-detail simulations, making them ideal for control design and operational planning. To enhance the system's capabilities, a Long-Term Evolution (QPSK) air interface-based wireless network is incorporated for efficient data transmission. QPSK technology, with its high spectral efficiency, low latency, and flexible frequency bands, is particularly well-suited for.

This architecture facilitates a flexible and efficient wireless networking air interface, achieving ultra-high spectral efficiencies and data transmission speeds ranging from 100 Mbps to 1 Gbps. The system is characterized by its high broadband capabilities, dependable connectivity, and extensive range, covering distances from 10 to 50 kilometers [2].

1. Implementation of PSK Modulation Schemes

Satellite communication systems typically utilize FSK and PSK modulation schemes due to their superior noise immunity compared to ASK. These schemes offer enhanced power efficiency, and higher bit rates, and are less susceptible to errors. A comparison is conducted between both modulation techniques, evaluating various parameters to determine which is more optimal for the satellite.

a. Generation of FSK and PSK Waveforms

MATLAB code is used to generate the fundamental modulation and demodulation waveforms for both FSK and PSK schemes.

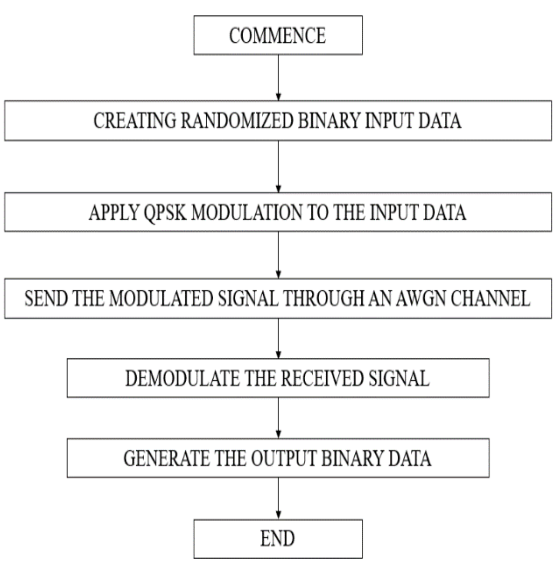

Fig 1. Architecture layout of waveforms for PSK modulation

Figure. 1 illustrates the progression of the MATLAB code and provides an overview of the signal pathway within the Simulink models.

2. Overview of Simulink Blocks

Inbuilt blocks provided by the communication toolbox of Simulink have been used for analyzing the parameters.

a) M-ary Modulation Technique

The M-ary signaling scheme allows for the transmission of two or more bits simultaneously, as opposed to sending a single bit at a time. This approach supports higher data rates while utilizing the same bandwidth and power, and is also referred to as multi-level signaling.

$$2^N = M \qquad (1)$$

Here, N represents the number of bits required, while M denotes the number of possible levels or combinations that can be formed with N bits. For instance, 8-level signaling can transmit 3 bits per symbol.

64-Frequency Shift Keying (64-QPSK)

The M-ary value, denoted as M, is 64, indicating that 5 bits are transmitted per symbol. This configuration involves 64 distinct carrier frequencies.

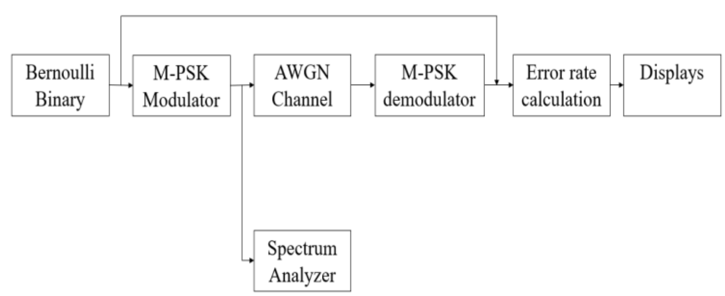

Fig 2. Simulink Model for QPSk in MATLAB

Quadrature Phase Shift Keying (QPSK)

In QPSK, the M-ary parameter, **M**, is 4, corresponding to the bit combinations 00, 01, 10, and 11. This modulation scheme facilitates the transmission of two bits per symbol by utilizing four unique phase states. Each symbol in QPSK is differentiated by a phase displacement of π/2 radians.

Literature review

As the global demand for connectivity grows, it is projected that by 2022, more than 20.4 billion devices will be connected worldwide. This unprecedented scale highlights the necessity for robust wireless communication systems offering enhanced coverage, efficient connections, and stable networking solutions. QBSK-based networks meet these requirements by being specifically designed for packet data transmission. With a focus on excellent spectral efficiency, high peak data rates, minimal latency, and a wide range of frequency options, QPSK has emerged as a critical enabler for next-generation applications. In this research, MATLAB and Simulink were used to simulate the physical layer of the QPSK system, encompassing essential components such as limited bandwidth, free-space path loss, channel effects, RF receiver dynamics, and demodulation processes. These simulations provide valuable insights into the performance and reliability of wireless data transmission in renewable energy systems, particularly when integrated with simplified wind power generation models [3].

i. GIS Features

Geographic Information Systems (GIS) have become indispensable tools across various fields, including military training, environmental conservation, and natural resource planning. These systems are uniquely designed to handle data associated with spatial or geographic coordinates. Essentially, GIS combines the functionalities of a database system tailored for spatially-referenced data with advanced operations for data analysis. It enables the capture, storage, validation, integration, manipulation, analysis, and visualization of spatial data, all tied to Earth-based references.

The future of GIS lies in its ability to further integrate with advanced technologies. Augmented Reality (AR) and Virtual Reality (VR) applications are expected to transform spatial data visualization, particularly in urban planning, disaster management, and defense. As 5G and satellite communications continue to evolve, GIS systems will offer unparalleled real-time insights across diverse applications, from autonomous vehicle navigation to climate change monitoring.

Advancements in communication systems have elevated the importance of dB measurements, particularly in optimizing network performance and ensuring signal quality. With the emergence of 5G and advanced wireless technologies, the precise calibration of signal strengths, interference reduction, and power efficiency will be critical.

The future will likely see more sophisticated methods of managing and interpreting dB-related data, powered by AI-driven algorithms. These tools will enhance network design, improve energy efficiency, and support the growing demands of global wireless communication systems. Together, GIS and advancements in signal power management will play pivotal roles in shaping technologies of the future.

$$P\,[\mathrm{dB}] = 10 \cdot \log(P/P0) \;\ldots\ldots\ldots\ldots\ldots\ldots \;(1)$$

It is customary to represent signal amplitude in terms of decibels (dB). Given that power exhibits a proportional relationship to the square of a signal's amplitude, the voltage level when expressed in decibels, is articulated through the following mathematical formulation:

$$V\,[\mathrm{dB}] = 20 \cdot \log(V/V0) \;\ldots\ldots\ldots\ldots\ldots\ldots \;(2)$$

Power transmission lines are equipped with substations located at the origin, termination points, and intermediate positions along the network. The presence of audible noise at substations is influenced by the ambient ground noise levels in their vicinity. Noise generated by the switching and protection equipment within these substations typically manifests as a low-frequency hum. The intensity and characteristics of this noise are contingent upon the operational state of the installed equipment.

i.MATLAB Simulink Model of Wind Power

Modeling wind power systems in MATLAB/Simulink provides a flexible and efficient platform for analyzing the behavior and performance of renewable energy systems. The Simplified Generator block in Simscape Electrical simplifies the representation of a generator's dynamic behavior while maintaining essential characteristics for grid-connected wind power systems. This makes it ideal for low-fidelity modeling, which focuses on planning, pitch control, and other strategic studies without the computational complexity of high-detail models. The image is shown in the figure 1. The example models a 1.5 MVA, 575 V, 60 Hz wind power system, designed to simulate the operational characteristics of a typical wind power generation setup. The system integrates Maximum Power Point Tracking (MPPT), a crucial technique used to optimize the efficiency of wind energy conversion by dynamically adjusting the turbine's operational parameters to extract the maximum available power from the wind [4].

The wind turbine is designed to operate within these parameters, ensuring that it can generate sufficient power to meet the grid requirements while maintaining stability and efficiency.

Maximum Power Point Tracking (MPPT): MPPT is employed to ensure that the wind turbine operates at the optimal point for power generation. The power output of a wind turbine is highly dependent on the wind speed, and the turbine's rotor speed must be adjusted to maximize the efficiency of energy capture. MPPT algorithms continuously adjust the turbine's operating conditions, such as blade pitch angle and rotor speed, to track and maintain operation at the maximum power point, where the energy conversion is maximized [5].

Dynamic Adjustment: The system is designed to dynamically track changes in wind speed and direction, adjusting the turbine's operation to extract the highest possible power under varying conditions. This is particularly important in environments with fluctuating wind patterns, where real-time adjustments allow for consistent and efficient power output [6].

Grid Connection: The system is designed to be connected to a 575 V, 60 Hz electrical grid, ensuring compatibility with standard power distribution systems. It includes all necessary components such as converters, transformers, and controllers to maintain stable power delivery to the grid [7].

Simulation and Control: Using MATLAB/Simulink, the system simulates the wind turbine's response to changes in wind speed, power output, and grid conditions. The simulation includes the implementation of MPPT algorithms, which enable real-time adjustments of turbine parameters. The performance of the wind power system can be analyzed for efficiency, stability, and grid compliance.

Efficiency and Performance Analysis: The MPPT algorithm continuously tracks the optimal operating point by adjusting the turbine's speed and other parameters. This ensures that the system operates at peak efficiency, even under varying wind conditions. The system's efficiency is measured by comparing the actual power output with the theoretical maximum power available from the wind at any given time [8].

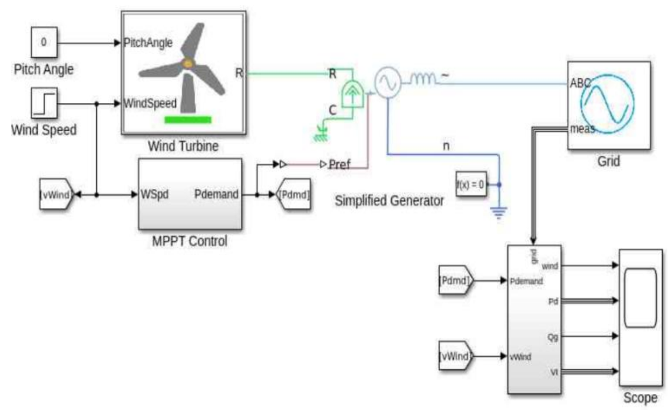

Fig 3. Model Wind Power System

Simulation Results

The simulation results include plots for wind speed, net active and reactive power, and phase voltage and current. The simplified generator model mechanically loads the wind turbine to meet the specified power demand, delivering the necessary electrical power to the grid while accounting for electromechanical losses. As wind speed increases, the power supplied by the wind system to the grid also rises, in accordance with the MPPT control algorithm. This dynamic adjustment ensures optimal energy extraction and efficient grid integration [9].

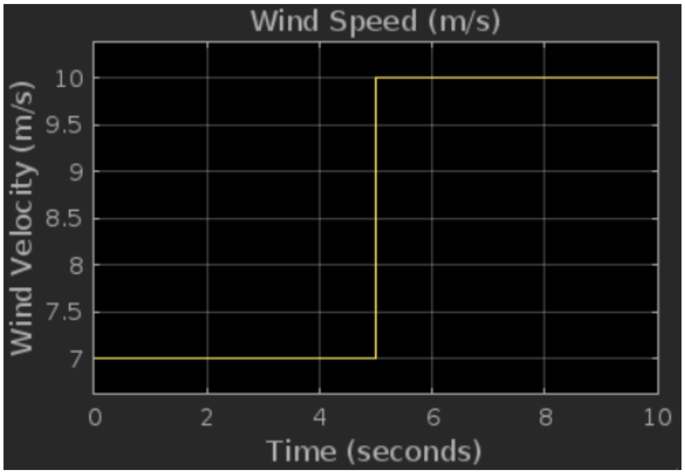

Fig 4. Plots for wind speed

The simulation result which is shown in Figure 4 includes plots for wind speed (ranging from 7 to 10 m/s). The simplified generator model mechanically loads the wind turbine to meet the specified power demand, supplying the required electrical power to the grid after accounting for electromechanical losses. As the wind speed increases within the range of 7 to 10 m/s, the power is supplied by the wind system.

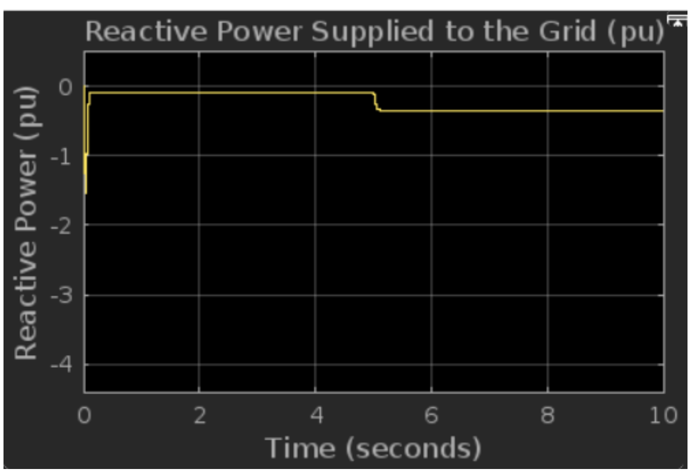

Fig 5. *Reactive Power Response of the Wind Power System Supplied to the Grid*

In Figure 5, the simulation results demonstrate the behavior of reactive power during the operation of the wind power system. Initially, the reactive power starts at -1.5 MVAR, reflecting the initial grid demand for reactive power compensation. Over the first 5 seconds, the reactive power stabilizes at 0 MVAR, indicating a balance between the system's reactive power generation and grid requirements. Beyond the 5-second mark, reactive power gradually decreases to -0.3 MVAR, signifying an adjustment in the system's operation to maintain grid stability as dictated by dynamic changes in wind speed and load conditions. This controlled reduction highlights the effectiveness of the wind power system's reactive power management in ensuring compliance with grid requirements and minimizing energy losses.

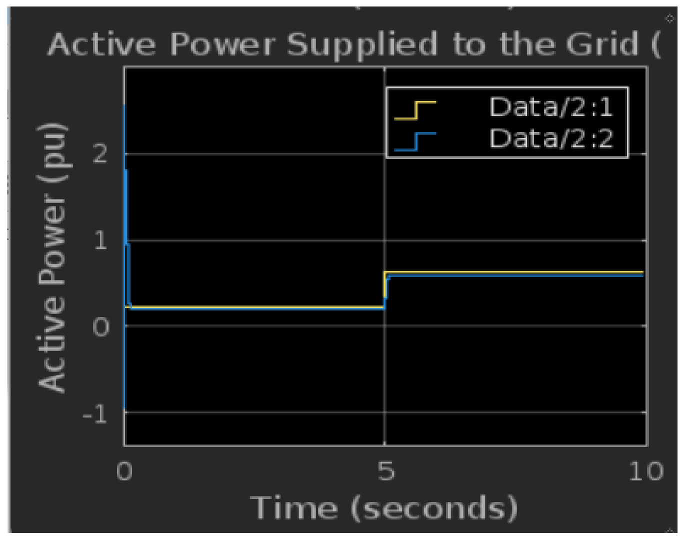

Fig 6. *Active Power Response of the Wind Power System Supplied to the Grid*

Figure 6 depicts the active power dynamics of the wind power system. The yellow line (Data/2:1) shows the power output delivered to the grid, while the blue line (Data/2:2) represents the grid's corresponding parameters. The interaction of these trends highlights the system's efficiency and responsiveness to changing operational conditions.

This Figure 7, graph illustrates the phase voltage and current (pu) over time. The yellow line (Data/4.Vsan) represents the phase voltage, while the blue line (Data/4.Isan) shows the phase current. The plot provides insights into the system's electrical performance and stability during operation.

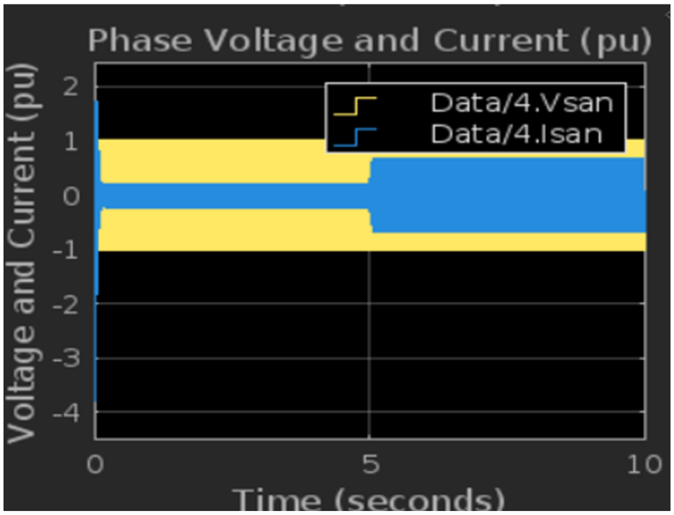

Fig 7. Phase Voltage and Current in Per Unit (pu)

ii. Communication Through the QPSK Transceiver Model

The wind power system incorporates a **QPSK (Quadrature Phase Shift Keying) transceiver model** for enhanced wireless data communication. technology, with its ultra-reliable low-latency communication (URLLC) and high-speed data transfer capabilities, provides a robust platform for real-time monitoring and control of renewable energy systems. The use of **QPSK modulation** ensures efficient spectrum utilization and reliable data transmission [10].

Key Features of the QPSK Transceiver Model:

High Data Rates: The network supports exceptionally high data rates, enabling the fast and efficient transfer of operational data such as power output, wind speed, and fault diagnostics.

Low Latency: The low latency of ensures near-instantaneous data communication, which is critical for time-sensitive applications like dynamic wind turbine control and grid synchronization.

QPSK Modulation: QPSK modulation is utilized for its ability to transmit two bits per symbol, doubling the data rate compared to traditional binary schemes. This modulation is robust against noise and distortion, making it suitable for the varying conditions encountered in wireless environments.

Simulated Physical Layer: MATLAB and Simulink are used to simulate the transceiver's physical layer. Key considerations include:

- **Channel Modeling:** Accounts for signal fading, interference, and path loss.
- **RF Receiver Dynamics:** Ensures signal integrity during reception.
- **Demodulation:** Accurately retrieves transmitted information for further processing.
- **Enhanced Coverage:** The network provides extended coverage and reliable connectivity over larger distances, making it ideal for wind farms in remote locations [11].

i.MATLAB Simulink model of Transceiver

The integration of a QPSK transceiver model ensures real-time data transmission with minimal errors, supporting advanced features like predictive maintenance, energy optimization, and fault detection. This enhances the overall efficiency, reliability, and responsiveness of the wind power system, aligning with modern smart grid requirements. The Simulink model of the QPSK transceiver is shown in the figure 8.

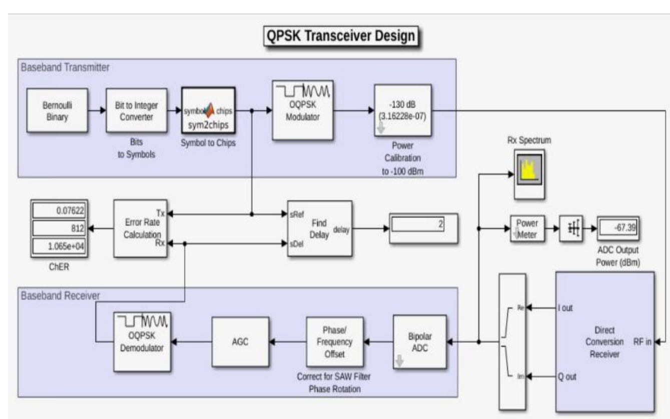

Fig 8. Model of QPSK Transceiver

Simulation Results of the QPSK Receiver

These findings validate the feasibility of integrating QPSK modulation in the wind power system's communication framework, offering high spectral efficiency and robust data transmission for real-time monitoring and control shown in Figure 9.

Figure 9. simulation of the QPSK receiver

The simulation of the QPSK receiver within the wind power system communication model highlights key performance metrics [12]:

1. **Receiver Performance Metrics:**
   - **Samples per Update:** 86
   - **Video Bandwidth (VBW):** 7.4063 Hz
   - **Resolution Bandwidth (RBW):** 46.5116 kHz
   - **Sample Rate:** 4.000 MHz
   - **Updates:** 895
   - **Time Duration (t):** 0.0192 seconds
2. **Frequency Spectrum Analysis:** The power spectral density graph demonstrates the signal characteristics over the frequency range:
   - **Power Range:** -84 dBm to -76 dBm
   - **Frequency Range:** 2.448 GHz to 2.452 GHz

The results show the QPSK receiver effectively operates within the specified parameters, maintaining strong signal integrity and efficient data communication. The narrow frequency band centered around **2.450 GHz** aligns with standard wireless communication protocols, ensuring minimal interference and reliable performance [13].

Conclusion

This study successfully demonstrates the modeling of a simplified wind power system integrated with advanced wireless communication technologies to optimize energy generation and real-time monitoring. Using MATLAB/Simulink, the system simulates a 1.5 MVA, 575 V, 60 Hz wind power system with Maximum Power Point Tracking (MPPT), ensuring efficient energy capture under varying wind conditions. The results highlight the system's ability to dynamically adapt to changes in wind speed and grid requirements, maintaining stability and optimizing power output.

The integration of QPSK wireless networks and QPSK transceiver models enhances the communication framework, enabling reliable data transmission with low latency and high spectral efficiency. Simulation results confirm the viability of this approach for real-time operational data sharing, predictive maintenance, and fault detection. This research underscores the potential of combining renewable energy systems with modern wireless technologies to achieve efficient, scalable, and reliable solutions for smart grid applications. The findings provide valuable insights for further advancements in wind power systems and their integration into next-generation energy infrastructures.

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