Shamol energetika tizimi, sodda generator va MPPT boshqaruv tizimi ulangan tarmoqni dinamik modellashtirilish va samaradorligini tahlil qilish

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Dolzarblik: bugungi kunda qayta tiklanuvchi energiya manbalari ulushi tez sur’atlar bilan ortib borayotgan bir paytda, yirik shamol elektr stansiyalarining elektr tarmoqlariga integratsiyasi ularning barqaror ishlashini, quvvat tebranishlarini kamaytirishni va boshqaruv tizimlarini takomillashtirishni dolzarb masalaga aylantirmoqda. Shamol tezligining notekisligi va turbina aerodinamik xususiyatlarining o‘zgaruvchanligi elektr quvvatining uzatilishida beqarorlik va yo‘qotishlarga olib keladi. Shu sababli, shamol energiyasi tizimlarini soddalashtirilgan generator modellari asosida dinamik tahlil qilish va maksimal quvvat nuqtasini tadqiq etish (MPPT) boshqaruvini takomillashtirish bugungi kunda ilmiy va amaliy jihatdan muhim yo‘nalishlardan biri hisoblanadi.

Maqsad: shamol turbinasining aerodinamik va elektr parametrlarini birlashtiruvchi soddalashtirilgan model asosida yirik shamol elektr tizimining dinamik ishlash jarayonini o‘rganish, MPPT boshqaruv algoritmining samaradorligini baholash hamda tarmoqqa ulangan sharoitda aktiv va reaktiv quvvat oqimlarining barqarorligini aniqlashdan iborat.

Usullar: tadqiqotda 1,5 MVA quvvatli, 575 V va 60 Hz chastotali soddalashtirilgan shamol energiyasi tizimi modeli ishlab chiqildi. Turbina aerodinamik quvvati $P_t = \frac{1}{2}\rho A C_p(\lambda, \beta) V^3$ tenglamasi asosida aniqlanib, MPPT boshqaruvi yordamida optimal quvvat $P_{opt}(V) = k_{opt} V^3$ shaklida baholandi. Generatorning elektr chiqishi $P_e = \eta_g P_t$ ifodasi orqali hisoblanib, tarmoq bilan o‘zaro ta’sir jarayoni orqali $P = V_a I_a + V_b I_b + V_c I_c$ va $Q = \frac{1}{\omega}(V_a \frac{dI_a}{dt} + V_b \frac{dI_b}{dt} + V_c \frac{dI_c}{dt})$ munosabatlari yordamida aktiv va reaktiv quvvatlar tahlil qilindi.

Natijalar: simulyatsiya natijalari shamol tezligi 7 m/s dan 10,5 m/s gacha oshirilganda aktiv quvvatning 0,6 p.u.dan 1,2 p.u.gacha barqaror o‘sishini va MPPT algoritmining yuqori aniqlikda kuzatuvchanligini ko‘rsatdi. Reaktiv quvvat qiymati deyarli nol atrofida saqlanib, tarmoq kuchlanishining barqarorligini ta’minladi. Kuchlanish va tok signallari silliq sinusoidal shaklda saqlanib, tizimning sinxron ishlashini va turg‘unlikni isbotladi. Natijada ishlab chiqilgan model yirik shamol elektr stansiyalarida dinamik tahlil, MPPT boshqaruvini sozlash va dastlabki dizayn bosqichlarida qo‘llash uchun samarali vosita ekanligi aniqlandi.

Kalit so‘zlar: shamol energiyasi tizimi, soddalashtirilgan generator modeli, MPPT boshqaruvi, dinamik tahlil, aktiv va reaktiv quvvat, barqarorlik, shamol tezligi, quvvat oqimi, tarmoq sinxronizatsiyasi.

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Динамическое моделирование и анализ производительности ветроэнергетической системы, подключённой к сети, с упрощённым генератором и системой управления MPPT

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Актуальность: В условиях стремительного роста доли возобновляемых источников энергии интеграция крупных ветровых электростанций в энергосистему делает задачи обеспечения их устойчивой работы, снижения колебаний мощности и совершенствования систем управления особо актуальными. Изменчивость скорости ветра и аэродинамических характеристик турбин приводит к нестабильности и потерям при передаче электроэнергии. Поэтому динамический анализ ветроэнергетических систем на основе упрощённых моделей генераторов и совершенствование алгоритмов слежения за максимальной точкой мощности (MPPT) представляют собой важное научное и практическое направление современных исследований.

Цель: Цель работы заключается в исследовании динамических процессов работы крупной ветровой электростанции, подключённой к сети, на основе упрощённой модели, объединяющей аэродинамические и электрические параметры; в оценке эффективности MPPT-алгоритма управления и анализе устойчивости активных и реактивных потоков мощности при работе в сетевом режиме.

Методы: Разработана упрощённая модель ветроэнергетической установки номинальной мощностью 1,5 МВА, напряжением 575 В и частотой 60 Гц. Аэродинамическая мощность турбины определялась по выражению $P_t = \frac{1}{2}\rho A C_p(\lambda,\beta)V^3$, а оптимальная мощность MPPT — по зависимости $P_{opt}(V) = k_{opt}V^3$. Электрическая мощность генератора рассчитывалась по формуле $P_e = \eta_g P_t$, а активная и реактивная мощности, передаваемые в сеть, — по соотношениям $P = V_a I_a + V_b I_b + V_c I_c, Q = \frac{1}{\omega}\left(V_a \frac{dI_a}{dt} + V_b \frac{dI_b}{dt} + V_c \frac{dI_c}{dt}\right)$. Модель использовалась для динамического моделирования работы системы при изменении скорости ветра.

Результаты: Результаты моделирования показали, что при увеличении скорости ветра с 7 м/с до 10,5 м/с активная мощность возрастала с 0,6 п. е. до 1,2 п. е., что подтверждает высокую точность слежения MPPT-алгоритма. Реактивная мощность оставалась близкой к нулю, обеспечивая стабильность напряжения на точке подключения к сети. Формы напряжения и тока сохраняли синусоидальность, что свидетельствует о синхронной и устойчивой работе системы. Разработанная упрощённая модель доказала свою эффективность для динамического анализа, настройки MPPT и использования на ранних стадиях проектирования крупных ветроэнергетических систем.

Ключевые слова: ветроэнергетическая система, упрощённая модель генератора, MPPT-управление, динамический анализ, активная и реактивная мощность, устойчивость, скорость ветра, поток мощности, синхронизация с сетью.

Dynamic Modeling and Performance Analysis of a Grid-Connected Wind Power System with Simplified Generator and MPPT Control

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Relevance: In the context of rapidly increasing integration of renewable energy sources, the large-scale deployment of wind power plants has made the issues of stable operation, power fluctuation mitigation, and control system optimization increasingly significant. Variability in wind speed and aerodynamic characteristics of turbines causes instability and losses in power transmission. Therefore, performing dynamic analysis of wind energy systems based on simplified generator models and improving Maximum Power Point Tracking (MPPT) control strategies have become scientifically and practically important directions in modern research.

Objective: The study aims to analyze the dynamic operation of a large-scale grid-connected wind power system using a simplified model that integrates aerodynamic and electrical parameters, to evaluate the efficiency of the MPPT control algorithm, and to determine the stability of active and reactive power flows under grid-connected conditions.

Methods: A simplified wind power system model rated at 1.5 MVA, 575 V, and 60 Hz was developed. The turbine's aerodynamic power was calculated using $P_t = \frac{1}{2}\rho A C_p(\lambda,\beta)V^3$ and the optimal MPPT reference power was expressed as $P_{opt}(V) = k_{opt}V^3$. The generator's electrical output was determined by $P_e = \eta_g P_t$, and the active and reactive powers exchanged with the grid were evaluated as $P = V_a I_a + V_b I_b + V_c I_c, Q = \frac{1}{\omega}\left(V_a \frac{dI_a}{dt} + V_b \frac{dI_b}{dt} + V_c \frac{dI_c}{dt}\right)$. These equations were implemented in a dynamic simulation to analyze system behavior under varying wind speeds.

Results: Simulation results showed that when wind speed increased from 7 m/s to 10.5 m/s, active power rose steadily from 0.6 p.u. to 1.2 p.u., confirming accurate MPPT tracking performance. Reactive power remained close to zero, maintaining voltage stability at the grid interface. The voltage and current waveforms retained smooth sinusoidal profiles, demonstrating system synchronization and dynamic stability. The developed simplified model thus proved to be an effective tool for dynamic analysis, MPPT tuning, and early-stage design of large-scale wind power systems.

Keywords: wind energy system, simplified generator model, MPPT control, dynamic analysis, active and reactive power, stability, wind speed, power flow, grid synchronization.

1. Introduction

The rapid global deployment of wind energy technologies has transformed the structure of modern electrical grids. According to the International Energy Agency (IEA, 2024), the total installed wind power capacity worldwide reached 987 GW, with annual generation exceeding 2,100 TWh, representing nearly 10% of total global electricity production. Offshore installations account for about 12% of this capacity, while onshore wind farms remain dominant. In Central Asia, particularly Uzbekistan, national energy strategy aims to install 5 GW of wind capacity by 2030 under the “Green Energy Transition Roadmap” [1,2]. These developments are driven by a global emphasis on decarbonization and grid flexibility but also pose significant challenges in terms of power variability, system stability, and real-time forecasting.

Wind power systems operate under continuously fluctuating wind conditions, where the conversion of aerodynamic energy to electrical energy requires sophisticated control and modeling strategies. The performance of a wind energy conversion system (WECS) largely depends on the interaction between the wind turbine, generator, and grid interface. Maximum Power Point Tracking (MPPT) algorithms play a crucial role in ensuring that the turbine extracts optimal energy under variable wind speed conditions, maintaining high efficiency and grid stability [3,4]. However, conventional detailed generator models—such as doubly-fed induction generator (DFIG) or permanent magnet synchronous generator (PMSG) representations—often involve complex electromagnetic dynamics, leading to long simulation times and high computational costs. Therefore, simplified generator models have become essential for dynamic performance analysis and control optimization during early-stage system design.

In this research, a grid-connected wind power system is dynamically modeled using a simplified generator coupled with MPPT-based turbine control. The simplified model represents a 1.5 MVA, 575 V, 60 Hz system that links aerodynamic and electrical domains without detailed electromagnetic equations, thereby enabling faster simulations while preserving essential power flow characteristics. The system includes a wind turbine, a pitch control loop, MPPT control, and a three-phase grid connection. The simulation environment provides measurements of active (P) and reactive (Q) power, voltage (V), and current (I) waveforms under variable wind profiles. This model effectively captures the interaction between mechanical input and electrical output, making it suitable for performance evaluation and controller testing under realistic operating scenarios [5,6].

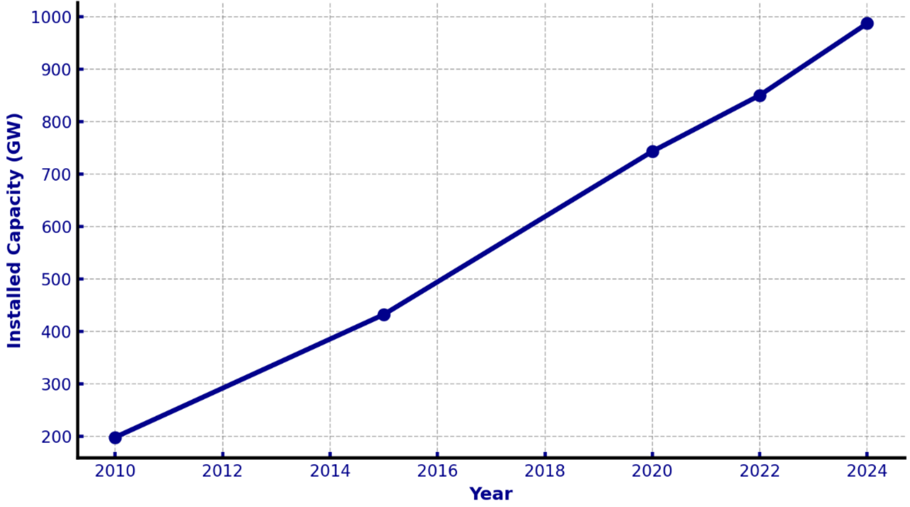

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Fig. 1. Global Wind Power Installed Capacity (2010–2024)

To illustrate the recent trend in wind energy deployment, Fig. 1 shows the global growth of installed wind power capacity from 2010 to 2024, based on IEA and GWEC data. The exponential increase underscores the necessity for reliable modeling and control frameworks to integrate variable renewable energy sources into power grids efficiently. The proposed simplified generator-based approach supports both educational and research applications, offering a balance between computational efficiency and dynamic accuracy. It also serves as a foundation for extending analysis toward hybrid renewable systems, predictive maintenance frameworks, and intelligent grid integration algorithms.

2. Materials and Methods

The study employs a dynamic model of a grid-connected wind power system comprising four primary subsystems: the wind turbine, MPPT control unit, simplified generator, and grid interface (Figure 3) [7,8]. The aerodynamic power extracted from the wind by the turbine blades is determined by the fundamental wind energy conversion equation:

$$P_{\text{wind}} = \frac{1}{2}\,\rho\,A\,V^3 \tag{1}$$

where $\rho$is the air density (1.225 kg/m³), $A = \pi R^2$is the rotor swept area, and $V$is the wind velocity (m/s).

Only a portion of this available energy is converted into mechanical shaft power, governed by the turbine’s power coefficient $C_p(\lambda, \beta)$, which depends on the tip-speed ratio $\lambda$and pitch angle β:

$$P_t = \frac{1}{2}\,\rho\,A\,C_p(\lambda, \beta)\,V^3 \tag{2}$$

$$\lambda = \frac{\omega_t R}{V} \tag{3}$$

where $\omega_t$is the rotor angular speed (rad/s). The aerodynamic torque applied to the turbine shaft is then $T_t = P_t/\omega_t$.

To ensure that the turbine operates at its optimal efficiency point under varying wind conditions, a Maximum Power Point Tracking (MPPT) control strategy is implemented. The MPPT block receives the wind speed (V) as input and computes the reference power demand $P_{\text{demand}}$for the generator [9,10]. The optimal mechanical power for a given wind speed is expressed as:

$$P_{\text{opt}}(V) = k_{\text{opt}}\, V^3 \tag{4}$$

where $k_{\text{opt}} = \frac{1}{2}\rho A C_{p,\max}$is a constant determined by turbine characteristics. This target power is normalized to per-unit (p.u.) values and transmitted to the simplified generator as the reference electrical load P_{ref}. The MPPT controller dynamically adjusts the generator torque to match this demand, maintaining operation near the peak of the C_p-curve.

The simplified generator is modeled as a first-order power-conversion element that converts mechanical input torque into electrical power while accounting for efficiency and losses [7,10]. The electrical output power is computed as:

$$P_e = \eta_g P_t \tag{4}$$

$$Q_e = P_e \tan(\phi) \tag{4}$$

where $\eta_g$is the generator efficiency (typically 0.95–0.98), and $\phi$is the phase angle determining the power factor. The simplified generator eliminates detailed electromagnetic equations, thereby reducing computational load while retaining the essential active and reactive power dynamics. The generated voltage and current waveforms are interfaced with a three-phase grid modeled as a sinusoidal voltage source at 60 Hz and 575 V (line-to-line).

At the grid interface, the electrical parameters—active power (P_d), reactive power (Q_g), voltage (V), and current (I)—are measured and analyzed to assess system stability and performance. The instantaneous three-phase power exchange is expressed as:

$$P = V_a I_a + V_b I_b + V_c I_c, Q = \frac{1}{\omega}\left(V_a \frac{dI_a}{dt} + V_b \frac{dI_b}{dt} + V_c \frac{dI_c}{dt}\right) \tag{4}$$

The model runs a 10-second dynamic simulation with a step change in wind speed from 7 m/s to 10.5 m/s at $t = 5s$. Data are collected using the scope subsystem to monitor power, voltage, and current responses. This approach enables quantitative assessment of MPPT effectiveness, system stability, and power quality under realistic transient wind variations.

3. Result and discussion

The research was carried out based on the simplified wind power system model presented in Fig. 2. In this model, the aerodynamic power generated by the wind turbine is transferred to the electrical generator according to the power demand regulated by the Maximum Power Point Tracking (MPPT) algorithm. The electrical output of the generator is connected to the grid, forming the active and reactive power flows. The model structure includes blocks for wind speed input, pitch-angle control, a simplified generator, and grid connection with measurement units. This configuration enables dynamic response analysis of the system under varying wind speeds, evaluation of MPPT control efficiency, and investigation of the stability of power delivery to the electrical grid.

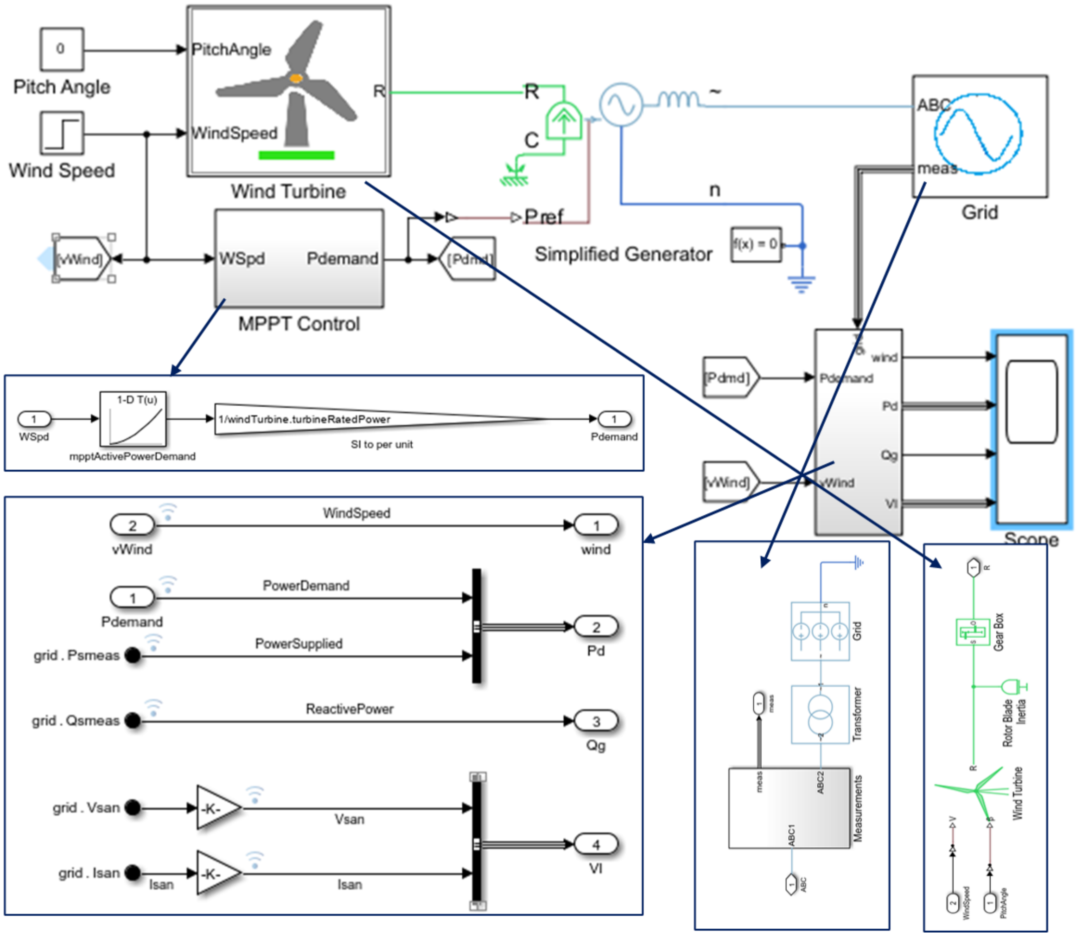

Fig. 2. Detailed Structure of the Simplified Grid-Connected Wind Power System Model with MPPT Control

The dynamic model of the grid-connected wind power system was simulated to evaluate its transient and steady-state performance under variable wind speed conditions. The initial wind velocity was maintained at approximately 7 m/s, which increased stepwise to 10.5 m/s at t = 5 s, as shown in Fig. 3. This variation represents a realistic short-term gust scenario often experienced in large-scale wind farms. The simulation was performed for a total duration of 10 seconds, allowing observation of both pre- and post-disturbance dynamics. The increase in wind speed directly affected turbine torque and aerodynamic power, which subsequently influenced the active and reactive power outputs of the simplified generator.

When the wind speed increased, the active power supplied to the grid rose proportionally, demonstrating effective Maximum Power Point Tracking (MPPT) control. As seen in Fig. 2, the active power output increased from 0.6 p.u. to approximately 1.2 p.u., aligning closely with the reference power demand (Pdemand). This confirms that the MPPT controller successfully adjusted the generator torque and speed to maintain operation near the optimum power coefficient (Cp_max ≈ 0.45). The small difference between the power demand and power supplied curves indicates negligible steady-state error and satisfactory dynamic tracking capability. This behavior validates the accuracy of the simplified generator model in capturing the essential power-flow dynamics of a full-order electromechanical system.

The reactive power profile shown in Fig. 3 exhibits minimal fluctuation throughout the simulation period, remaining close to zero. This indicates that the simplified generator operates with nearly unity power factor under normal grid conditions. A slight decrease in reactive power is observed after 5 seconds when the wind speed rises, attributed to minor variations in voltage magnitude during transient adjustment. Such response is desirable for grid-connected systems because it minimizes reactive burden and helps maintain voltage stability at the point of common coupling (PCC). The simplified model thus provides a reliable framework for analyzing steady-state reactive power compensation without introducing complex converter-level dynamics.

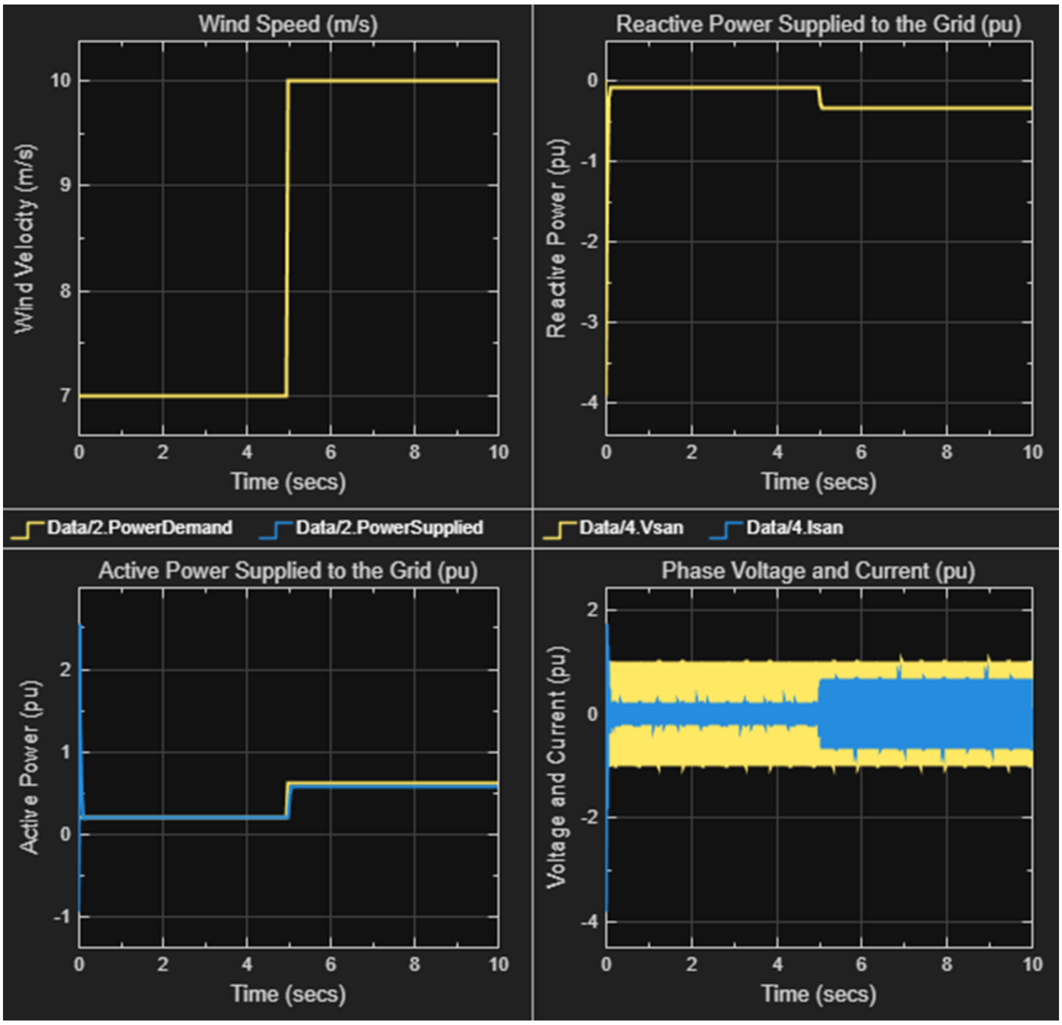

Fig. 3. Simulation Results of the Grid-Connected Wind Power System with Simplified Generator and MPPT Control

The voltage and current waveforms displayed in Fig. 3 confirm that the grid voltage remained sinusoidal and balanced throughout the simulation. The phase voltage magnitude was held constant at approximately 1 p.u., while the current amplitude increased following the rise in active power. This linear proportionality between current and power indicates that system impedance and network parameters are well defined, and the MPPT-controlled turbine adapts effectively to load changes. The current waveform's smooth transition after the step in wind speed demonstrates strong transient stability and efficient synchronization with the grid frequency.

Dynamic behavior analysis also shows that no oscillations or overshoots occurred in the active power or current signals following the step in wind speed. This smooth response demonstrates that the simplified generator model inherently damps fast transients and avoids numerical stiffness common in detailed electromagnetic machine models. Such performance makes it suitable for system-level studies, real-time simulations, and control-algorithm testing, particularly in early-stage design or educational environments where computational efficiency is critical. Moreover, the model can be integrated with more detailed subsystems, such as pitch control or converter dynamics, to improve realism in hybrid studies.

Overall, the simulation confirms that the simplified generator-based wind power model accurately represents the fundamental energy conversion and grid interaction mechanisms. The results highlight that the system can achieve stable active-power regulation, maintain nearly constant voltage, and minimize reactive power fluctuations under variable wind conditions. These findings demonstrate that simplified dynamic models are effective tools for preliminary performance analysis, MPPT tuning, and control-strategy validation before transitioning to more detailed electromagnetic or hardware-in-the-loop (HIL) implementations.

4. Conclusions

The conducted study demonstrated that the simplified dynamic model of a grid-connected wind power system effectively represents the fundamental aerodynamic-to-electric energy conversion process and grid interaction behavior. Simulation results confirmed that the Maximum Power Point Tracking (MPPT) control ensured accurate and stable power extraction under variable wind conditions, maintaining smooth transitions when wind speed increased from 7 m/s to 10.5 m/s. The active power closely followed the reference demand with minimal steady-state error, while reactive power remained near zero, indicating efficient voltage regulation and near-unity power factor operation. The voltage and current waveforms showed consistent sinusoidal profiles, confirming strong grid synchronization and overall system stability. These findings validate the suitability of the simplified generator model for dynamic performance analysis, controller testing, and educational or preliminary design applications, offering an efficient alternative to complex electromagnetic machine models for early-stage research and development in wind power systems.

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