

## DEVELOPMENT OF AN EXCITATION CONTROL ALGORITHM FOR INCREASING THE EFFICIENCY OF SMALL WIND TURBINE GENERATORS

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*Received 18 May 2026; Accepted 4 June 2026*

**Abstract.** This paper presents the development and investigation of an excitation-current-based control approach for improving voltage stabilization and operating performance of a small-scale wind energy conversion system operating under variable wind speed conditions. The proposed system employs a synchronous generator with regulated excitation integrated into a subsystem-oriented MATLAB/Simulink simulation model intended for analysis of aerodynamic and electromechanical operating processes. A mathematical model of the wind energy conversion system was developed considering aerodynamic power conversion, synchronous generator electromechanical dynamics, excitation current regulation, and electrical loading conditions. A PI/PID-based excitation control algorithm was implemented for continuous adjustment of excitation current according to generator terminal voltage deviations under transient wind operating modes. Simulation studies were performed under different wind speed and loading conditions in order to investigate generated voltage, electrical power, excitation current, and rotor rotational speed characteristics. The obtained results demonstrated that excitation-current regulation improves voltage stabilization performance, reduces transient voltage oscillations, and enhances operating stability of the generating system under stochastic wind disturbances. The developed control approach also improved adaptation of the synchronous generator to variable mechanical loading conditions and reduced the influence of aerodynamic disturbances on electromechanical operating behavior. The proposed excitation-based regulation method represents a practically applicable and comparatively low-complexity approach for improving the operating efficiency and voltage stabilization characteristics of small-scale wind energy conversion systems.

**Keywords:** Wind energy conversion system; synchronous generator; excitation current control; voltage stabilization; MATLAB/Simulink; PID controller; small-scale wind turbine.

### 1. INTRODUCTION

The rapid development of renewable energy technologies has significantly increased the role of wind energy in modern electrical power systems. According to the Global Wind Report 2025, 117 GW of new wind power capacity was installed worldwide in 2024, increasing the cumulative global wind capacity to 1136 GW [1]. The continuous growth of renewable energy capacity demonstrates the increasing importance of environmentally sustainable and low-carbon electricity generation technologies in the global energy sector [2].

Modern wind energy conversion systems are considered among the most promising technologies for distributed and autonomous electricity generation. Wind energy is widely available in many regions of the world and possesses considerable long-term potential for sustainable power supply applications [3]. Regions characterized by favorable wind conditions are especially attractive for the deployment of small-scale and autonomous wind power systems operating independently or as part of hybrid renewable energy complexes [4].

The operational efficiency of wind turbine generators strongly depends on wind speed conditions. The stochastic nature of wind flow causes fluctuations in turbine rotational speed and generated electrical power, which negatively affect the stability and operating characteristics of wind energy

conversion systems [5]. In practical operating conditions, unstable wind speed may lead to voltage fluctuations, deterioration of generated power quality, and reduction of electromechanical energy conversion efficiency [6]. In addition, stable operation of wind turbine generators under continuously changing mechanical loads remains one of the important engineering problems in modern wind power systems [7].

Various generator configurations are currently applied in wind energy conversion systems, including synchronous and induction generator systems [8]. Variable-speed wind turbine generators provide improved operational flexibility and more efficient adaptation to changing wind conditions compared with fixed-speed operating systems [9]. The application of synchronous and induction generators in wind turbine systems makes it possible to improve the regulation characteristics and operational efficiency of electrical power generation under variable operating conditions [10].

One of the promising approaches for improving the operating characteristics of wind turbine generators is the application of excitation current control systems. Regulation of generator excitation allows stabilization of operating modes, improvement of voltage characteristics, and enhancement of power generation efficiency under variable wind speed conditions. However, maintaining stable operating characteristics of small-scale wind energy conversion systems under continuously changing aerodynamic conditions remains a significant engineering challenge.

The main contribution of this study consists in the development of an excitation-current-based control structure for improving voltage stabilization and operational stability of a small-scale wind energy conversion system under variable wind speed conditions. In contrast to conventional fixed-excitation operating approaches, the proposed system employs continuous excitation current regulation of a synchronous generator integrated into a subsystem-oriented MATLAB/Simulink model of the wind energy conversion system. The developed approach enables investigation of the interaction between aerodynamic disturbances, generator electromechanical operating behavior, and excitation-based voltage stabilization processes under transient wind operating conditions.

The aim of this study is to develop and investigate an excitation control algorithm for a synchronous generator with regulated excitation in order to improve the efficiency and operational stability of a small-scale wind energy conversion system operating under variable wind speed conditions.

## 2. SYSTEM DESCRIPTION AND MATHEMATICAL MODEL

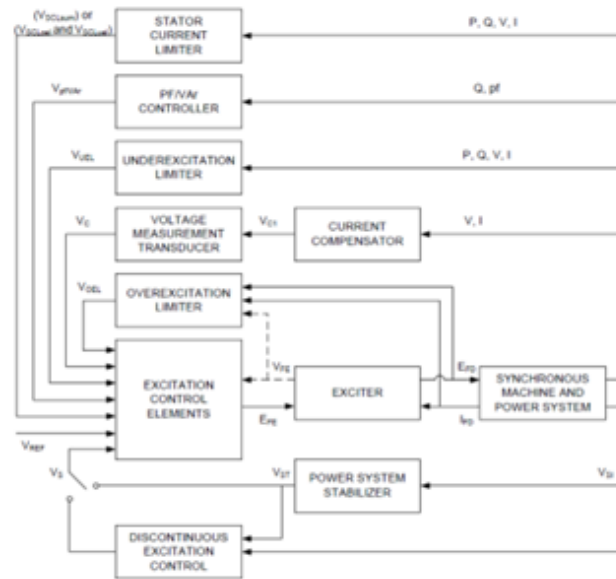
### 2.1. Structure of the Wind Energy Conversion System

The developed wind energy conversion system is based on the application of a synchronous generator with regulated excitation operating under variable wind speed conditions. The general functional structure of the proposed system includes a wind turbine, a synchronous generator, an excitation control system, a rectifier unit, a DC link, and an electrical load, as shown in Figure 1.

The wind turbine converts the kinetic energy of the airflow into mechanical rotational energy transmitted to the generator shaft. Variations in wind speed cause continuous changes in the rotational speed and electromagnetic operating conditions of the generating system. Under such operating conditions, stable voltage regulation and maintenance of generator operating characteristics become important tasks for small-scale wind energy systems.

Excitation systems of synchronous machines include excitation control elements, voltage measurement units, excitation regulation subsystems and additional stabilizing components that ensure stable operation of the synchronous machine in dynamic operating modes [11]. The excitation system structure is formed using voltage feedback signals obtained from the generator terminal conditions and excitation regulating elements responsible for the stabilization of generator operating modes.

The excitation control subsystem performs regulation of the generator magnetic field by control-



**Figure 1** – Functional structure of the proposed wind energy conversion system

ling the excitation current supplied to the field winding of the synchronous generator. Regulation of the excitation current allows stabilization of generator terminal voltage and improvement of operating characteristics under continuously changing mechanical loading conditions caused by wind speed fluctuations.

According to IEEE excitation system representation principles, excitation control structures may include voltage transducers, excitation regulators, stabilizing elements, and supplementary feedback loops used for maintaining stable synchronous machine operation under transient operating conditions [11]. In the proposed wind energy conversion system, voltage feedback from the generator output is used as the main control signal for excitation current regulation.

The electrical energy generated by the synchronous generator is transferred through a rectifier and DC link to the electrical load. The developed system structure provides the possibility of investigating the influence of excitation current regulation on voltage stabilization, generated power characteristics, and operational efficiency of the wind energy conversion system under variable wind speed conditions.

### 2.2. Synchronous Generator with Regulated Excitation

The operating performance of small-scale wind energy conversion systems is strongly influenced by variable wind speed conditions causing continuous changes in turbine rotational speed and generator electromechanical operating modes. Under such conditions, conventional generating systems operating without effective excitation regulation may experience voltage instability, deterioration of generated power characteristics, and reduction of energy conversion efficiency.

In synchronous generators, the electromagnetic operating state is determined by the interaction between the rotor magnetic field and stator electromagnetic processes. The magnetic field of the rotor is created by the excitation winding supplied with direct current, while the generated electromotive force depends on the excitation current magnitude and magnetic flux distribution inside the machine [12]. Therefore, excitation current variation directly influences generator terminal voltage, reactive power characteristics, and dynamic operating behavior.

One of the important advantages of synchronous generators in wind energy applications is the

possibility of active control of electromagnetic operating conditions through excitation current regulation. Unlike fixed-excitation operating modes, regulated excitation systems allow adaptation of generator operating characteristics to continuously changing wind conditions. Under variable mechanical torque conditions caused by wind speed fluctuations, excitation regulation provides compensation of voltage deviations and improves stabilization of generator operating parameters.

According to modern excitation control principles, excitation systems play an important role not only in voltage regulation but also in maintaining electromechanical stability and improving transient operating performance of synchronous generating systems [12]. Fast excitation response allows the generating system to maintain more stable operating conditions during disturbances and rapidly changing mechanical loading modes.

For small-scale wind energy systems, the application of regulated excitation becomes especially important due to the stochastic nature of wind flow and increased sensitivity of low-power systems to voltage fluctuations. In such operating conditions, excitation current control may significantly influence voltage stabilization characteristics and the overall efficiency of electrical energy conversion.

Therefore, in the proposed wind energy conversion system, a synchronous generator with regulated excitation is used as the main generating unit. The excitation subsystem performs continuous excitation current adjustment according to generator operating conditions, providing improved voltage stabilization and more stable operation of the generating system under variable wind speed conditions.

### 2.3. Mathematical Model of the Wind Turbine Generator

The mathematical model of the developed wind energy conversion system is based on the electromechanical relationships describing the interaction between the wind turbine mechanical subsystem and the synchronous generator electromagnetic subsystem. The developed model is intended for investigation of the influence of excitation current regulation on voltage stabilization and operating characteristics of the generating system under variable wind speed conditions.

The mechanical power extracted from the wind flow by the wind turbine is determined by the following expression:

$$P_m = \frac{1}{2} \rho A v_w^3 C_p(\lambda, \beta) \quad (1)$$

where  $P_m$  is the mechanical power of the wind turbine,  $\rho$  is the air density,  $A$  is the turbine swept area,  $v_w$  is the wind speed, and  $C_p(\lambda, \beta)$  is the aerodynamic power coefficient of the wind turbine.

According to (1), the generated mechanical power strongly depends on wind speed variations due to the cubic relationship between wind velocity and extracted aerodynamic power. Therefore, changes in wind speed directly influence the mechanical torque transmitted to the synchronous generator shaft and affect the electromechanical operating conditions of the generating system.

The electromechanical dynamics of the synchronous generator are determined by the balance between the mechanical torque produced by the wind turbine and the electromagnetic torque developed by the generator. According to synchronous machine dynamic principles, the rotor motion equation may be represented as follows [13]:

$$J \frac{d\omega}{dt} = T_m - T_e - B\omega \quad (2)$$

where  $J$  is the rotor moment of inertia,  $\omega$  is the angular rotational speed,  $T_m$  is the mechanical torque produced by the wind turbine,  $T_e$  is the electromagnetic torque of the synchronous generator, and  $B$  is the damping coefficient.

Under variable wind speed conditions, fluctuations of the mechanical torque lead to changes in rotor speed and generator electromechanical operating parameters. Such operating conditions may cause voltage instability and deterioration of generated power characteristics, especially in small-scale wind energy systems operating under continuously changing mechanical loading conditions.

The generated electromotive force of the synchronous generator depends on the magnetic flux created by the excitation system and rotor rotational speed. The relationship between generated electromotive force and excitation conditions may be expressed as:

$$E = k\Phi\omega \quad (3)$$

where  $E$  is the generated electromotive force,  $k$  is the machine constant,  $\Phi$  is the magnetic flux created by the excitation winding, and  $\omega$  is the angular rotational speed of the rotor.

According to (3), excitation current variation directly affects the magnetic flux of the synchronous generator and influences the generated electromotive force and terminal voltage characteristics. Therefore, excitation current regulation becomes one of the main control mechanisms for stabilization of generator operating conditions under variable wind speed modes.

The developed mathematical relationships form the basis for implementation of the excitation control algorithm and further simulation studies of the wind energy conversion system in the MATLAB/Simulink environment.

#### 2.4. Excitation System Model

The excitation system developed for the proposed wind energy conversion system is intended for continuous regulation of the synchronous generator excitation current under variable wind speed operating conditions. The excitation subsystem performs stabilization of generator operating characteristics by controlling the magnetic field of the synchronous generator according to changes in generator terminal voltage and electromechanical operating conditions.

In the developed model, the generator terminal voltage is used as the main feedback signal for the excitation control subsystem. Variations in wind speed and mechanical loading conditions cause changes in generator operating parameters and voltage characteristics. The excitation control subsystem continuously monitors generator voltage conditions and forms the required excitation control action for stabilization of the generating system operating mode.

The excitation control process is based on continuous adjustment of the excitation current supplied to the rotor field winding of the synchronous generator. Under reduced generator terminal voltage conditions, the excitation subsystem increases the excitation current to strengthen the magnetic field and compensate voltage deviations. Conversely, under increased voltage conditions, the excitation current is reduced to maintain stable generator operating characteristics.

The developed excitation system model provides adaptive response of the generating system to continuously changing wind speed conditions and electromechanical operating modes. Excitation current regulation improves voltage stabilization characteristics and reduces the influence of wind speed fluctuations on generator operating performance.

The developed excitation subsystem is integrated into the mathematical model of the wind energy conversion system and forms the basis for implementation of the excitation control algorithm in the MATLAB/Simulink environment. The proposed excitation system structure provides the possibility of investigating the influence of excitation current regulation on generated voltage stability and operational efficiency of the small-scale wind energy conversion system.

### 3. EXCITATION CONTROL ALGORITHM

#### 3.1. Principles of Excitation Current Regulation

One of the main operating challenges of small-scale wind energy conversion systems is the instability of generator operating conditions under variable wind speed modes. Wind speed fluctuations continuously affect turbine rotational speed and mechanical torque transmitted to the synchronous generator shaft, resulting in variations of generator voltage and generated electrical power. Under such operating conditions, maintaining stable voltage characteristics becomes one of the key tasks of the generating system control process.

In synchronous generators, the excitation current directly determines the rotor magnetic flux and significantly influences the generated electromotive force and terminal voltage characteristics. Therefore, excitation current regulation may be used as an effective control mechanism for stabilization of generator operating conditions under continuously changing wind energy input conditions [14].

Unlike fixed-excitation operating modes, regulated excitation systems provide adaptive adjustment of generator electromagnetic operating parameters according to changes in generator terminal voltage and electromechanical operating conditions. In modern wind energy systems, excitation current regulation is considered one of the important approaches for improving voltage stabilization characteristics and increasing operational stability under transient operating modes.

The proposed control approach is based on continuous monitoring of generator terminal voltage and dynamic adjustment of excitation current according to voltage deviation conditions. Under reduced voltage conditions caused by decreasing wind speed or increased loading, the excitation subsystem increases excitation current in order to strengthen the rotor magnetic field and compensate voltage deviations. Conversely, under increased voltage conditions, the excitation current is reduced to maintain stable operating parameters of the generating system.

The excitation control process forms a closed-loop regulation structure in which generator terminal voltage acts as the feedback signal for the excitation controller. Such a control structure allows continuous correction of excitation operating conditions according to changes in generator electromechanical parameters and wind operating modes [14]. The excitation control subsystem operates according to the closed-loop control principle in which the generator terminal voltage is continuously compared with the reference voltage value. The resulting voltage error signal is processed by the excitation controller to generate the required excitation current correction signal. According to PID-based control principles, the proportional component provides fast response to voltage deviations, the integral component reduces steady-state regulation error, and the derivative component improves transient operating performance and damping characteristics [15].

The proposed excitation control approach is focused on minimizing voltage deviations and improving transient operating performance of the generating system during wind speed disturbances. The controller continuously adjusts the excitation current in order to reduce dynamic voltage oscillations, improve response speed, and maintain stable generator terminal voltage under variable operating conditions. Particular attention is given to reducing steady-state regulation error and improving stability of the generating system during rapidly changing wind modes. The application of PID-based excitation current regulation allows the generating system to dynamically compensate voltage deviations caused by continuously changing wind conditions and improve voltage stabilization performance under transient operating modes. In the proposed wind energy conversion system, excitation current regulation is used not only for voltage stabilization but also for improving the dynamic operating performance and operational efficiency of the generating system under variable wind speed conditions.

### 3.2. *PI/PID-Based Control Algorithm*

The proposed excitation control algorithm is developed for stabilization of synchronous generator operating conditions under variable wind speed modes in a small-scale wind energy conversion system. The control approach is based on continuous regulation of the excitation current according to generator terminal voltage deviations and dynamic operating conditions of the generating system.

In the proposed control structure, the generator terminal voltage is continuously measured and compared with the predefined reference voltage value. The resulting voltage deviation signal is used as the input parameter for the excitation controller. According to the developed control logic, the excitation subsystem dynamically adjusts the excitation current in order to compensate voltage deviations caused by fluctuations of wind speed and mechanical loading conditions.

The developed excitation control algorithm employs a PID-based regulation structure due to its relatively simple implementation, high operational reliability, and effective dynamic response characteristics under continuously changing operating conditions [16]. The proportional component of the controller provides rapid response to voltage deviations, the integral component minimizes steady-state regulation error, and the derivative component improves damping characteristics and transient operating stability of the generating system.

The proposed control algorithm operates according to a closed-loop excitation current regulation principle. Under decreasing generator terminal voltage conditions, the controller increases excitation current supplied to the rotor winding in order to strengthen the magnetic field and compensate voltage reduction. Conversely, under increasing voltage conditions, the excitation current is reduced to maintain stable operating characteristics of the synchronous generator.

Unlike conventional fixed-excitation operating modes, the proposed excitation regulation approach provides continuous adaptation of generator electromagnetic operating parameters according to changing wind conditions. Such an operating principle improves voltage stabilization performance and reduces the influence of transient wind disturbances on generator operating conditions [17].

In the developed control structure, excitation current is used as the main control parameter of the synchronous generator operating process. The application of excitation-current-based regulation allows stabilization of generator terminal voltage without the need for complicated converter structures and high-power control equipment. Such an approach is especially important for small-scale wind energy systems where system simplicity, operational reliability, and reduced control complexity are significant engineering requirements [18].

The proposed excitation control algorithm is intended for implementation in the MATLAB/Simulink environment for further investigation of voltage stabilization characteristics and dynamic operating performance of the generating system under variable wind speed conditions.

### 3.3. *Control Structure under Variable Wind Speed Conditions*

The operating performance of the developed wind energy conversion system is strongly influenced by continuously changing wind speed conditions causing dynamic variations of turbine rotational speed, mechanical torque, and synchronous generator operating parameters. Under such operating conditions, the excitation control subsystem continuously adapts the generator excitation current in order to maintain stable voltage characteristics and improve operating stability of the generating system.

The proposed control system operates according to a closed-loop voltage stabilization principle. During generator operation, the terminal voltage is continuously monitored and compared with the predefined reference voltage value. Variations caused by wind speed disturbances or changing loading conditions produce a voltage deviation signal that is processed by the excitation controller. Based

on the generated control signal, the excitation subsystem dynamically adjusts the excitation current supplied to the rotor winding of the synchronous generator.

Under increasing wind speed conditions, the mechanical power transmitted to the generator increases, causing changes in generator electromagnetic operating parameters and terminal voltage characteristics. In such operating modes, the proposed control algorithm performs continuous correction of excitation current in order to prevent excessive voltage deviations and maintain stable operating conditions of the generating system.

Under decreasing wind speed conditions, generator terminal voltage may decrease due to reduction of mechanical torque and generator rotational speed. In this case, the excitation controller increases the excitation current to strengthen the rotor magnetic field and compensate voltage reduction. Such an operating principle improves voltage stabilization performance and reduces the influence of transient wind disturbances on generator operating conditions.

The proposed control system continuously adapts excitation operating parameters according to changing electromechanical operating modes of the synchronous generator. The closed-loop excitation regulation structure provides improved dynamic response characteristics and reduces steady-state voltage regulation error under variable wind speed conditions [19].

Particular attention in the developed control approach is given to stabilization of transient operating performance during rapidly changing wind conditions. The proposed excitation control logic allows reduction of dynamic voltage oscillations and improves damping characteristics of the generating system under electromechanical disturbances. Continuous excitation current correction also improves operational stability of the synchronous generator during variable mechanical loading modes [20].

The developed operating logic of the excitation control system forms the basis for further simulation studies of voltage stabilization characteristics and dynamic operating behavior of the proposed wind energy conversion system in the MATLAB/Simulink environment.

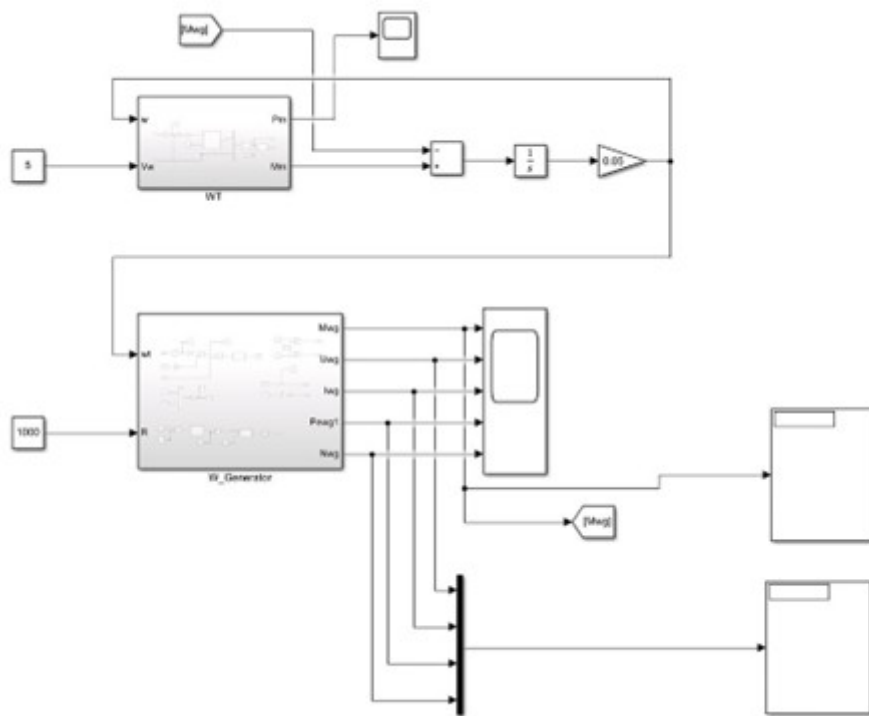
## 4. MATLAB/SIMULINK MODELING AND DYNAMIC ANALYSIS

### 4.1. MATLAB/Simulink Model of the Proposed Wind Energy Conversion System

The developed wind energy conversion system was implemented in the MATLAB/Simulink environment using a subsystem-based modeling approach for investigation of aerodynamic and electromechanical operating processes in a small-scale wind energy conversion system [21]. The proposed simulation model includes interconnected subsystems representing the wind turbine, aerodynamic conversion process, and synchronous generator operating subsystem.

Figure 2 presents the general MATLAB/Simulink structure of the proposed wind energy conversion system. The developed model consists of aerodynamic and electrical subsystems interconnected through the electromechanical energy conversion process. Mechanical power generated by the wind turbine subsystem is transferred to the synchronous generator subsystem, where electrical energy conversion and operating parameter calculations are performed. The developed model structure enables investigation of voltage characteristics, generated power, rotational speed behavior, and dynamic operating response of the system under variable wind conditions.

The wind turbine aerodynamic subsystem shown in Figure 3. performs calculation of the main aerodynamic operating parameters of the wind energy conversion system. The subsystem determines the mechanical power and mechanical torque generated by the wind turbine according to wind speed, turbine rotational speed, and aerodynamic operating conditions. The developed subsystem structure enables investigation of transient aerodynamic operating behavior under changing wind conditions and variable turbine operating modes.



**Figure 2** – General MATLAB/Simulink model of the proposed wind energy conversion system

The aerodynamic efficiency of the wind turbine is determined according to the aerodynamic power coefficient  $C_p(\lambda, \beta)$ , which depends on the tip-speed ratio  $\lambda$  and blade pitch angle  $\beta$ . The corresponding aerodynamic power coefficient subsystem is discussed in subsection 4.2.

The electrical energy conversion process is performed by the synchronous generator subsystem, which calculates the main electrical operating parameters of the generating system. The corresponding synchronous generator subsystem model and dynamic electrical operating characteristics are discussed in subsection 4.3.

The developed MATLAB/Simulink model provides an integrated simulation platform for further investigation of dynamic operating characteristics and voltage stabilization processes in the proposed wind energy conversion system. The subsystem-based structure of the model also enables implementation and investigation of excitation-current-based control approaches under variable wind operating conditions [22].

#### 4.2. Simulation Parameters and Operating Conditions

The simulation studies of the proposed wind energy conversion system were performed in the MATLAB/Simulink environment under variable aerodynamic and electromechanical operating conditions in order to investigate the dynamic operating behavior of the generating system [23]. Particular attention was given to investigation of voltage characteristics, generated electrical power, and rotational speed response under changing wind operating modes.

The aerodynamic operating characteristics of the wind turbine were determined according to the aerodynamic power coefficient  $C_p(\lambda, \beta)$ , which depends on the tip-speed ratio  $\lambda$  and blade pitch angle  $\beta$ . Figure 4 presents the developed aerodynamic power coefficient subsystem implemented in the MATLAB/Simulink environment. The subsystem performs nonlinear calculation of aerodynamic operating efficiency according to changing turbine operating conditions and wind speed variations.

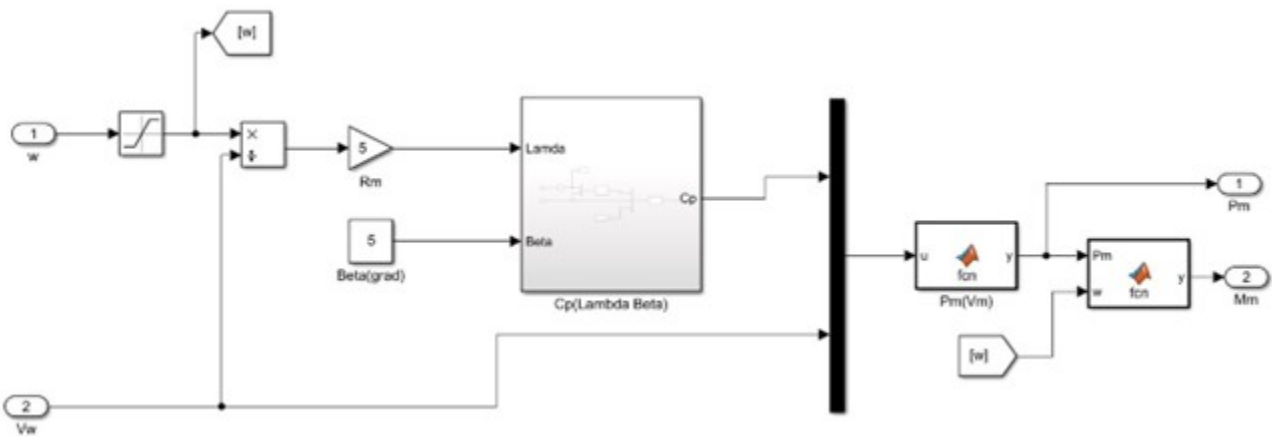


Figure 3 – Wind turbine aerodynamic subsystem model

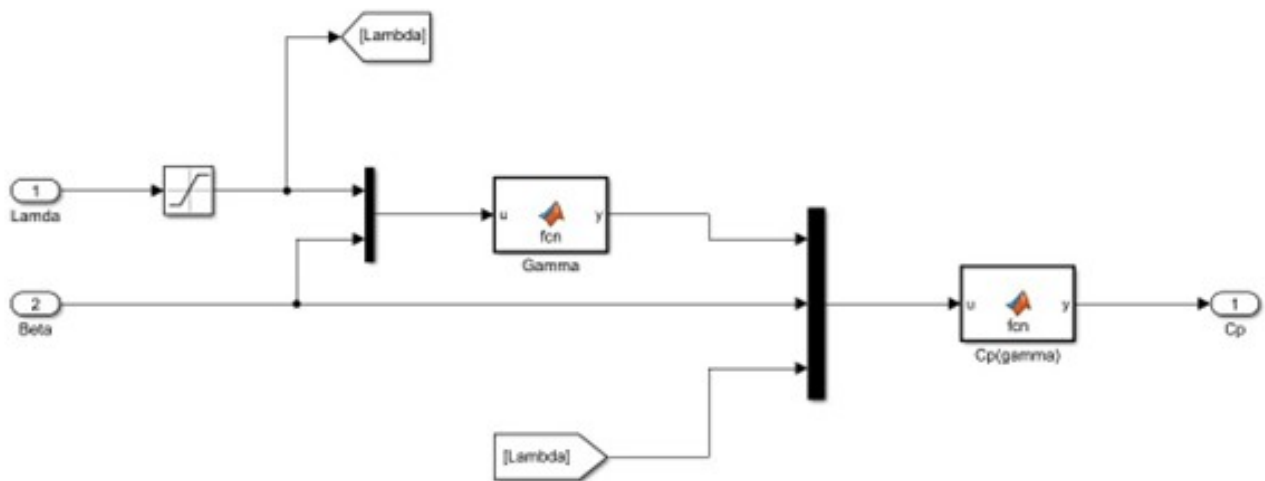


Figure 4 – Aerodynamic power coefficient subsystem  $C_p(\lambda, \beta)$

The aerodynamic power extracted from the wind flow was determined according to the wind turbine power relationship presented in 1, where the aerodynamic power coefficient depends on the tip-speed ratio and blade pitch angle [23].

During the simulation process, variable wind speed conditions were applied in order to investigate transient operating characteristics of the wind energy conversion system under changing aerodynamic operating modes. The blade pitch angle  $\beta$  was considered constant during the simulation studies, while the tip-speed ratio  $\lambda$  varied according to turbine rotational speed and wind velocity changes.

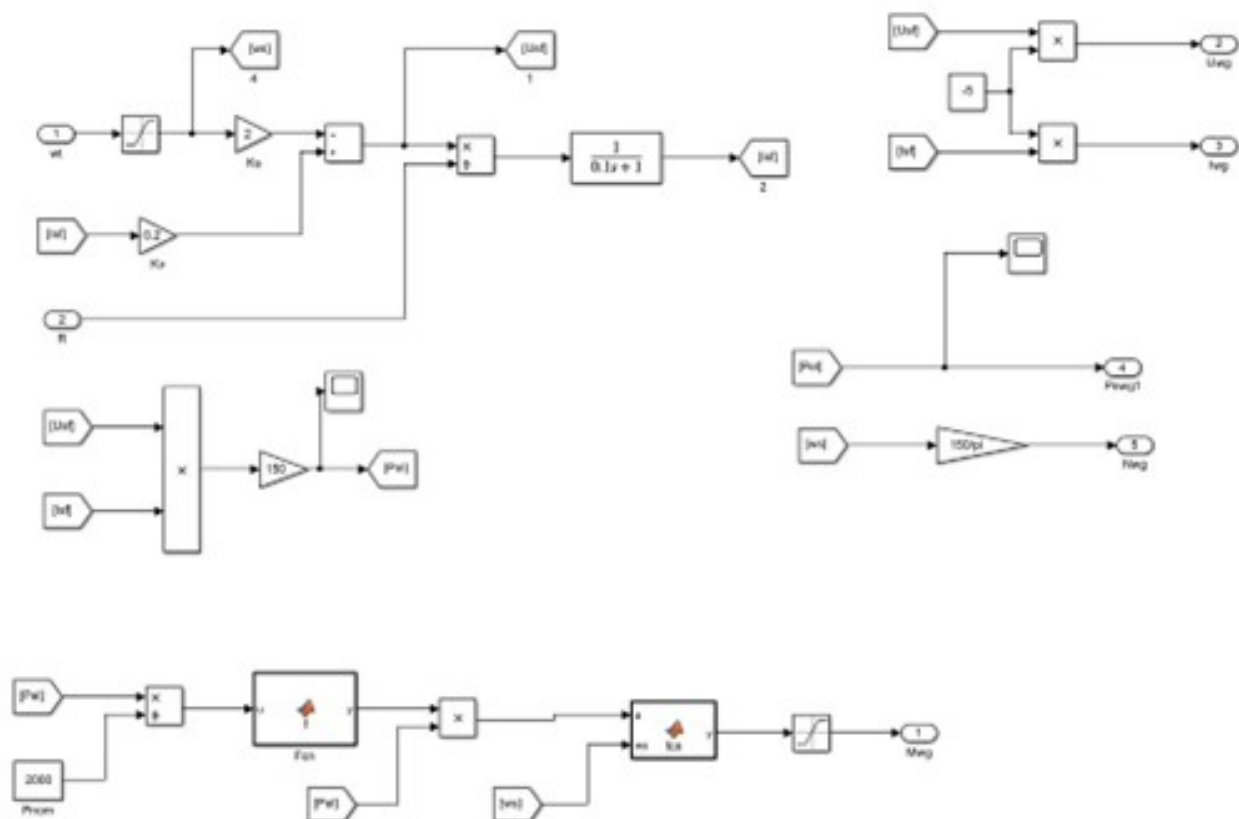
The developed simulation model also included operating parameters associated with the synchronous generator, including generated voltage, electrical power, and rotational speed characteristics. The simulation conditions enabled investigation of the interaction between aerodynamic operating processes and electrical energy conversion under transient wind disturbances.

The MATLAB/Simulink simulation environment provided the possibility for dynamic investigation of operating stability and voltage stabilization characteristics of the proposed wind energy conversion system under variable wind conditions.

### 4.3. Dynamic Operating Characteristics of the Proposed WECS

The dynamic operating characteristics of the proposed wind energy conversion system were investigated using the developed MATLAB/Simulink model under variable wind operating conditions. Particular attention was given to the analysis of transient voltage response, electromechanical operating stability, and the influence of excitation-current regulation on the dynamic behavior of the synchronous generator subsystem [24].

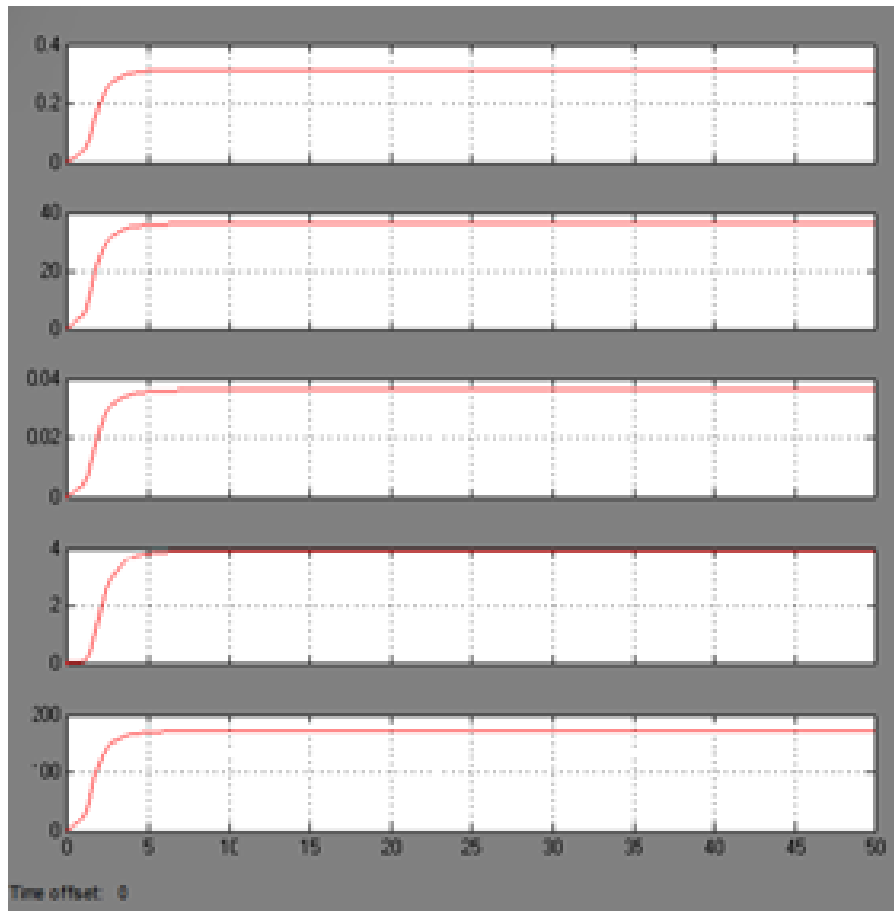
Figure 5. presents the developed synchronous generator subsystem implemented in the MATLAB/Simulink environment. The subsystem performs calculation of generated voltage, electrical power, generated current, and rotor rotational speed during transient operating conditions. The developed model structure enables investigation of the electromechanical interaction between aerodynamic power variation and electrical energy conversion processes in the generating system.



**Figure 5** – Synchronous generator electrical subsystem model

Under variable wind speed conditions, fluctuations of aerodynamic input power produce corresponding variations in turbine mechanical torque and rotor rotational speed. These disturbances directly affect the electromagnetic operating state of the synchronous generator and may lead to transient voltage deviations and oscillatory operating behavior during rapidly changing wind conditions. The transient voltage response of the proposed wind energy conversion system obtained during simulation studies is presented in Figure 6. The simulation results demonstrate the dynamic voltage stabilization characteristics of the synchronous generator subsystem under changing wind operating conditions.

Figure 6. shows that transient changes in aerodynamic input power produce corresponding voltage deviations and oscillatory electromechanical response of the generating system. During rapidly



**Figure 6** – Generator terminal voltage response under transient wind operating conditions

changing wind operating modes, imbalance between turbine mechanical power and generator electromagnetic operating conditions causes temporary voltage instability and dynamic disturbances in the synchronous generator subsystem.

The obtained simulation results demonstrated that excitation-current regulation improves voltage stabilization performance and enhances the transient operating response of the generating system. Continuous adjustment of excitation current enabled dynamic compensation of voltage deviations caused by variations in turbine rotational speed and aerodynamic power fluctuations. As a result, the proposed excitation control structure reduced transient voltage oscillations and improved damping characteristics during electromechanical disturbances.

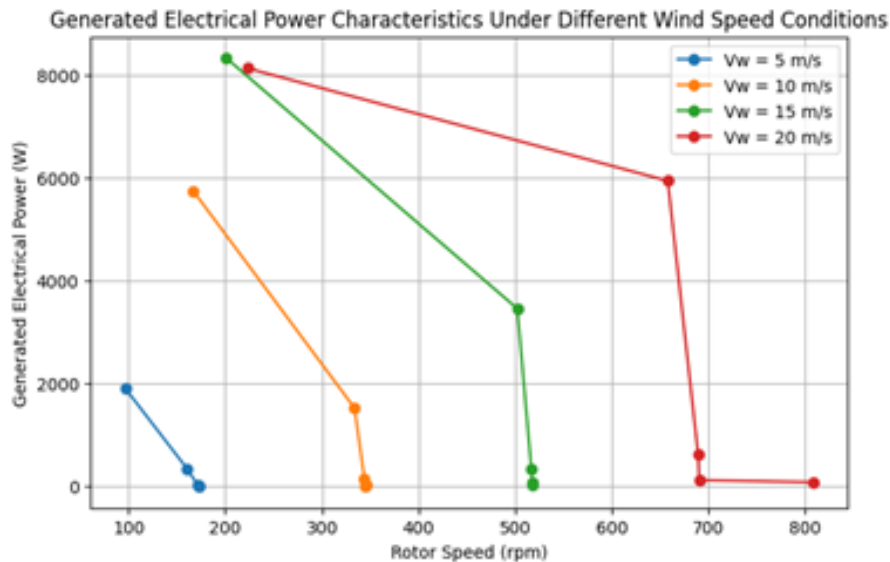
The performed simulation analysis confirmed that excitation-current-based regulation improves adaptation of the synchronous generator to variable mechanical operating conditions and enhances operating stability under stochastic wind disturbances. The developed MATLAB/Simulink model can therefore be effectively used for investigation of transient electromechanical processes and dynamic voltage stabilization characteristics in small-scale wind energy conversion systems.

#### **4.4. Analysis of Voltage Stabilization Performance**

Analysis of the simulation results demonstrated that the operating characteristics of the proposed wind energy conversion system strongly depend on the interaction between aerodynamic operating conditions and synchronous generator electromechanical response. Variations in wind speed directly influence turbine rotational speed, generated electrical power, excitation current, and voltage stabi-

lization characteristics of the generating system.

The generated power characteristics of the proposed wind energy conversion system under different wind speed conditions are presented in Figure 7. The obtained simulation results demonstrate the nonlinear relationship between turbine rotational speed and generated electrical power under changing aerodynamic operating modes.



**Figure 7** – Generated electrical power characteristics under different wind speed conditions

As shown in Figure 7, increasing wind speed significantly affects the generated electrical power and operating range of the wind energy conversion system. Under higher wind speed conditions, the turbine produces increased mechanical power, resulting in higher generator rotational speed and increased electrical power generation. The obtained characteristics also demonstrate the strong dependence of generated electrical power on aerodynamic operating conditions and turbine rotational speed variation.

The main simulation results of the proposed wind energy conversion system obtained under different wind speed and loading conditions are presented in Table 1.

The obtained simulation data demonstrate that variations in wind speed and electrical loading conditions significantly influence generator voltage, excitation current, generated electrical power, and rotor rotational speed characteristics. Under increased wind speed conditions, the generated electrical power and generator voltage increase due to higher aerodynamic input power transmitted to the synchronous generator subsystem.

The performed simulation analysis also showed that electrical loading conditions strongly affect the electromechanical operating characteristics of the generating system. Under reduced load resistance conditions, the generated electrical power increases while rotor rotational speed decreases due to increased electromagnetic loading of the synchronous generator. At the same time, excitation-current regulation improves stabilization of generator operating parameters and reduces the influence of transient aerodynamic disturbances on voltage response characteristics.

The obtained results confirm that excitation-current-based regulation represents an effective approach for improving voltage stabilization performance and operating efficiency of small-scale wind energy conversion systems under variable wind operating conditions. The developed MATLAB/Simulink model can therefore be effectively used for further investigation of advanced excitation control approaches and adaptive operating strategies for distributed renewable energy systems.

**Table 1.** Simulation results under different wind speed conditions

<b>R</b>	$U_{sf}$	$I_{sf}$	$P_{el}$	$n_{wt}$
<b><math>V_w, 5 \text{ m/s}</math></b>				
1000	36,19	0,03618	3,94	172,6
500	35,98	0,07196	7,727	172,4
100	35,94	0,3594	38,74	171,2
10	34,56	3,563	351,9	160,3
1	24,25	24,25	1907	96,46
<b><math>V_w, 10 \text{ m/s}</math></b>				
1000	72,34	0,07234	15,69	345,3
500	72,31	0,1446	31,37	346,1
100	72,16	0,7217	156,3	344
10	71,28	7,128	1526	333,8
1	43,83	43,83	5735	167,1
<b><math>V_w, 15 \text{ m/s}</math></b>				
1000	108,5	0,1085	35,32	518
500	108,5	0,2169	70,6	517,8
100	108,4	1,084	352,8	516,8
10	107,4	10,73	3457	502,3
1	52,66	52,66	8319	201,2
<b><math>V_w, 20 \text{ m/s}</math></b>				
1000	169,5	0,1693	86,07	809
500	169,1	0,2893	125,6	690,6
100	144,7	1,447	628,2	689,5
10	140,6	14,07	5937	658,1
1	58,38	58,37	8124	223

## 5. CONCLUSION

This paper presented the development and investigation of an excitation-current-based control approach for improving voltage stabilization and operating performance of a small-scale wind energy conversion system operating under variable wind speed conditions. The proposed system was developed using a synchronous generator with regulated excitation integrated into a MATLAB/Simulink-based electromechanical simulation model intended for investigation of transient aerodynamic and electrical operating processes.

A subsystem-oriented mathematical and simulation model of the wind energy conversion system was developed, including aerodynamic power conversion, synchronous generator dynamics, excitation regulation, and electrical loading processes. The developed model enabled investigation of the interaction between aerodynamic disturbances, turbine mechanical operating conditions, and synchronous generator electromechanical response under variable wind operating modes.

The performed simulation studies demonstrated that variations in wind speed significantly affect generator terminal voltage, excitation current, generated electrical power, and rotor rotational speed characteristics. Under transient operating conditions, imbalance between aerodynamic input power and generator electromagnetic response causes voltage deviations and oscillatory electromechanical behavior, negatively influencing operating stability and energy conversion performance of the generating system.

To improve operating stability under such conditions, a PI/PID-based excitation-current control

algorithm was implemented for continuous regulation of the synchronous generator magnetic field according to generator terminal voltage deviations. The obtained simulation results confirmed that excitation-current regulation improves voltage stabilization characteristics, reduces transient voltage oscillations, and enhances damping performance of the generating system during rapidly changing wind operating modes.

The developed excitation-based regulation approach also improved adaptation of the synchronous generator to variable mechanical loading conditions and reduced the influence of aerodynamic disturbances on electromechanical operating behavior. In comparison with more complicated converter-based regulation structures, the proposed approach provides comparatively low control complexity while maintaining effective voltage stabilization performance in small-scale wind energy conversion systems.

The obtained results confirm that excitation-current-based regulation represents an effective and practically applicable approach for improving operating stability and energy conversion efficiency of distributed renewable energy systems operating under stochastic wind conditions. The developed MATLAB/Simulink model can be further used for investigation of adaptive, intelligent, and hybrid excitation control methods intended for improvement of transient response characteristics, voltage quality, and operating efficiency of autonomous wind energy conversion systems.

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