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Original scientific paper

Numerically Enhanced Perturb-and-Observe Approach for Power Optimization in Wind Energy Systems

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Abstract: Modern power systems are facing increasing demands for decarbonization and a higher share of renewable energy sources, with wind energy systems playing an important role. However, the variable nature of wind complicates the stable and efficient operation of these systems, making the application of effective Maximum Power Point Tracking (MPPT) algorithms essential. Among the most commonly used methods is the Perturb and Observe (P&O) algorithm, characterized by its simplicity but limited by oscillations around the maximum power point and reduced efficiency under rapid wind speed variations. In this paper, a numerically enhanced P&O strategy with a variable perturbation step size based on different numerical approximations of the power–voltage (*P-V*) curve is proposed. The algorithm is applied to a wind energy conversion system with a Permanent Magnet Synchronous Generator (PMSG) and tested in the MATLAB/Simulink environment under various operating conditions. Simulation results demonstrate that the proposed approach provides faster dynamic response and higher generated energy values compared to the conventional P&O algorithm.

Keywords: MPPT, Wind energy system, P&O algorithm, Numerical approximation, PMSG, MATLAB/Simulink.

1 Introduction

The energy sector is facing increasing demands for carbon emissions reduction and an accelerated energy transition, which has led to the rapid development of renewable energy sources [1]. In this context, wind energy is of particular importance due to its technological maturity, high energy potential, low

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operating costs, and the absence of emissions during operation, which is driving its growing share in modern power systems [2, 3]. However, the integration of wind energy systems is complicated by the variable and difficult-to-predict nature of wind, which creates challenges regarding the stability and efficiency of power system operation [4, 5]. A wind energy conversion system is shown in Fig. 1. The system consists of a wind turbine coupled to a permanent magnet synchronous generator (PMSG), which converts the mechanical energy of the wind into electrical energy. The generated electrical power is then processed through a diode rectifier and a DC-DC boost converter to obtain the desired DC voltage level. Furthermore, a maximum power point tracking (MPPT) control strategy is implemented to regulate the converter operation and ensure optimal extraction of available wind energy under varying wind speed conditions.

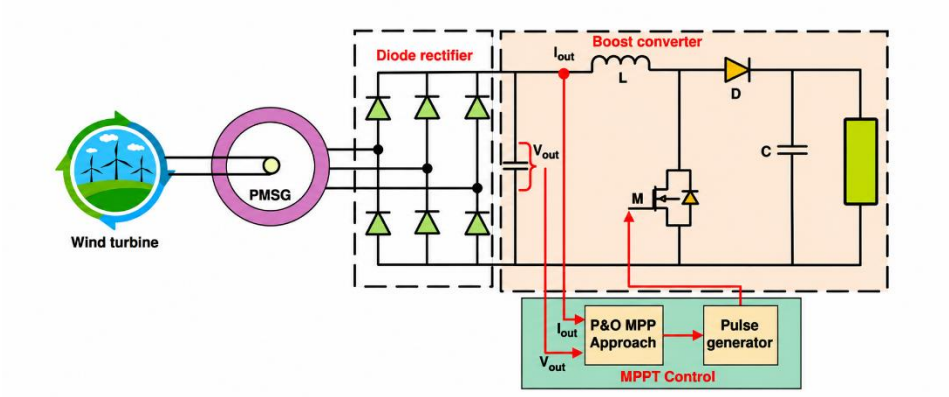


Fig. 1 – *Block diagram of a PMSG-based wind energy conversion system with a diode rectifier and DC–DC boost converter, controlled by a P&O MPPT algorithm.*

Wind turbines convert wind energy into the mechanical energy of the rotor through aerodynamic processes. The obtained mechanical energy is then converted into electrical energy by means of a generator [6]. In modern Wind Energy Conversion Systems (WECS), the most commonly used generators are Doubly Fed Induction Generators (DFIG) and Permanent Magnet Synchronous Generators (PMSG) [7]. The PMSG enables direct-drive operation without the use of a gearbox, thereby eliminating the need for gears, reducing maintenance costs, and increasing the overall reliability of the system [8]. In order to adapt the generated electrical energy to the requirements of the power grid, the application of power converter circuits is necessary. Their role is to perform electrical energy conversion, most commonly AC–DC and DC–AC conversion, regulate voltage and current, and ensure stable and efficient operation of the entire system [9].

MPPT algorithms are applied for the control of power converter circuits in wind energy systems, with the primary objective of optimizing the energy

conversion process and maximizing the utilization of available wind energy under variable operating conditions [10]. An MPPT algorithm represents a control strategy in which the operating point of the system is continuously adjusted in order to maintain operation near the maximum power point under different wind speed conditions. Depending on the control principle and the type of feedback used, MPPT methods are commonly classified into indirect (IPC), direct (DPC), hybrid, and intelligent algorithms [11]. This classification is shown in Fig. 2.

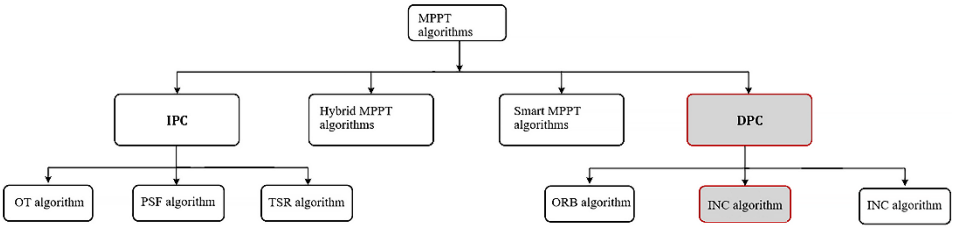


Fig. 2 – *Classification of MPPT algorithms.*

IPC methods use previously known turbine and system characteristics to determine the optimal operating point (e.g., Optimal Torque – OT, Power Signal Feedback – PSF, and Tip Speed Ratio – TSR methods), where wind speed and rotor speed measurement or estimation is often required; therefore, these methods are applied when such variables are reliably available. DPC methods rely on feedback from electrical quantities (voltage, current, and power) and dynamically adjust the operating point without detailed knowledge of turbine characteristics, enabling simpler implementation and faster response to wind variations. This group includes the P&O algorithm, Incremental Conductance (INC), and Optimal Relation-Based (ORB) methods. Hybrid algorithms combine IPC and DPC approaches in order to achieve a compromise between stability and tracking speed while reducing oscillations under dynamic operating conditions. Intelligent algorithms (fuzzy logic, neural networks, and adaptive methods) utilize learning and adaptation capabilities, making them particularly suitable for nonlinear and variable operating conditions of WECSs.

Among DPC methods, the P&O algorithm is the most widely used due to its simplicity and low dependence on system parameters. The conventional P&O algorithm is often highlighted as a practical solution that significantly alleviates the drawbacks of many MPPT methods, since it is simple and does not require wind speed measurement; however, it may exhibit limited tracking accuracy and pronounced oscillations around the MPP. Its adaptive and modified variants aim to improve the stability and reliability of tracking through dynamic adjustment of the perturbation step size and direction, particularly during sudden wind speed

variations, at the cost of increased complexity and, in some cases, slower convergence.

In paper [12], an analysis of different MPPT methods from the aforementioned four groups was conducted, with particular emphasis on comparing their complexity, convergence speed, and performance under variable wind speed conditions. Various approaches have been proposed in the literature [13], including perturbation step adaptation based on the (k_{opt}) constant, sector-based division of the operating characteristic for perturbation determination [14], inclusion of DC current information to reduce oscillations and drift [15], as well as the generation of a reference maximum power curve for more reliable determination of the optimal perturbation step [16]. A particularly important research direction is the integration of the P&O method with numerical techniques, such as the trapezoidal integration rule, which further reduces oscillations and improves the stability of MPP tracking [17].

The approach proposed in this paper is based on enhancing the conventional P&O algorithm by introducing a numerical estimation of power variation along the *P-V* characteristic, in order to ensure more reliable maximum power point tracking under wind speed fluctuations in a wind energy system. In addition to the trapezoidal rule, rectangular approximation methods (left- and right-hand rules), as well as Simpson's 3/8 rule, were also investigated, where the results of these numerical integration methods are used as additional information in the decision-making process. Furthermore, a variable perturbation step strategy was introduced, enabling faster transient response and reduced oscillations in the vicinity of the MPP.

This paper is organized as follows. Following the introduction, Section 2 is devoted to the proposed system configuration and includes a detailed explanation of the wind energy conversion system model, along with the corresponding mathematical equations, block diagrams, and implementation procedure in the MATLAB/Simulink environment, thereby ensuring the reproducibility of the obtained results. Section 3 provides a detailed description of the proposed MPPT algorithm and its operating principle. Section 4 presents the simulation scenarios and the obtained results. The analysis and discussion of the results are presented in Section 5, while Section 6 provides the conclusions and summarizes the main contributions of the paper.

2 Proposed System Configuration

The complete wind energy conversion system was modeled in the MATLAB/Simulink environment, including aerodynamic, mechanical, and electrical subsystems. The performance evaluation of the proposed algorithm was conducted on a wind turbine model equipped with a PMSG and its corresponding

power converter circuits, in which the MPPT algorithm controls the boost converter to enable maximum power point tracking.

2.1 Turbine and PMSG

Wind turbines are devices that convert the kinetic energy of wind into mechanical energy, which is then converted into electrical energy through a generator. In the considered wind energy conversion system, a Permanent Magnet Synchronous Generator (PMSG) is used as the generator. Equations (1) – (3) represent the mathematical model of the turbine.

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

where P_t is the mechanical power extracted from the wind, $C_p(\lambda,\beta)$ is the power coefficient, ρ is the air density, A is the swept area of the wind turbine rotor, and ν is the wind speed. The parameter λ represents the tip-speed ratio, while β denotes the blade pitch angle.

$$c_p(\lambda,\beta) = c_1\left(c_2\frac{1}{\lambda_i} - c_3\beta - c_4\beta^x - c_5\right)e^{-c_6\frac{1}{\lambda_i}}, \tag{2}$$

where $c_1 - c_6$ are empirical coefficients of the wind turbine power coefficient model, and x is an empirical exponent. The values of these coefficients depend on the characteristics of the considered wind turbine.

$$T_m = \frac{P_m}{\omega_m}, \tag{3}$$

where T_m is the mechanical torque applied to the generator shaft, P_m is the mechanical power supplied by the wind turbine to the generator, and ω_m is the mechanical angular velocity of the generator rotor.

The electrical dynamics of the Permanent Magnet Synchronous Generator (PMSG) are described in the rotor reference frame (dq frame), with all quantities referred to the stator. The mathematical model is expressed by (4) – (6).

$$\frac{\mathrm{d}}{\mathrm{d}t}i_d = \frac{1}{L_d}V_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}p\omega_m i_q \tag{4}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}i_q = \frac{1}{L_q}V_q - \frac{R}{L_q}i_q - \frac{L_d}{L_q}p\omega_m i_d - \frac{\psi_f p\omega_m}{L_q}, \tag{5}$$

$$T_e = 1.5p\left[\psi_f i_q + (L_d - L_q)i_d i_q\right], \tag{6}$$

where L_q and L_d are the q-axis and d-axis inductances, respectively, R is the stator winding resistance, i_q and i_d are the q-axis and d-axis current components, V_q and

V_d are the q-axis and d-axis voltage components, ω_m is the angular velocity of the rotor, ψ_f is the amplitude of the magnetic flux induced by the rotor permanent magnets in the stator phases, p is the number of pole pairs, and T_e is the electromagnetic torque.

For the purpose of wind turbine simulation, the Wind Turbine block from the Simulink environment was used. The parameters of the applied model are presented in **Table 1.**

Table 1
The parameters of the applied model.

Parameter	Value
Nominal mechanical output power (W)	3×10^3
Base wind speed (m/s)	12
Maximum power at base wind speed (p.u.)	0.73
Base rotational speed (p.u.)	1.2
Pitch angle β (deg)	0

For PMSG modeling, a permanent magnet machine capable of operating in both motor and generator modes was used, where the operating mode depends on the sign of the applied mechanical torque. A positive torque indicates motor operation, while a negative torque indicates generator operation. The parameters of the three-phase machine model are given in **Table 2**, while Fig. 3 shows the PMSG model in Simulink.

Table 2
Parameters of the Three-Phase PMSG Machine Used in the Simulation.

Parameter	Value
Stator phase resistance (R_s)	0.0485 Ω
Inductances [L_d, L_q]	L_d = 0.0003752 H, L_q = 0.0004148 H
Flux linkage	0.1194 Vs
Inertia	0.0027 kgm^2
Viscous damping	0.0004924 N m s
Pole pairs	4
Initial conditions [ω_m , θ, i_a, i_b]	0.0 rad/s, 0.0 deg, 0.0 A, 0.0 A
Rotor flux position (θ = 0)	90º
Number of phases	3

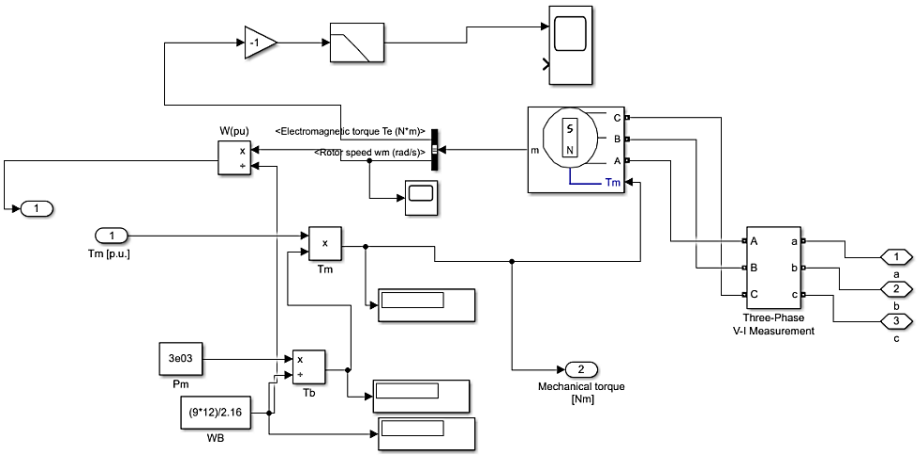


Fig. 3 – *PMSG realisation in Simulink.*

2.2 Power converters and MPPT

A model including a three-phase diode bridge rectifier and a boost chopper was developed in the MATLAB/Simulink environment. The diode Graetz rectifier was modeled using the Universal Bridge block, while the parameters used in this work are presented in **Table 3.** An RC filter is connected at the output of the diode bridge to reduce voltage ripple and improve the quality of the output signal. The parameters of the RC filter are presented in **Table 3**.

Table 3

Diode Rectifier and RC Filter Parameters.

Parameter	Value
Number of bridge arms	3
Snubber resistance R_s	1×10^5 Ω
Snubber capacitance C_s	∞
Power electronic device	Diode
RC filter resistance	0.005 Ω
RC filter capacitance	$500^2\times10^{-6}$

The MATLAB/Simulink model of the three-phase diode rectifier with the RC filter connected at its output is shown in Fig. 4.

Fig. 5 shows the power electronics components, along with the MPPT algorithm and the load. **Table 4** presents the boost converter parameter values**.**

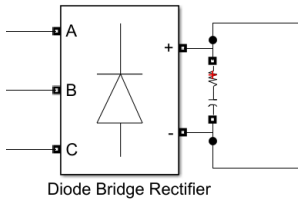


Fig. 4 – *Three-phase diode rectifier with the RC filter.*

Table 4
Parameters used in the Boost Converter Model.

Parameter	Symbol	Value
Inductance	L	8.8×10^{-5} H
Capacitance	C	3×10^{-4} F
Resistance	R	35 Ω
Voltage ripple	ΔV	0.005 V

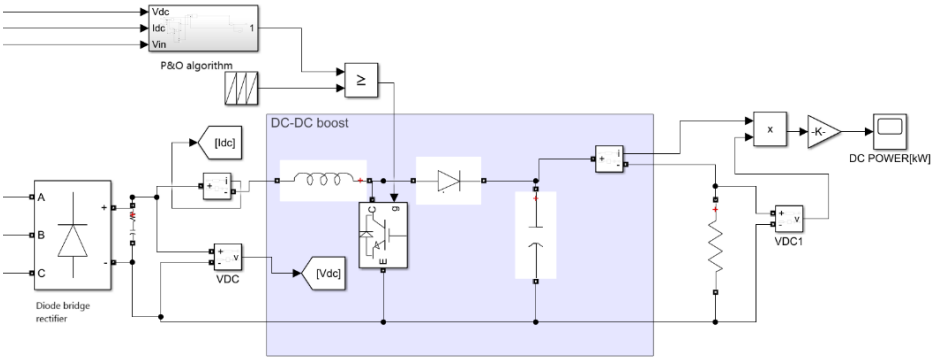


Fig. 5 – *Power electronic components and the MPPT Algorithm.*

3 Proposed Algorithm

In practice, the P&O algorithm faces a trade-off between perturbation step size and the speed–efficiency relationship, as well as possible incorrect determination of the perturbation direction caused by sudden wind speed variations. As a solution, this paper considers an approach based on numerical estimation of the power–voltage (P-V) curve using rectangular, trapezoidal, and Simpson's integration rules. The conventional P&O MPPT algorithm is shown in Fig. 6, where its basic operating principle and decision-making flow are presented.

The approach proposed in this paper is based on the numerical estimation of the power–voltage (P-V) curve using rectangular, trapezoidal, and Simpson's integration rules.

Based on these numerical methods, the area between the current and previous values of the DC power (P_{dc}) on the P-V curve is determined, allowing the calculation of the reference power and voltage values, (P_{ref}) and (V_{ref}), which represent the input parameters for the P&O algorithm and the variable perturbation step algorithm. This addition enables a more accurate estimation of output power variations and improves the overall performance of the algorithm.

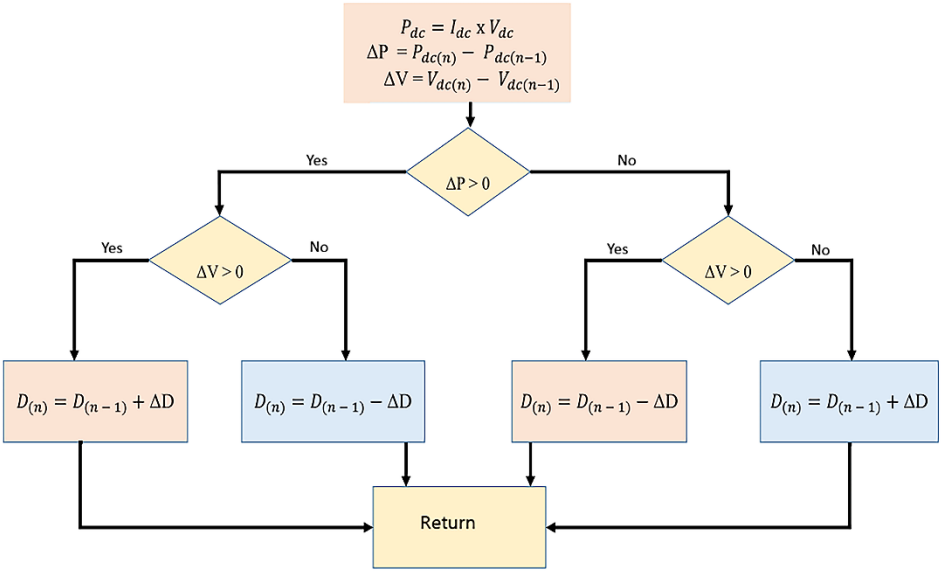


Fig. 6 – *Perturb and Observe algorithm.*

The equations used to determine the areas by applying the considered numerical integration rules are given in the corresponding section of the text, while Fig. 7 presents the concept of the proposed MPPT algorithm.

Fig. 7a illustrates the implementation of the algorithm based on the left rectangular rule, whereas Fig. 7b shows the variant of the algorithm that uses the trapezoidal integration rule.

The flowchart of the proposed algorithm is presented in Fig. 8.

Left rectangular rule

$$A = (V_{dc} - V_{dcprev})P_{prev}\,. \tag{7}$$

Right rectangular rule

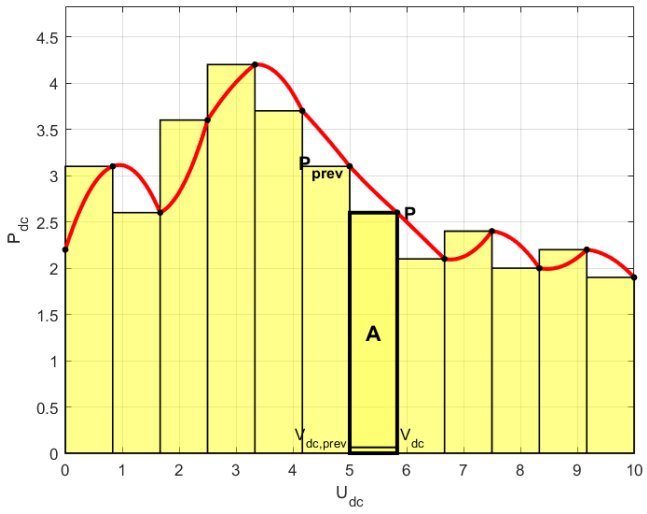
$$A = (V_{dc} - V_{dcprev})P\,. \tag{8}$$

Trapezoidal rule

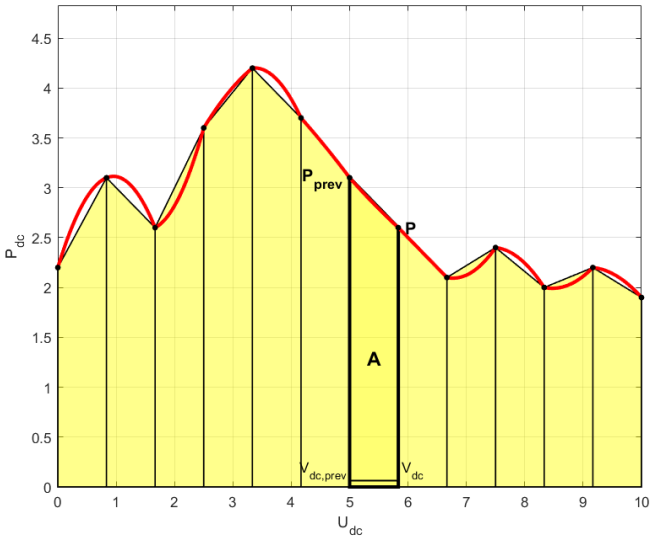
$$A = (P - P_{prev}) \frac{V_{dc} - V_{dcprev}}{2}. \tag{9}$$

Simpson's 3/8 rule

$$A = 1/8\,(V_{dcprev3} - V_{dc})(P_{prev3} + 3P_{prev2} + 3P_{prev} + P). \tag{10}$$



(a)



(b)

Fig. 7 – (a) *Concept of the proposed algorithm using the rectangular method;* (b) *Concept of the proposed algorithm using the trapezoidal method.*

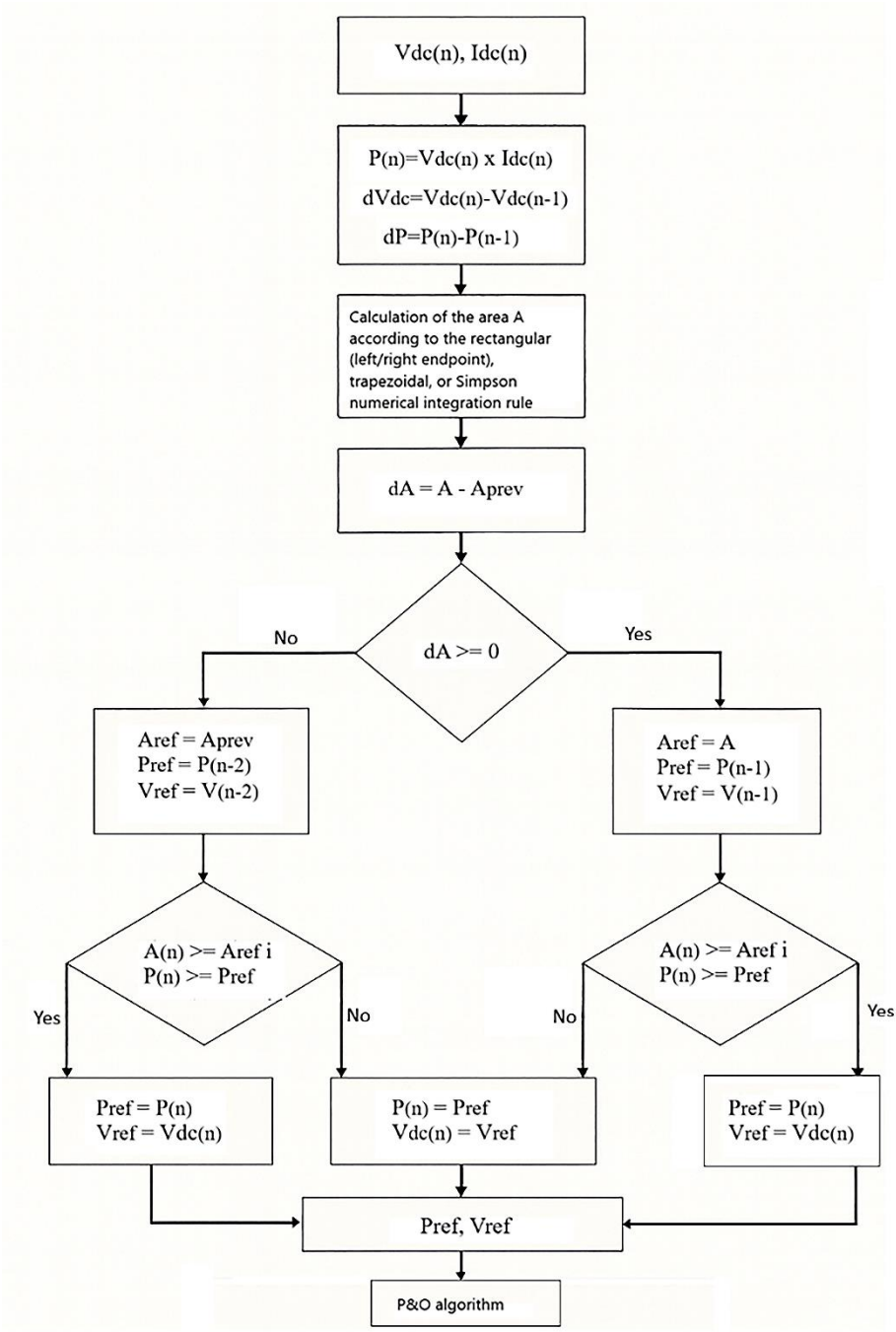


Fig. 8 – *Flowchart of the proposed Algorithm.*

3.1 Variable step size

In the conventional P&O algorithm, the perturbation step (ΔD) is fixed, which, under variable wind-speed conditions, can cause pronounced oscillations and deviations from the Maximum Power Point (MPP). In order to improve stability and performance, a variable perturbation step was introduced, which is dynamically adjusted during each iteration.

The output of the considered algorithms represents the reference power (P_{ref}), based on which the parameter (R) is defined as the ratio between the reference power (P_{ref}) and the current output power (P). The value of parameter (R) is used to adjust the perturbation step size (ΔD): a larger step is applied when the system is far from the MPP, while in the vicinity of the MPP the step size is reduced in order to limit oscillations. Appropriate threshold values of parameter (R) were determined experimentally, resulting in optimal algorithm performance, as illustrated in Fig. 9.

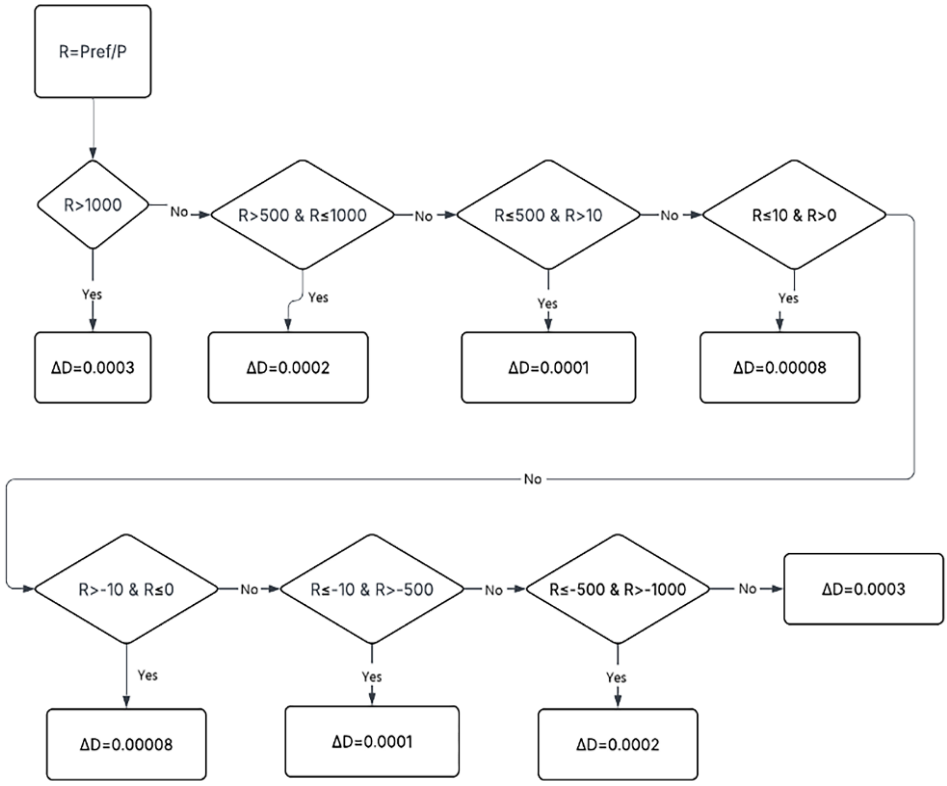


Fig. 9 – *Flowchart of the variable step size.*

4 Simulation Results

This section presents the responses of the proposed MPPT algorithms to the wind speed variations shown in Fig. 10.

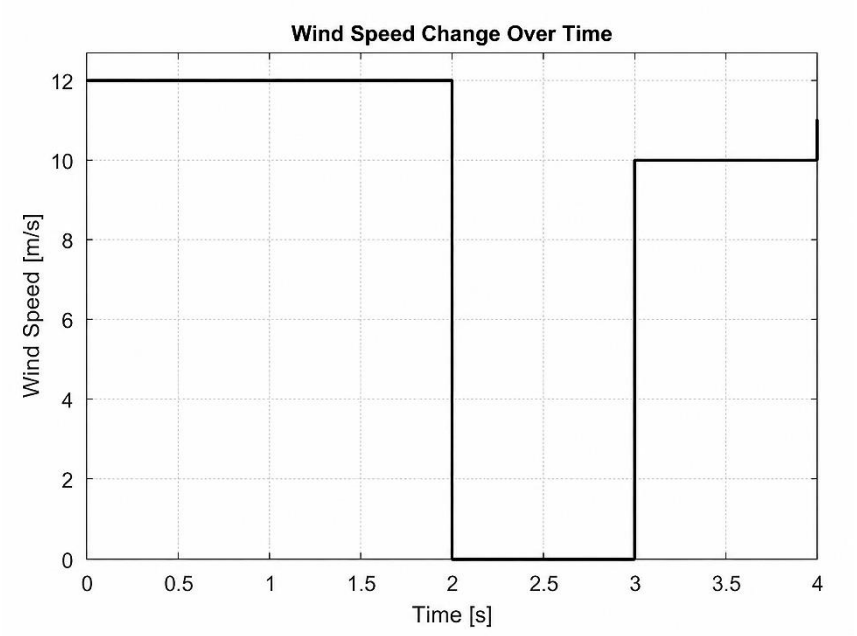
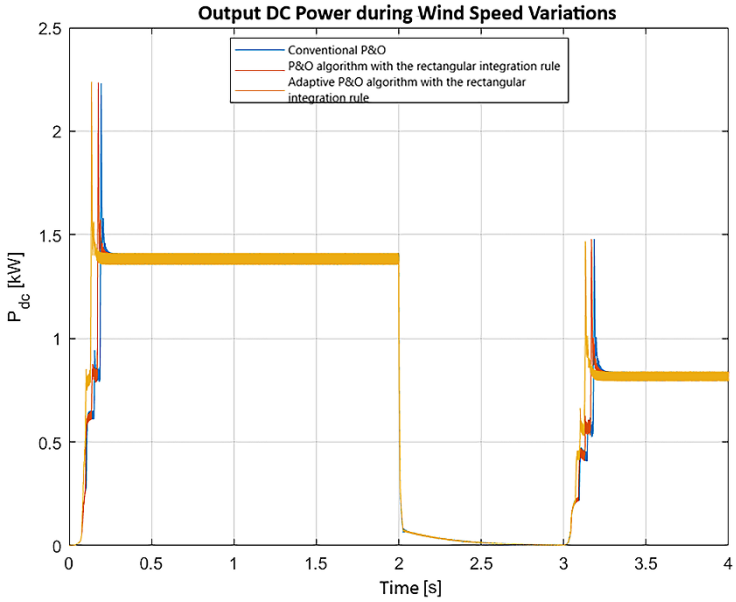


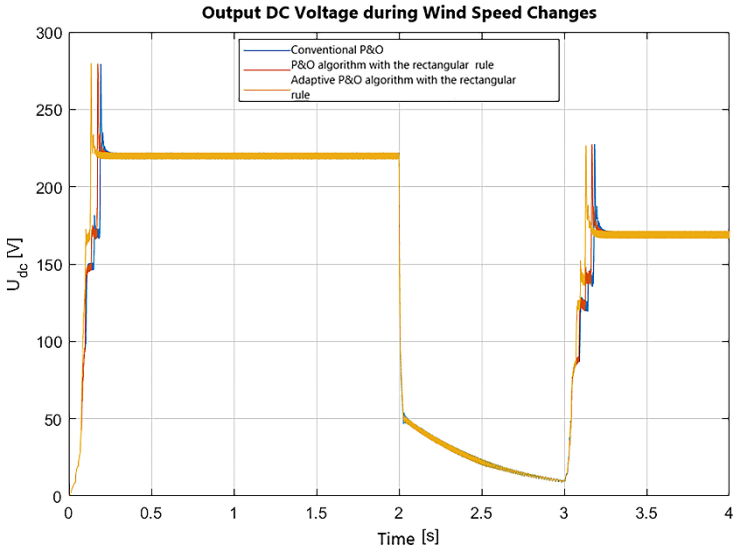
Fig. 10 – *Wind speed variations.*

Figs. 11a and 11b present the responses of the DC power (P_{dc}) and DC voltage (V_{dc}) to the wind speed variation shown in Fig. 10, where the area (A) is determined using the left rectangular rule of numerical integration with a variable perturbation step size. The responses of the algorithm in which A is calculated using the right rectangular rule of numerical integration are shown in Figs. 12a and 12b for wind speed variations. Figs. 13a and 13b present the responses of the DC quantities (P_{dc}) and (V_{dc}) obtained using the trapezoidal rule of numerical integration with an adaptive perturbation step size. Finally, the responses of the algorithm based on Simpson's 3/8 numerical integration rule are shown in Figs. 14a and 14b for wind speed variations.

Fig. 15 presents the comparative response of all considered MPPT algorithms with a variable perturbation step size, enabling the analysis of their dynamic behavior and stability under wind speed variations. Fig. 16 shows a comparative analysis between the conventional P&O algorithm and the best-performing variable-step variant based on the trapezoidal numerical integration rule.

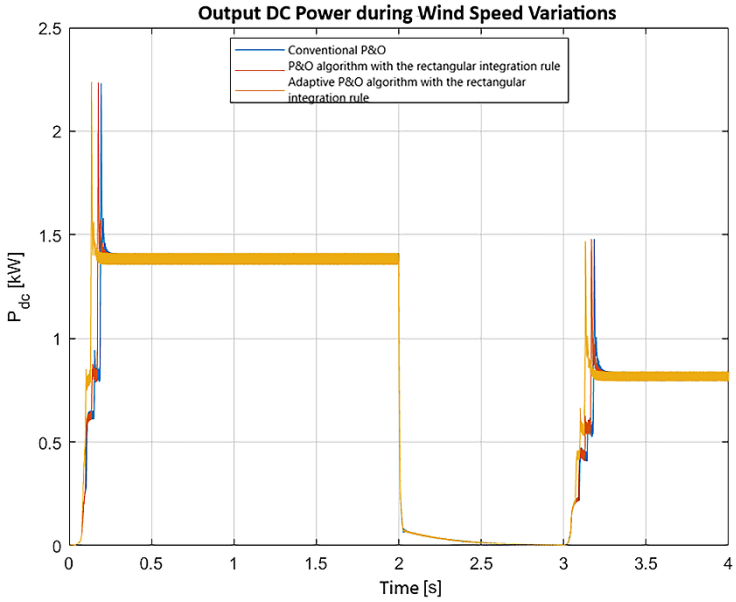


(a)

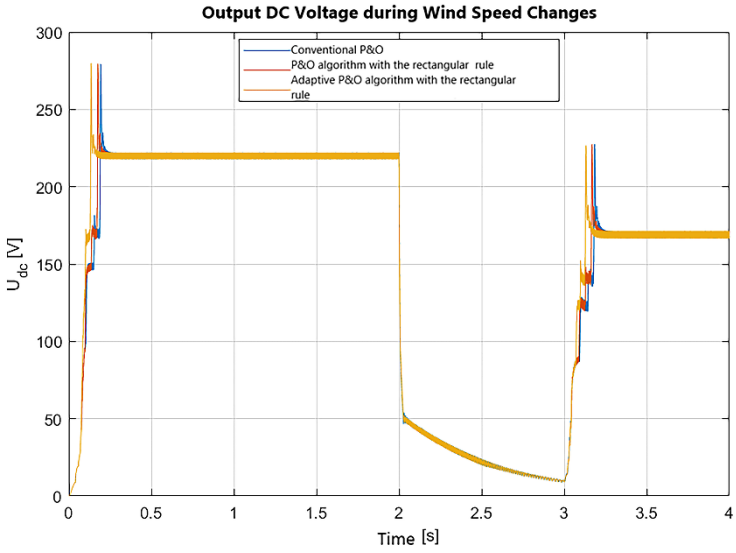


(b)

Fig. 11 – (a) *Output DC power during wind speed variations using the left rectangular rule;* (b) *Output DC voltage during wind speed changes using the left rectangular rule.*

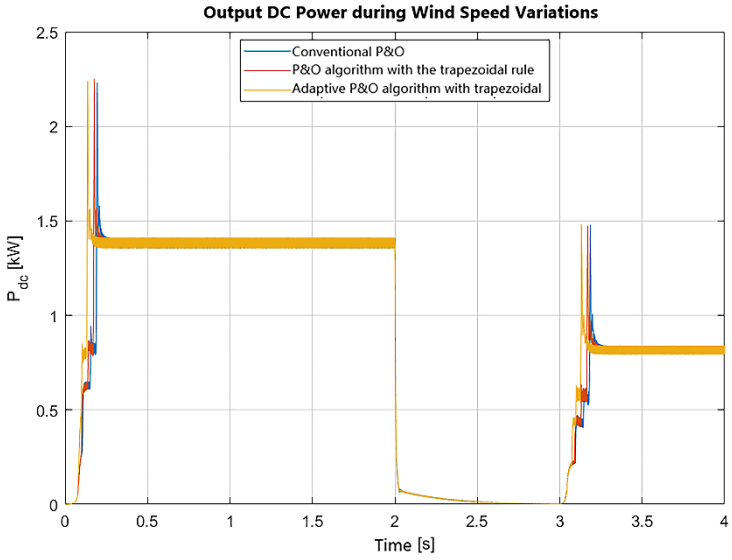


(a)

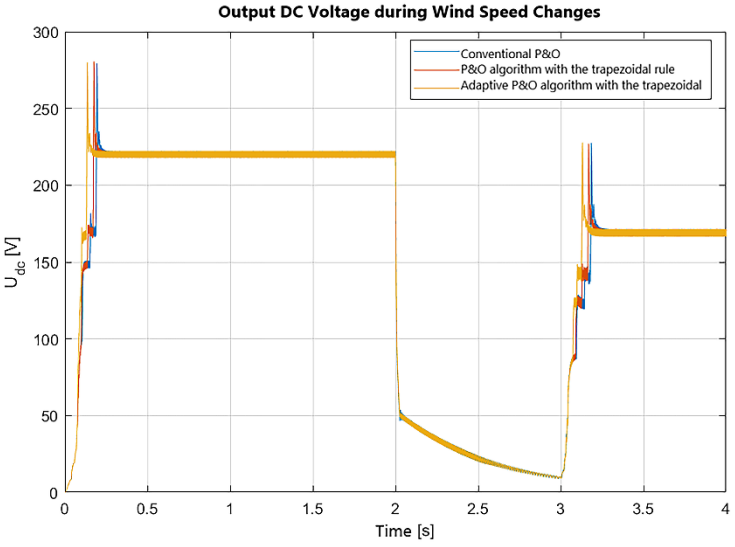


(b)

Fig. 12 – (a) *Output DC power during wind speed variations using the right rectangular rule;* (b) *Output DC voltage during wind speed changes using the right rectangular rule.*

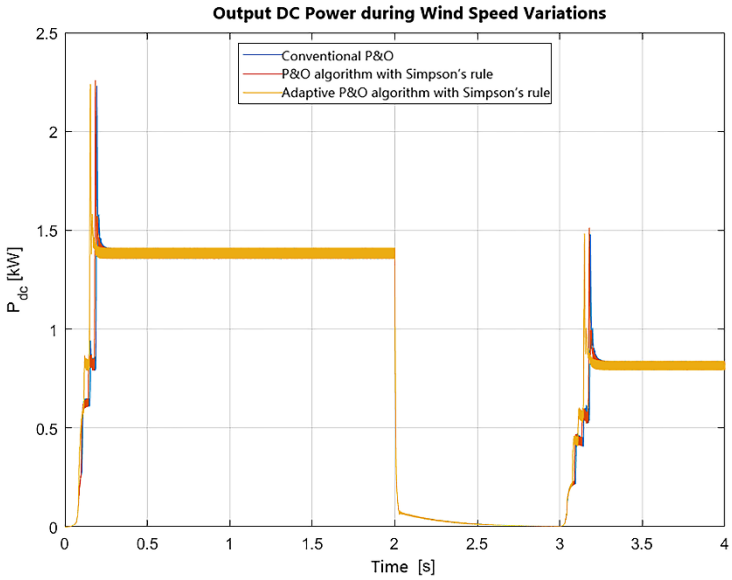


(a)

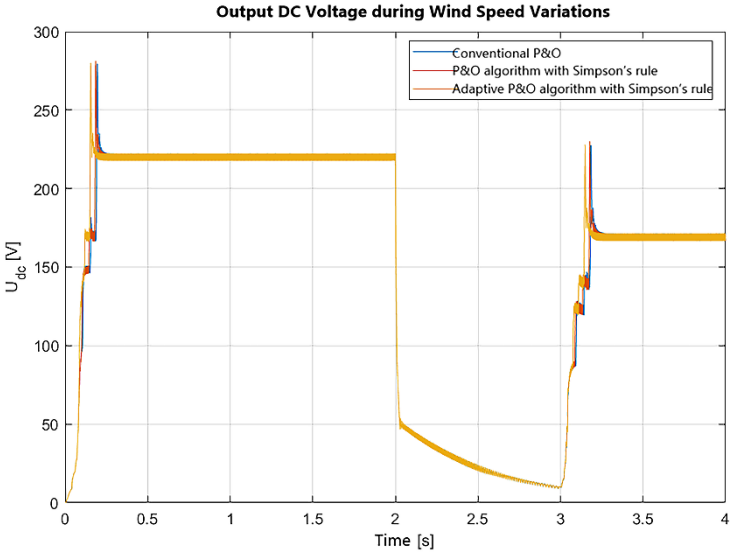


(b)

Fig. 13 – (a) *Output DC power during wind speed variations using the trapezoidal rule;* (b) *Output DC voltage during wind speed changes using the trapezoidal rule.*



(a)



(b)

Fig. 14 – (a) *Output DC power during wind speed variations using Simpson's rule;* (b) *Output DC voltage during wind speed changes using Simpson's rule.*

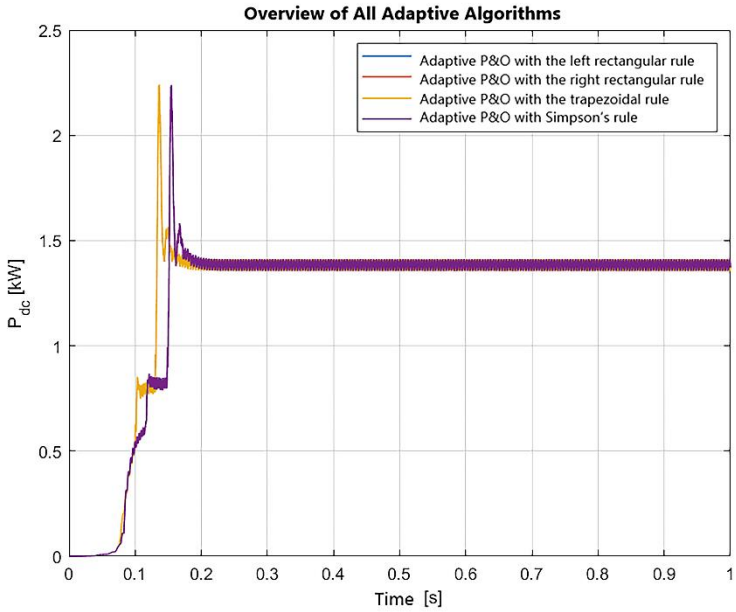


Fig. 15 – *Power response of all algorithms.*

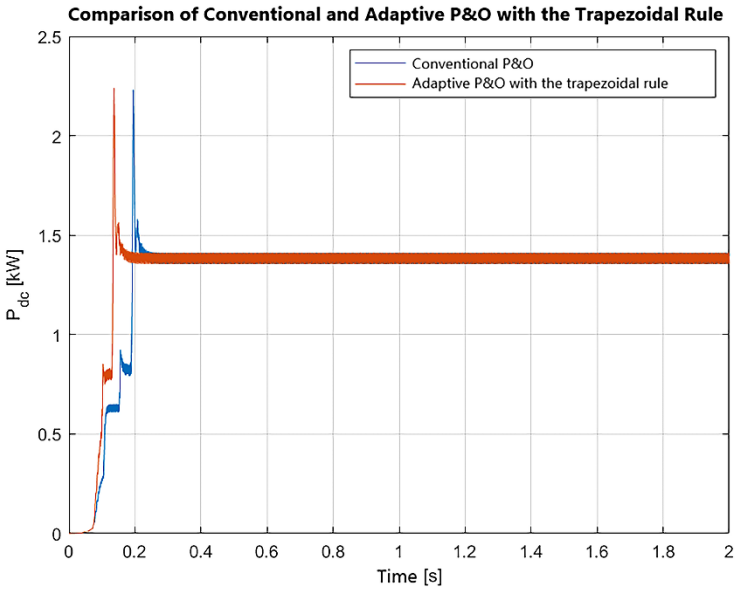


Fig. 16 – *Power response of the conventional and trapezoidal algorithms.*

5 Discussion

The simulation results clearly demonstrate that the application of numerical integration methods for estimating the *P-V* characteristic enables more stable and reliable decision-making in the MPPT algorithm compared to the conventional P&O approach. The proposed methods provide faster achievement of the steady-state operating condition. In particular, the combination of the trapezoidal integration rule and the adaptive perturbation step size exhibits the fastest transient response and the shortest settling time. Adaptive adjustment of the perturbation step size enables rapid convergence when the system is far from the MPP, resulting in higher average power values and greater total generated energy compared to the conventional P&O algorithm.

It can be observed that voltage and power do not decrease immediately after the wind speed falls below the threshold value V_{in} which is a consequence of the energy stored in the system elements, primarily the capacitors. The analysis of dynamic scenarios, including sudden wind speed variations, complete shutdown, and restoration of power generation, shows that all considered methods maintain stability; however, the proposed adaptive approach provides a more robust response and faster adaptation to varying operating conditions.

The main advantage of the proposed MPPT strategy lies in its ability to improve the energy and dynamic performance of the system without significantly increasing control complexity. The method does not require additional mechanical sensors or precise knowledge of wind turbine parameters, making it suitable for practical implementation. Furthermore, the adaptive approach effectively addresses the trade-off between tracking speed and stability, which represents a key limitation of the conventional P&O algorithm. However, certain limitations of the method are related to the need for careful selection of the threshold values of the adaptive parameter in order to ensure optimal algorithm performance under all operating conditions. It can be concluded that the numerically enhanced and adaptive P&O MPPT strategy represents an efficient and practical solution for improving the performance of wind energy systems under variable wind speed conditions.

6 Conclusion

Based on the conducted simulations, it can be concluded that numerically enhanced MPPT strategies based on integration methods (rectangular, trapezoidal, and Simpson's 3/8 rules) achieve better dynamic and energy performance compared to the conventional P&O algorithm. The introduction of an adaptive perturbation step size further improves the system response, reduces transient time, and decreases oscillations, while all considered methods maintain stability under sudden wind speed and load variations. The best overall results are achieved by the combination of the trapezoidal integration rule and the

adaptive P&O algorithm, which provides the fastest response, the highest average power and total generated energy values, as well as the shortest settling time, thereby confirming the effectiveness of the proposed approach for application in wind energy systems.

Possible directions for future work include the application of more advanced DC–DC converter topologies, such as the three-level boost converter, with the aim of further reducing voltage ripple and increasing the energy efficiency of the system. In addition, the proposed MPPT algorithm can be extended through the integration of intelligent or hybrid control strategies, which could further improve the robustness of the algorithm under conditions of significant wind speed fluctuations and noise presence. Further research may also include experimental verification on a real hardware prototype, as well as analysis of system behavior in grid-connected operation and in combination with energy storage system s.

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