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Boost efficiency performance through the enhancement of duty cycle based MPPT algorithm

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ABSTRACT

The use of direct power control (DPC) has become popular as an effective control strategy for pulse width modulated (PWM) converters. The incremental conductance algorithm (INC) is utilized to control the duty cycle (D) in tracking the optimal point to increase power efficiency in wind energy conversion systems (WECS). WECS parameters are adjusted to achieve unity power factor, allowing the system to extract maximum power (P_{max}) from WECS. Simulation results show that wind speed has a significant impact on the captured power, with a proportional relationship between wind speed and power. Control strategies are employed to optimize the (D) to reach the desired operating point. A DC-DC boost converter is connected to WECS, where the (D) controls the MOSFET to maintain V_{out} at the optimal level on the DC link. Various wind speed profiles are simulated in this study to evaluate system efficiency, especially under conditions of rapid wind speed fluctuations. The controller based on (D) demonstrates superior tracking performance through the DC link, ensuring that V_{out} remains at an optimal level.

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1. INTRODUCTION

Renewable energy sources have garnered significant attention due to insistent environmental issues, especially those related to global warming [1], [2]. Among these sources, we consider wind energy as the utmost extensive and holds immense potential [3]. Though it requires various enhancing advancements in high-tech capabilities. Thus, the maximum power point tracking (MPPT) is essential to increase the power effectiveness of the wind energy conversion system (WECS) [4]-[6].

Pulse width modulated (PWM) converters are considered one of the highest performing power conversion interfaces that have found widespread application in renewable energy systems, active power filters, and AC transmission hardware [7]-[9]. They offer advantages over conventional diode-bridged rectifiers by improving DC voltage control, reducing capacitor storage, enabling bi-directional power flow, enhancing power quality control, and other factors [10]. Numerous control approaches have been developed to enhance the performance of PWM converters. One classification is voltage-oriented control (VOC), which uses the grid current to indirectly regulate converter power. While VOC can achieve a constant switching frequency and transient performance, it heavily relies on nested current control loops.

Another class is direct power control (DPC), which directly correlates the switching patterns of the PWM converter with rated power. DPC selects the converter's switching pattern from a predefined table based on power error and grid voltage angular position, eliminating the need for inner current loops, PWM schemes, and phase-locked loops. In summary, DPC provides a super dynamic response and easier structuring compared to VOC. In the realm of DPC literature, many approaches have been used to reduce power ripples with improved switching tables or sequences, maintain a constant switching frequency through the modulation space vector, and enhance robustness using the virtual flux (VF) concept. Current advancements have focused on combining model predictive control (MPC) with DPC to further enhance performance, as demonstrated in the pioneering work of [11], [12].

Extensive research has been directed towards improving MP-DPC performance without increasing the sampling frequency. One approach explored the implementation of multi-vector techniques using either two or three vectors. The three-vector method, in particular, aims to create an optimal sequence by concatenating voltage vectors, referred to as the voltage vector sequence. This sequence consists of dual adjacently active one/zero vectors and is determined based on the flux vector, grid voltage, and vector angular position [13], [14]. However, using three vector methods can lead to a significant computational burden during online calculations and can be relatively complex to implement when using low-cost microcontrollers. An alternative and more efficient method is to use a two-vector approach along with optimizing the duty cycle (D) [15]. This approach avoids the need for online selection of voltage vectors by using a predefined switching table, resulting in acceptable steady-state performance and simplified control. Optimizing the (D) is crucial in MP-DPCs as it is used to minimize power errors [16]. Calculating the (D) can sometimes result in impractical outcomes, such as values exceeding one (D > 1) or falling below zero (D < 0).

This issue has been examined to some extent in previous literature, but a comprehensive study has not been conducted. The conventional approach involves rounding D to 1 for cases where (D) is greater than 1 and setting (D) to 0 for cases where (D) is less than 0. According to [17], the author addressed the problem of (D) being less than 0 in the three-vector method under a well-balanced grid state. However, they have not provided any arguments or actual resolution for dealing with the common problem of (D) being greater than 1 in MP-DPCs using DCO. Furthermore, there is still a lack of methodical discussion regarding the case of (D) being greater than 1 under the condition of an unbalanced grid [18].

This study conducts a detailed investigation of the (D), particularly when it is above 1 (D > 1) scenario, within the framework approach of a two-vector to address the existing gap in the literature. It is identified that the occurrence case of (D > 1) is attributed to incorrect control actions of active power during the initial phase of each segment. This leads to a significant decline in the converters' quality of power due to the generation of surging power and spikes in current. To mitigate these issues, a novel switching-based MPPT controller is formulated to eliminate instances when (D) is greater than 1 and the encounters related to the quality of power. The overall performance of the system is intended to be improved through the implementation of an efficient voltage vector for power regulation, achieved by introducing a sub-sector within each sector. The approach relies on the concept of "extended reactive power," which has been proven to effectively address active/reactive power oscillations concurrently in the realm of unbalanced grid circumstances. The planned technique is not only appropriate for DPC utilizing the classical instant power concept but also offers advantages from the legacy of nullifying power oscillations. The planned technique's efficiency is validated over a set of outcomes from the simulation applied and overall experiments.

WECS is represented in Figure 1. The permanent magnet synchronous generator (PMSG) was selected to enhance output power and optimize energy capture by utilizing full-scale converter configurations [19]. Two essential parameters included in this setup are the conversion of mechanical energy to magnetic energy, which is then converted to the electrical energy of the grid. The swept area of wind turbines can be projected by the overall length of the wind turbine's blades through the swept area of circles, as shown in (1). The (2) is used to calculate the output power of the turbines [20], [21].

$$A = \pi r^2 \tag{1}$$

$$P = 0.5 c_{P(\lambda,\beta)} \rho \pi R^2 V_w^3 \tag{2}$$

Where P is the air density, R is the radius of the rotor, Vw is the wind velocity, and Cp is the power coefficient for wind turbine.

Theoretically, a wind turbine may extract up to 59% of the total power from the wind. However, in ideal conditions, it can typically extract around 40% of the total power available in the wind. In the model, the β parameter is normally set to zero when the applications are related to small-scale wind turbines [22]-[24].

$$\lambda = \frac{V_{tip}}{V_w} = \frac{\omega_r}{V_w} \tag{3}$$

From both (2) and (3), the P_{max} output of wind turbine is denoted as shown in (4).

$$P_{max} = K_{opt}\omega_{ropt}^{3} \tag{4}$$

$$K_{opt} = \frac{0.5\pi\rho C_{pmax}R^{5}}{\lambda_{opt}^{3}} \tag{5}$$

Where K_{opt} is the wind constant and c_{pmax} is the wind turbines' Pmax coefficient (power curves' peak point). The (6) specifically pertains to the rated speed of PMSG.

$$\omega_{opt} = \frac{\lambda_{opt}V_{\omega}}{R} \tag{6}$$

Achieving a unity power factor is possible by adjusting tuning parameters in the initial stage of the microcontroller scheme. This allows the DC-DC boost converter to implement MPPT control when the PMSG operates at its rated speed with the desired unity power factor, enabling the WECS to capture the highest maximum amount of power. Subsequently, MPPT is designed to engage the wind turbine at the optimal speed (ω_{opt}) for each wind velocity, along with the controller determining the maximum peak point [25].

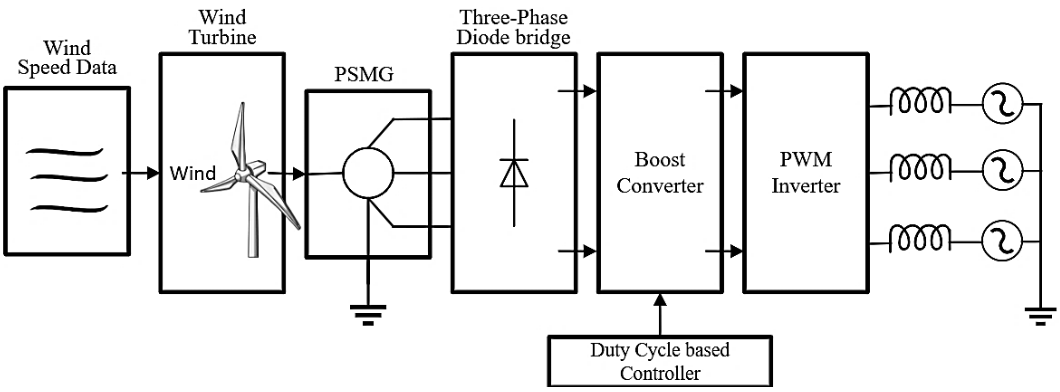

Figure 1. Interconnected wind turbine to permanent magnet synchronous generator (PMSG)

2. DC-DC BOOST CONVERTER

Such converters are classified as a type of power converter that harvests a higher output voltage compared to input voltage. This converter falls under the category of switching power supplies, which require at least two semiconductors; (diode and a switch) and an energy storage component such as a capacitor (C) or an inductor (L). The typical configuration of this converter is demonstrated in Figure 2. The inductor (L) is utilized to control current ripples, while the (C) capacitor filter is employed to regulate the voltage ripples at the output. The calculation of inductor current ripples is typically done by disregarding the ripples at the output voltage. The calculation of inductor current ripples typically involves disregarding any ripples present in the output voltage. Mathematical formulas provided in reference can be utilized to determine the appropriate values for the inductor and capacitor [26]-[30]. The (L) inductor is utilized to control the current ripples.

$$L = \frac{V_{out}}{4.f.\Delta IL_{max}} \tag{7}$$

$$c = \frac{IL_{max}}{4.f.\Delta V_{out\_max}} \tag{8}$$

Adjustment of the (D) of the switching components is the approach employed to regulate the output voltage (V_{out}) of the converter. One frequently utilized method to varying (D) involves modulating the PWM signal, which assists control the switch. Within this research, the incremental conductance algorithm (INC) will be employed to manage and regulate (D) and achieve the optimal position in the DC link [31]-[33].

The converter's output voltage can be adjusted by changing the D of the switching module. One common method is to modulate the PWM signal to alter the (D). In this study, the D will be controlled using an INC algorithm to optimize the DC link. The predetermined values for the boost converter are listed in Table 1.

Figure 3 shows the WECS model connected with the controller. The PMSG is used to harvest electrical energy. It is well known for its reliability, power factor, least maintenance, flexible reactive power/active power capabilities, and gearless mechanism resulting in higher efficiency. The three-phase diode bridge rectifier converts the three-phase AC power output to DC. The INC algorithm is used for controlling (D) due to its fast response. The (D) controls the MOSFET to increase the V_{out} to maximize P_{out} [34]-[36].

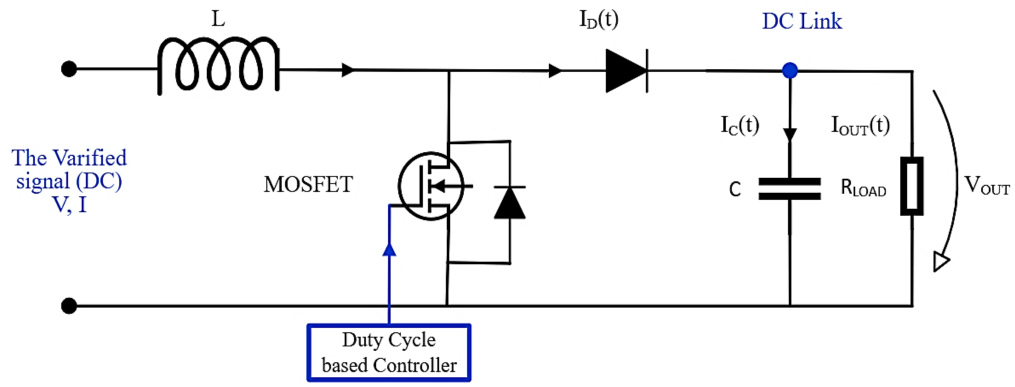

Figure 2. The DC-DC boost converter

Table 1. Boost converter parameters

Parameter	Value
Capacitor	1000 μF
Resistance	100 kΩ
Inductor	10 mH

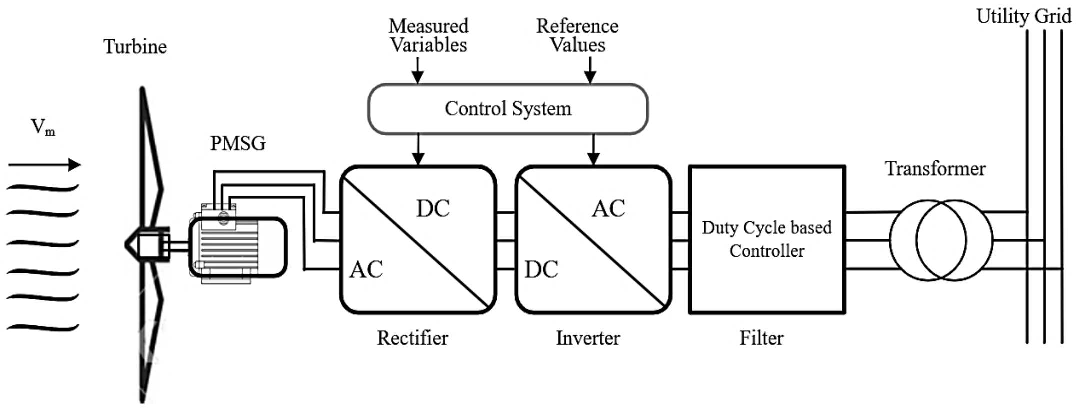

Figure 3. Wind turbine and PMSG with controller

3. RESULTS AND ANALYSIS

Figure 4 shows the three-phase power output of the PMSG. The power factor is equal to 1. The rotor of the PMSG reaches the rated speed by tuning parameters of the WECS. The x-axis represents time (t) and the y-axis represents output power (Pout). The effective value of Pout is around 618 watts at the specific time scale from (7.18 to 7.19) seconds. The three-phase voltage and current are shaped as pure sine curves. From Figures 5 and 6, the signals are in phase, indicating no lagging or leading in the phase shift. Consequently, the power factor pf = 1, $cos\phi = cos0 = 1$.

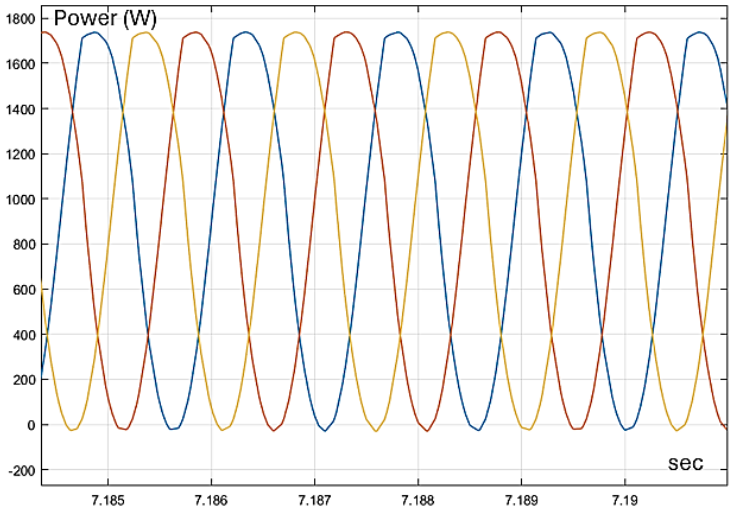

Figure 4. Three-phase output power is produced using the PMSG WECS

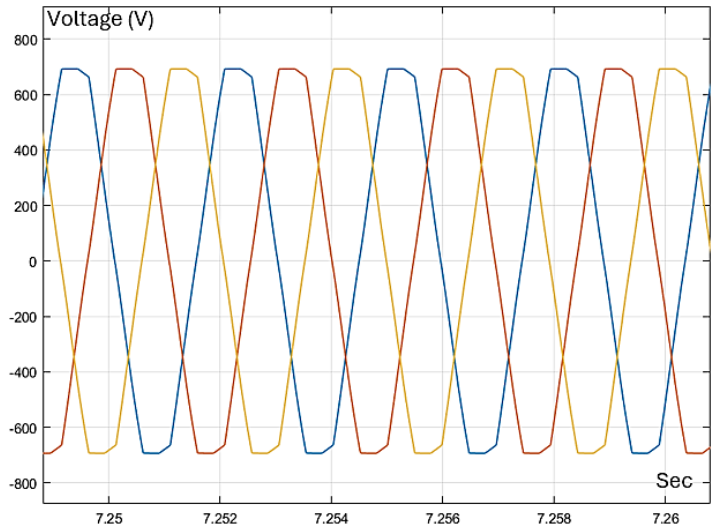

Figure 5. The three-phase output voltage is formed using PMSG-WECS

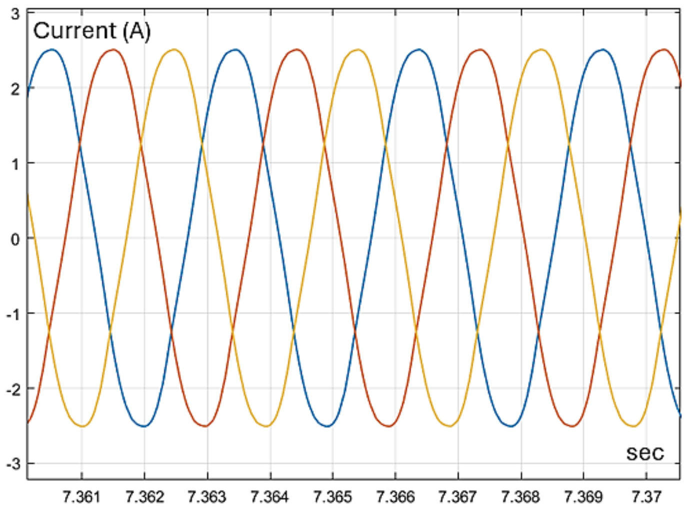

Figure 6. The three-phase output current produced using the PMSG WECS

Figure 7 represents the rotor speed of the PMSG, where the amplitude increased dramatically due to the rising wind speed. There is a fluctuation from (3 to 3.7 sec) due to the rapid change in wind speed profile when it was applied to the PMSG. As denoted in Figure 8, an inversely proportional relationship exists between the electromagnetic torque and rotor wind speed. This relationship highlights the crucial role that wind speed plays in determining the speed of the rotor. Figure 9 illustrates the PMSG stator current. Stator current I_{peak} = 2.5 A from the interval 7.11 to 7.13 sec.

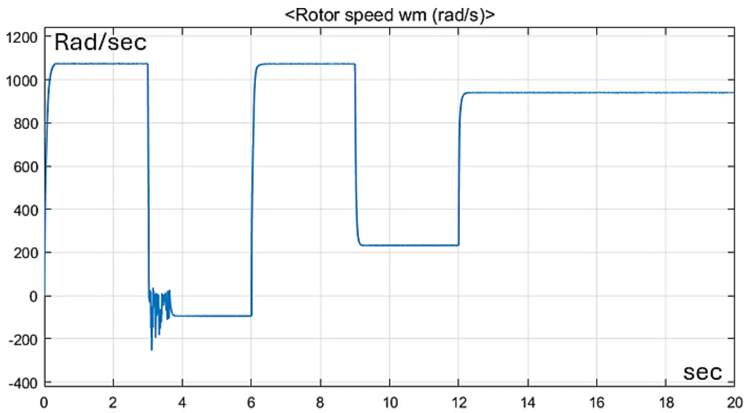

Figure 7. Illustrates PMSG rotor speed

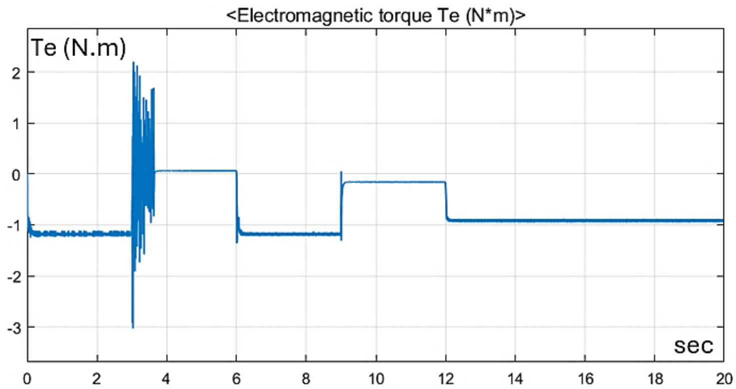

Figure 8. Electromagnetic torque of the PMSG

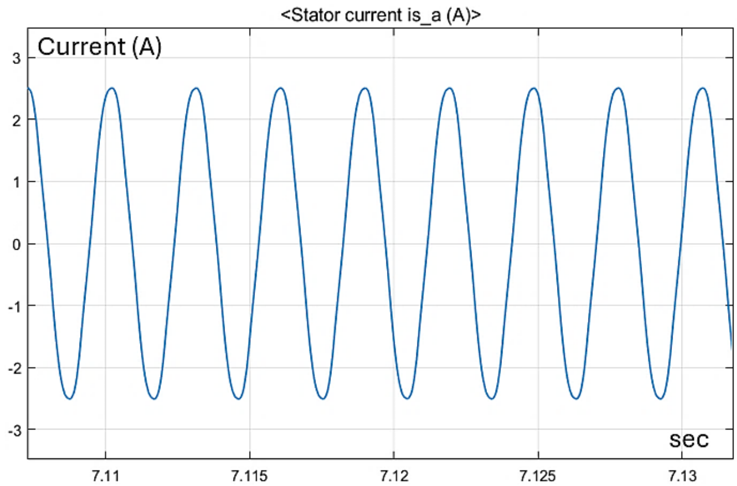

Figure 9. PMSG stator current

Figure 10 shows the AC voltage of the PMSG stator. The voltage curve dynamically changes in accordance with the rotor speed. According to the figure, there is a fluctuation between 3 to 3.7 seconds. This fluctuation is caused by the rapid change in the applied wind speed profile. It can be observed from Figures 7 and 9 that there is a proportional relationship between the wind speed, stator voltage, and rotor speed.

Figure 11 illustrates the PWM D formed according to the INC algorithm. The (D) changes rapidly to control the switching process of the MOSFET in the boost converter. Further, the D increases to reach 1 at 0.13 seconds to drive the MOSFET and increase V_{out} at the DC link. Figure 12 represents the rectified voltage of the PMSG. Three-phase diode bridge rectifier is used to convert the AC signal to DC. As per Figure 11 the voltage is fluctuating according to the rotor speed.

Figure 13 shows the DC link's DC voltage (after the controller). The DC voltage signal reaches an optimal value at different wind speeds. When control implementation is applied, there is a noticeable increase in signal stability, transforming the signal to be smooth without fluctuations. The (D) of the boost converter increases the efficiency of V_{out} at the DC link. The total power of WECS can be increased by efficiently controlling the (D) that is fed to the boost converter.

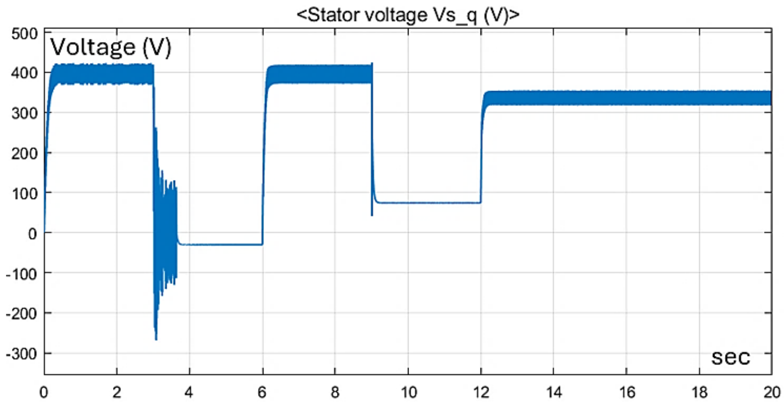

Figure 10. PMSG stator voltage

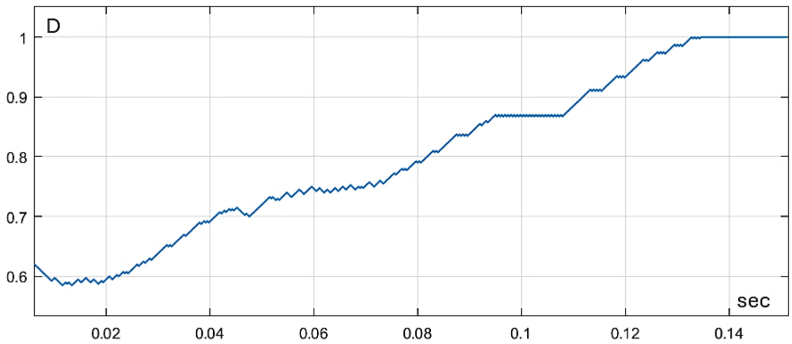

Figure 11. D curve

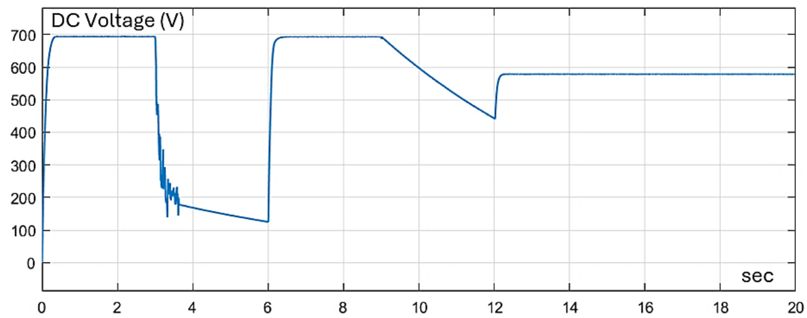

Figure 12. Rectified voltage of the PMSG before the controller

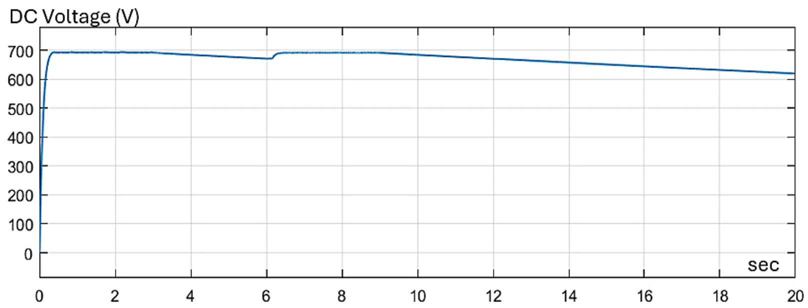

Figure 13. PMSG DC voltage after the controller

4. CONCLUSION

In order to enhance power efficiency in DPC, a new switching technique was proposed in this research paper. This technique incorporates an INC algorithm developed to minimize power errors. Enhancing the operational efficiency of WECS can be achieved by adjusting the parameters of PMSG. Following such processes, the output power of the PMSG needs to be rectified through a three-phase diode bridge rectifier to produce a stable power signal. Subsequently, the application of the (D) for the MOSFET is essential in attaining an optimal operating point in the DC link of the boost converter. The performance of the new switching technique was examined in detail using MATLAB Simulink. To boost the total power quality of the power converter in both unbalanced and balanced grids, tuning the parameters of the boost converter is crucial to raise the overall effectiveness of the system.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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I. M. Elzein		✓				✓		✓	✓	✓	✓	✓	✓	
Walid Alqaisi	✓		✓	✓			✓			✓	✓			
Al Hareth Zyoud	✓	✓	✓	✓	✓		✓	✓		✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

The data supporting the findings of this study are available upon reasonable request to the corresponding author.

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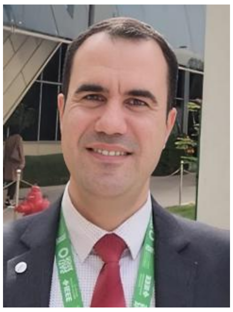

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