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# Performance Evaluation of Incremental Conductance and Adaptive HCS MPPT Algorithms for WECS

**Ahmed Badawi[1], Hassan Ali[1], I. M. Elzein[1] and Alhareth M. Zyoud[2]**

[1] *College of Engineering and Technology, University of Doha for Science and Technology, Doha, Qatar*
[2] *Department of Electrical and Computer Engineering, Faculty of Engineering, Birzeit University, Birzeit, Ramallah, Palestine*

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**Abstract:** This paper presents a novel Maximum Power Point Tracking (MPPT) algorithm designed for Wind Energy Conversion Systems (WECS) to achieve optimal power extraction ($P_{max}$). The controllers employed in this study utilize a Direct Power Control (DPC) framework to assess efficiency and performance, particularly under uncertain and rapid variations in wind speed profiles. The research aims to evaluate the effectiveness of the Incremental Conductance (INC) and adaptive Hill-Climbing Search (HCS) algorithms for MPPT in WECS under such conditions. The modeling of the WECS system utilizes a Permanent Magnet Synchronous Generator (PMSG) due to its reliability and robustness. Simulation results demonstrate the significant impact of wind speed on rotor speed and electromagnetic torque, highlighting the proportional relationship between wind speed parameters and power output. The controller performance is evaluated using INC and adaptive HCS, with the latter demonstrating superior efficiency under rapid wind speed changes. Additionally, simulation results show that the INC algorithm exhibits rapid tracking capability in approaching the peak maximum power point. Overall, this study provides valuable insights into the performance of MPPT algorithms in WECS, particularly under varying wind conditions.

**Keywords:** : Incremental conductance algorithm, Hill-climbing search, Wind power, Maximum power point tracking, Permanent magnet synchronous generator, Wind energy conversion system

## 1. INTRODUCTION

Maximum Power Point Tracking (MPPT) plays a pivotal role in advancing renewable energy systems by maximizing power efficiency within specific operational parameters [1]–[7]. Beyond technical specifications, its efficacy in reducing installation costs and optimizing power quality during operations is well-documented [8]–[13].

In the realm of photovoltaic (PV) modules, the prevalent approach in literature involves the implementation of either "hill climbing" or "incremental conductance" MPPT algorithms due to their simplicity [14], [15]. However, when focusing on innovative MPPT methods, researchers often provide comprehensive summaries of various algorithms [16]–[18]. Critically, research has extensively analyzed the limitations of conventional perturb and observe (*P&O*) algorithms, particularly regarding perturbation step size selection. To address issues like oscillations and convergence speed, variable step-size *P&O* algorithms have been developed, classified into modified and adaptive *P&O* categories.

Figure 1 illustrates a classified model of MPPT with respect to total maximum power captured. Types of MPPT include Direct Power Control (DPC) [11], [19]–[21] and Indirect Power Control (IPC) [1], [2], [8], [11], [22]–[29]. IPC encompasses three approaches: Tip Speed Ratio (TSR), Power Signal Feedback (PSF), and Optimal Torque (OT). The TSR entails an anemometer to measure the speed of the wind as per literature of [30]. The PSF does not require an anemometer but it utilizes turbine blade parameter values. The OT technique does not require an anemometer either, but still necessitates turbine blade parameter values [11], [28], [31]–[33].

The study by [34] proposes a TSR-based controller to adapt to turbine characteristics near the MPP. Equation (1) defines the relationship between output power ($P_o$) and mechanical power, influenced by generator and converter efficiencies [35], [36]:

$$P_o = \eta_g \eta_c P_{\text{wind}} \tag{1}$$

This paper focuses on the Hill-Climbing Search (HCS) and Incremental Conductance (INC) algorithms under the DPC controller to enhance power output by operating the turbine closer to its peak maximum point at the DC link [37], [38]. Equation (2) calculates potential power output $P_{out}$ based

*E-mail address: ahmed.badawi@udst.edu.qa, hassan.ali@udst.edu.qa, 60101973@udst.edu.qa, alhmtz@gmail.com*

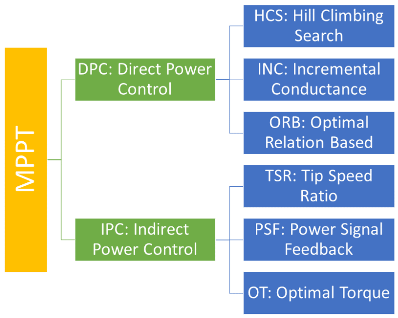


Figure 1. MPPT classified model with respect to total maximum power captured.

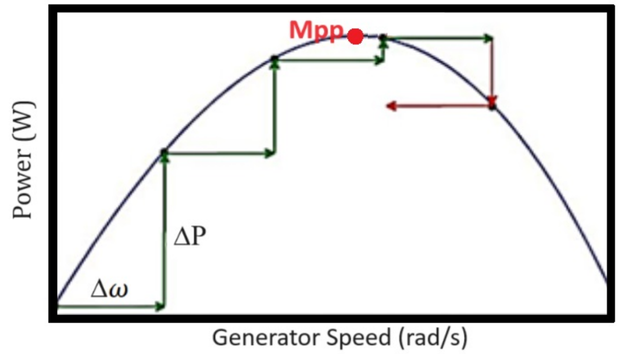


Figure 2. HCS algorithm main principle.

on average wind speed [20], [39]:

$$P = 0.5C_P(\lambda,\beta)\rho\pi R^2 V_w^3, \quad (2)$$

where $\rho$ is the density of air, $V_w$ is the velocity of wind, $R$ is the radius of rotor, and $C_p$ is the power coefficient [40].

The power coefficient ($C_p$) depends on blade tip speed ($\lambda$) and blade pitch angle ($\beta$). As a result of the Betz limit a wind turbine can ideally and theoretically excerpt 59% maximum wind power [39], [41]–[43]. On the other hand, practically the maximum power that can be produced from the wind turbine is up to 40% [44].

Addressing step-size selection, this research introduces a variable step size technique to balance speed control and step-size application efficiently. By monitoring the operating point's distance from the Maximum Power Point (MPP) and transitioning between optimal curves, this technique selects an appropriate step size, enhancing MPP tracking. However, reliance on wind speed measurement and step-size range limitation constrain its effectiveness. The operational methodology leverages adaptive step-size at each operating point, minimizing oscillations and improving WECS performance.

This paper serves as a benchmark for evaluating INC and adaptive HCS algorithms in terms of convergence speed, oscillations, and efficiency performance.

## 2. DEVELOPMENT OF HILL CLIMBING SEARCH ALGORITHM

### *A. Conventional Hill Climbing Search Controller*

An algorithm such as HCS is used to observe and control the rotors speed variances and output power where an addition to minor decreases or increases to the rotor speed reference. That would eliminate the necessity wind speeds anemometer. Such a controlling technique is adapted through the *P&O* algorithm. By consistently varying the rotor speed reference, the system will continuously search, leading to a fluctuation in rotor speed referred to as hysteresis around the peak point. The HCS algorithm utilizes electrical power as its input, which is measured using a power converter. Realistically, turbine power plays a crucial role during the controlling stage in reaching the peak point. Those powers equally considered when the systems module is at steady-state condition, waiting for a period of time for which the generator powers transient has dissipated [9].

HCS algorithm is a well familiar type of algorithms however it has a very common problem that is weak in reaching MPP of a designated module as well has a slow response time in achieving that. This would result in having a cause of oscillation which leads to losses in power since this algorithm tries to track the MPP and keep trying to reach it without being able to do that and in addition will fluctuate around it [24].

Figure 2 shows HCS principles in tracking the optimal power. Therefore, utilizing the electric power measurement, to estimate the control of the next step. The benefit of over-passing wind turbine data is to guarantee the wind turbine will always operate at its actual MPP, regardless of disparities in the blades external characteristics or other influencing parameters. Though the unique characteristics drive HCS to be the optimal selection in MPPT control at various WECS environments; thus is suitable for wind speed conditions that change slowly [7], [45]. Applying large step size perturbations can enhance the convergence speed but at the negative impact of affecting efficiency which is called a trade-off. Raising the convergence speed also results in more oscillations around the maximum power point, because HCS control keeps oscillating around the peak point, leading to inevitable fluctuations. Conversely, a reduced step size can improve proficiency but may cause the controller to slow down and struggle to track the peak point under dynamic changes in wind factors. The determination of the next perturbation stage in the conventional mechanism is based on the power decrease or increase caused by the previous perturbation step. However, this approach can be misleading if the factors of wind change are not taken into account. In such cases, the change in wind can override the effect of the applied perturbation, leading to an incorrect estimation by the traditional algorithm used in HCS. Consequently, the tracking of the peak point becomes insufficient, and the

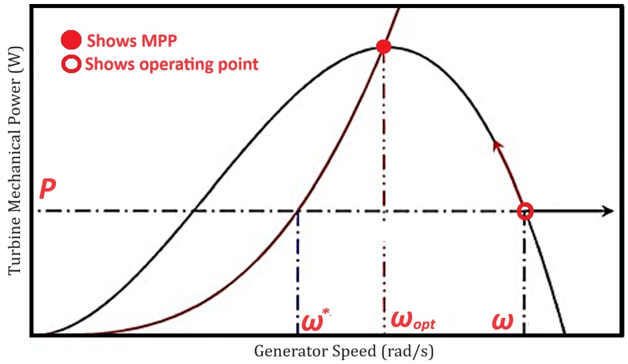


Figure 3. Adaptive HCS.

HCS goes downward. From the literature, researchers have proposed using algorithms with variable-step sizes to get to the optimal peak point. Nevertheless, these algorithms have several drawbacks when the operating point is far from MPP. This is primarily caused by the increased extent of the $P - \omega$ slope as shown in Figure 3.

*B. Adaptive/HCS-Three Mode*

Numerous structures incorporate a primary control unit known as the ”master control” that determines the operational mode of the controller, based on wind speed and disparities in wind speed. Such an approach enables the controller to respond accordingly to minor or significant fluctuations in wind speed, or alternatively, maintain a constant rotor speed within a specified dead band limit.

Figure 3 demonstrates adaptive HCS and shows how to reach the MPP point. The potential for adaptive controllers emerges when they initially operate in a knowledge mode to ascertain the crucial parameters based on a specific wind pattern [7], [46], [47]. Other techniques in the HCS domain are also stated, such as HCS with variable dual step size, as well as search recollect algorithms that hold in a special memory the MPP during the knowledge stage [1], [37], [46]–[52].

*C. Hill Climbing Search Adaptive with Power Prediction mode*

In the literature Badawi et al 2020 used a novel algorithm that relies on two main mode stages and an intelligent tools which introduced in [9], [10] known as power predicting mode. The introduced algorithm constructed a set of two different modes in detecting the MPP. The main goal of the enhancement is to achieve MPPT in a short time frame. And hence improving the power efficiency of WECS. Note that no iterations calculation is involved and further improving any trade-off as a result of the convergence rate and efficiency [48].

The design and structuring of such algorithm took into consideration how to be simple. It can be applied at different wind speed profiles. Therefore, it can be reached to the most possible power out of the WECS. A novel algorithm can estimate and predict captured power at wind turbine. Thus, the duty cycle can be applied to the MOSFET to detect the optimal point on the real time without delay [8], [29]. Through the “power prediction technique” a division in the range’s references for the wind-speed is actioned for the purpose in getting maximum wind-energy. Through this mechanism, speed of wind identifies the ($P_{out}$) established at wind-speed range. The results obtained based on the theory would assure that the proposed enhanced algorithm is notable to be fast and further being efficient as compared to a three mode HCS algorithm. In the power prediction there are five main intervals based on the wind speed data ; interval1: less than 2.5m/s which is considered a very low wind speed; interval 2: wind speed range that’s initiated at (2.5 m/s) and may reach a value of up to (8 m/s), interval 3: The speed of wind range from an initial value of (8 m/s) to a value that may reach (13.3 m/s); interval 4: Range of the speed of wind may take an initial value of (13.3 m/s) up to an incremental value of up to (20.3 m/s) and finally, interval 5: A dedicated wind speed above 20.3m/s [10].

## 3. Incremental Conductance algorithm (INC)

INC is a popular algorithm used in tracking the $P_{max}$. Mostly used extensively because of its ease of use and abilities in tacking the MPP. In addition, the INC algorithm is considered to be utilized as baseline and assumed one of the most standardized references as compared with other novel algorithms.

At the initial start of the process, both the voltage ($V$) and current ($I$) determine the WECS output. The changes in the values of the above-mentioned parameters ($I\&V$) are identified during the calculation in predicting the I and V derivative. Conventional INC algorithms rely on the basis of comparing the current’s derivative value (function of voltage) with the instantaneous current of the WECS against voltage. Simply, the MPP is tracked through this technique by incrementing and decrementing an applied reference voltage in accordance with the current operating point of the module [53]. When this method drives the operating point to reach the MPP and hence to conclude the following [54];

$$\frac{dP}{dV} = 0 \tag{3}$$

$$\frac{dP}{dV} = \frac{d(V \cdot I)}{dV} \cdot dV = I\frac{dV}{dV} + V\frac{dI}{dV} \tag{4}$$

$$\frac{dI}{dV} = -\frac{I}{V}, \tag{5}$$

where, $dI/dV$ is the current derivative, and $I/V$ is the instantaneous PV current to voltage.

Further, this method is based on the slope of P-V slope. The $P_{max}$ is reached when it gets a zero slope [55], [56].

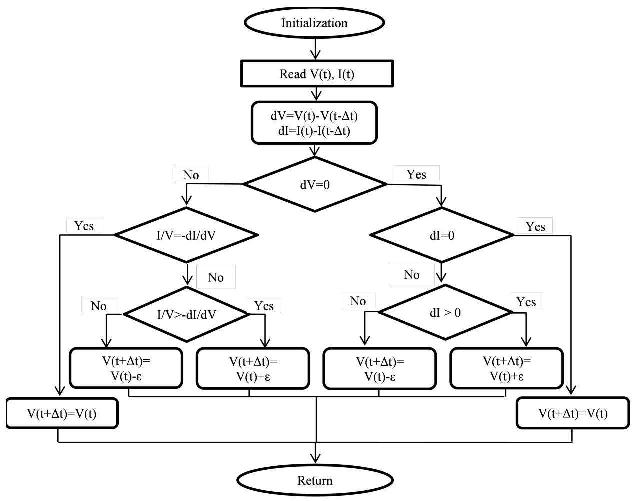


Figure 4. INC algorithm flowchart.

The below equations sum up the INC scheme [57]:

$$p = VI \tag{6}$$

$$\frac{dp}{dv} = I + V\frac{di}{dv}. \tag{7}$$

Note that when $\frac{dP}{dV} > 0$; $\frac{I}{V} > -\frac{dI}{dV}$ then in this scenario the voltage must be increased (incremented) and vice versa when $\frac{dP}{dV} < 0$; $\frac{I}{V} < -\frac{dI}{dV}$ then the voltage must be decreased or (decremented). INC flowchart is represented in Figure 4. In a conventional context of INC scheme, "$\epsilon$" demonstrates a nominal voltage (fixed) that serves for decrementing and incrementing it accordingly based on the system requirements and needs.

## 4. MODELLING WIND ENERGY CONVERSION SYSTEM BASED ALGORITHMS

The INC algorithm and HCS adaptive algorithm were applied to the WECS using different wind speed profiles with rapid changes based on time. In the first part, the (INC) controller is applied to WECS to obtain $P_{max}$. The following model represents the main components in the system as exposed in Figure 5. The synchronous generator dynamic model used in this study is a result of two key phases' reference synchronous; ($d$) direct and the other one is ($q$) quadrature axis frame. Angle formed angle among those two terms is roughly around 90º degrees. This angle is estimated to be the direction of rotation. The $dq$ transformation that was utilized in the three-Phase of WECS is illustrated through Equation (8) [58]. Note that another illustration of the inverse transform is reflected in Equation (9) [1], [8], [26], [40], [59]–[64].

$$\begin{bmatrix} F_d \\ F_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin\omega t & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos\omega t & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \end{bmatrix}\begin{bmatrix} F_a \\ F_b \\ F_c \end{bmatrix}, \tag{8}$$

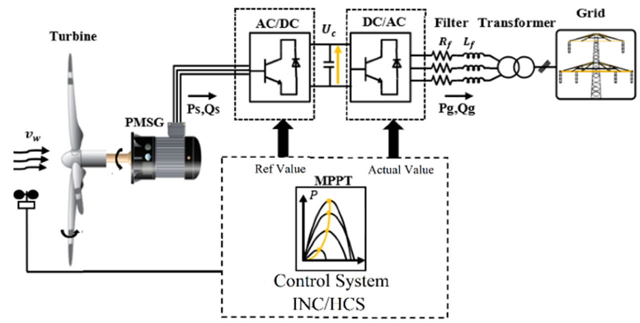


Figure 5. PMSG wind turbine controller algorithm.

$$\begin{bmatrix} F_a \\ F_b \\ F_c \end{bmatrix} = \begin{bmatrix} \sin\omega t & \cos\omega t \\ \sin(\omega t - \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3}) \\ \sin(\omega t + \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \end{bmatrix}\begin{bmatrix} F_d \\ F_q \end{bmatrix}. \tag{9}$$

In the frequency domain, the synchronous generator stator current's d-axis illustrated in Equation (10) and the same applies to q-axis [8].

$$i_{qs} = \frac{\begin{pmatrix} -v_{qs} & -R_s i_{qs} & -\omega_r(L_{ds} + L_{ls}) \end{pmatrix}\begin{pmatrix} i_{ds} \\ \omega_r\phi_r \end{pmatrix}}{S\left(L_{ds} + L_{qs}\right)}, \tag{10}$$

where, $i_{ds}$ is the stator currents $d$-axis, $i_{qs}$ is the stator current's $q$ axis, $v_{ds}/v_{qs}$ is the stator voltage $d-q$ axes, $\omega_r$ is the angular speed generator, $R_s$ is the stator resistance, $\phi_r$ is the rotor's flux, and $\frac{L_q}{L_d}$ is the self-inductance of stator $q-d$ axes.

The below equations are setting up the parameters of ($L_d$) and ($L_q$) respectively.

$$L_d = L_{ls} + L_{dm} \tag{11}$$

$$L_q = L_{ls} + L_{qm} \tag{12}$$

Knowing that ($L_{ls}$) is inductance leakage and ($L_{dm}$) and ($L_{qm}$) representing in this scheme a magnetized inductance at ($d_q$-axes) under the influence of a synchronous generator. ($d_q$)-axis streamlined model in synchronous frame rotor field is addressed in [8].

The calculations of both parameters ($\omega_r$) and ($T_e$) of PMSG are reflected at Equations (13) and (14) [8];

$$T_e = \frac{3N_p}{2}\left(\phi_r i_{qs} - (L_d - L_q)i_{ds}i_{qs}\right), \tag{13}$$

$$\omega_r = \frac{N_p}{JS}(T_e - T_m). \tag{14}$$

where; $N_{pp}$ is the pole pairs numbers, $T_m$ is the generator mechanical torque, and $J$ is the inertia rotation.

Another set of terms to define are the generator speed

($pu$) and synchronous generator torque $T_m(pu)$. As per the rotor of PMSG, an applied torque can be addressed as follows [8], [65], [66].

$$T_m = \frac{0.5 C_P(\lambda, \beta) \rho \pi R^2 V_w^3}{\omega_r}. \tag{15}$$

At a certain model, note that ($\beta$) is given a determined value however it is assigned a value of $\beta = 0$; such a value is used in wind turbine with a trivial scale.

$$\lambda = \frac{V_{\text{tip}}}{V_w} = \frac{\omega_r}{V_w}. \tag{16}$$

From the derived Equations (2) and (16), wind turbine output maximized power is calculated using Equation (17), and constant optimal wind is calculated through Equations (18) and (19).

$$P_{\max} = K_{\text{opt}} \omega_{\text{ropt}}^3, \tag{17}$$

$$K_{\text{opt}} = \frac{0.5 \pi \rho C_{\text{pmax}} R^5}{\lambda_{\text{opt}}^3}, \tag{18}$$

$$\omega_{\text{opt}} = \frac{\lambda_{\text{opt}} V_\omega}{R}. \tag{19}$$

In exceptional cases formulations, Equation (19) is used to determine ($\omega_{opt}$) when a condition is applied where the rated speed at both the PMSG and MPPT [8], [24].

Reaching a unity power is a challenging task when it comes to micro controllers where adjusting the module parameters may have a great effect on the overall performance. Again, when rated speed was addressed, an assurance is required to ensure this is ideally reaching PMSG along with the power factor (unity stage) and a dc-dc boost converter can be controlled at this case by Duty cycle. The overall advantage is to collect the maximum power available from WECS [67]–[70].

MPPT algorithm drives the integrated module of wind turbine to the highest and ultimate possible speed denoted and addressed as $\omega_{opt}$ for every and single wind potential velocity. As a result of the preceding discussions, we may conclude at this stage that, arriving towards the maximum power point will solely be dependable purely on the MPPT scheme control [71], [72].

## 5. RESULTS AND DISCUSSION

PMSG's induction generator type with WECS model connected with the controller (INC/ HCS) Adaptive to check the performance effectiveness in reaching MPP. The 3-phase output voltage from PMSG is rectified in the sense of converting an AC power waveform to its DC component and then feed it into a predefined controller. To control the voltage ($V_{dc}$) a dc-dc converter unit is designated for this task. Where a reference voltage ($V_{ref}$) is supplied by the MPPT controller. This supplied ($V_{ref}$) is driven to be compared with the ($V_{dc}$) value and eventually, the final value's reading goes into the controller. Knowing that at this point the controllers' output is checked against the $(k-1)$ state in a forward step to seek the best switching process of a DC-DC convertor, i.e. the "ON"/"OFF" states.

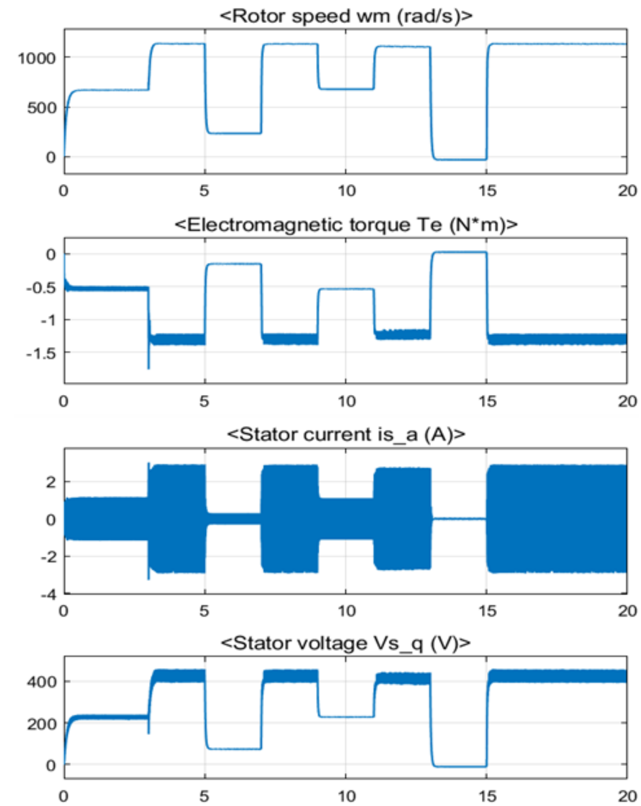


Figure 6. (Stators I&V), speed of rotor, and WECS electromagnetic/torque.

From Figure 6 the rotor speed increased rapidly because of wind speeds' raised value. The electromagnetic torque is following the rotor speed based on wind speed value.

Stator voltage and current increased dramatically by mean of increasing the mean wind speed data and as mentioned in the literature [10], [24], [29], [56] the mean wind speed has cubic proportional relation with the power value. It can be noticed that the rotor speed value changed due to the wind speed data. The electromagnetic torque has inverse proportional relation with the rotor speed. This is displayed in Figure 6. Stator (I) and (V) raised intensely as per the data of winds' speed and followed the rotor speed behaviour which is due to the proportional relations.

Figure 7 shows a sinusoidal 3-phase power output for the PMSG. It is noticed that the amplitude was increasing due to the fact that the speed of the mean wind is incrementing. The three-phase power value followed the ($I$) and ($V$) in the phase angle value, where the phase angle is stable without notable leading/lagging issues. Power factor is symbolized by $PF = cos(\phi) = 1$ where, in this case the rated power value can be captured from the wind turbine. Therefore,

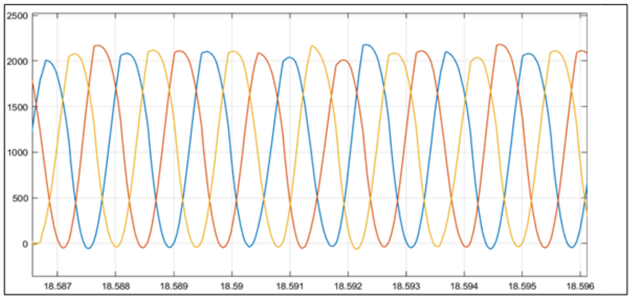


Figure 7. Three-phase power value of the induction generator $P_{abc}$ between 18.587s and 18.596s power generator.

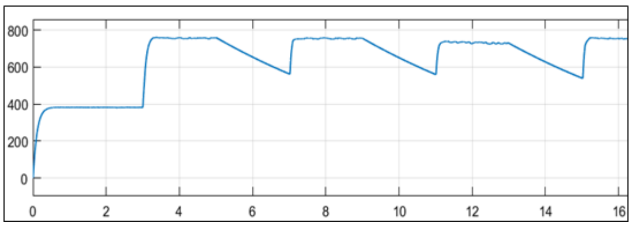


Figure 8. DC voltage illustration at the incident of 3-phase bridge rectifier (no controller involved).

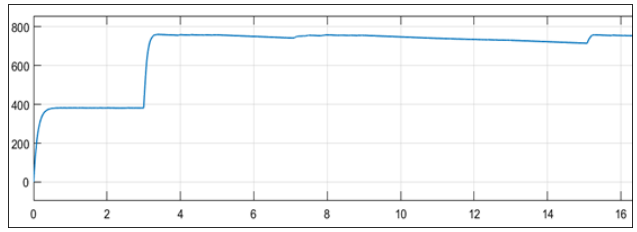


Figure 9. DC voltage after the INC controller.

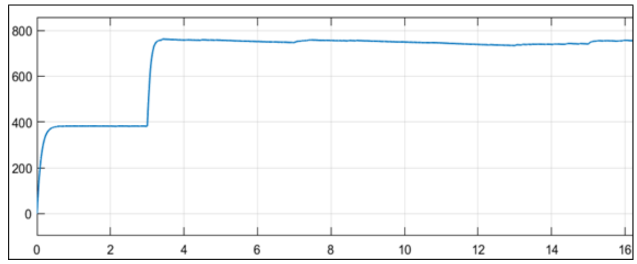


Figure 10. DC voltage after HCS Adaptive controller.

the system in this situation is considered ready to rectify the power output to utilize the controller on the DC linkage that belongs to the boost DC-DC converter.

Figure 8 represents a rectified signal from the PMSG using the 3-diode rectifier bridge (no controller), where DC voltage value decreased steadily because of decrease wind speed. In addition, the DC voltage raised sharply when the wind speed increases because of cubic proportional relation taking place through wind speed and power as shown in Equation (1). It can be noticed from the Figure 8 the fluctuation was due to the instability of the applied wind speed. Two different controllers will be applied to this signal to assess how the performance of efficiency acts as the next figures exhibit.

In Figure 9 INC controller had been applied to the rectified signal to reach the optimal peak point and to enhance the efficiency performance.

The result shows fast-tracking capability in detecting the optimal operating point on the power curve, as compared to Figure 8 which shows fluctuations in the captured power. However, the efficiency performance decreased dramatically based on rapid changes in wind speed.

Based on Figure 9, the INC technique has a minimal ripple observed at 7.2 sec, and at 15.3 sec. It can be seen the curve raised roughly at 3.1 sec due to the raised wind speed from 6 m/s to 13 m/s. Here, the incremental technique provided lower oscillation as compared with adaptive HCS. Hence, the INC shows fast tracking capability to reach the optimal point. In the steady-state conditions of the wind speed profile, Incremental and adaptive techniques have similar efficiency performance as shown in Figures 8 and 9. However, the adaptive HCS has higher captured power compared to the INC, particularly during the rapid change in wind speed.

In Figure 10, it shows the DC volt signal after applying the adaptive HCS. It can be noticed that the adaptive HCS algorithm with power prediction mode along a rapid response upheld the Pmax value successfully which offers a valuable insight into power efficiency. Adaptive HCS algorithm shows the best efficiency performance under rapid change wind speed. Adaptive HCS at every wind speed value, the operating condition is kept at its optimal point. This is due to the power prediction mode stage with high accuracy as compared to incremental technique. Thus adaptive HCS technique captures $P_{max}$ even during wind speeds' dynamic fluctuations, as shown in Figure 10. Further, adaptive HCS technique has a lower overshoot than the incremental technique from 6-8 seconds and 14-16 seconds through wind speed instabilities.

## 6. Conclusion

In this study, we have addressed two essential algorithms within control structured techniques for wind turbines, integral to tuning WECS with the unique goal of driving PMSG to optimal efficiency by achieving unity power factor. The INC and adaptive HCS algorithms have demonstrated accurate tracking and detection of the MPP.

Theoretical results confirm that INC exhibits fast tracking capability to reach the MPP, albeit with decreased efficiency performance under rapid changes in wind speed. Conversely, adaptive HCS demonstrates higher efficiency and performance in response to rapid changes in wind speed, with enhancements observed in steady-state efficiency.

These findings underscore the importance of algorithm selection and adaptation in optimizing WECS performance under varying wind conditions, contributing to the advancement of renewable energy systems. Further research could explore refinement and integration of these algorithms to enhance overall efficiency and stability in wind energy applications.

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**Ahmed Badawi** is an Assistant Professor at the University of Doha for Science and Technology (UDST), Qatar. Dr. Badawi holds a PhD in Electrical Engineering from the International Islamic University Malaysia (IIUM). Dr. Badawi has been honored with several awards and scholarships throughout his academic career. He has contributed to numerous high-ranking journals in Electrical Engineering and renewable energy with his published papers. Dr. Badawi possesses extensive expertise in renewable energy, power control systems, as well as automation and control systems.He serves as a Reviewer for Energy Elsevier and IET Power Generation journals.

**Hassan Ali** holds a PhD in Electrical Engineering from the University of Melbourne, Australia, and currently serves as an Assistant Professor (Electrical Engineering) at UDST, Qatar. With extensive experience in machine learning, Internet of Things, embedded systems, wireless communications, and electrical engineering domains, Dr. Ali is a Senior Member IEEE, USA. He has authored numerous research articles and spearheaded several RD projects focused on pioneering technologies and innovative solutions.

**I. M. Elzein** is an electrical and electronics engineer who pursued his undergraduate and graduate level degrees in Electrical and computer engineering from Wayne State University, Michigan, USA in 2004. Currently, Dr. Elzein is holding an academic lecturing role in the department of telecommunication and networking engineering at the University of Doha for Science and Technology. Dr. Elzein has more than 70 research papers in multi-international conferences and journals as well being a reviewer committee member and technical program committee. His research profile is mainly in the fields of electrical and electronic engineering with a concentration on (PV) photovoltaic systems, robotics design, renewable energy and information technology.

**Alhareth Zyoud** received his bachelor's degree in Electrical Engineering from Palestine Polytechnic University in 2006, followed by his master's and Ph.D. degrees in Communication Engineering from the International Islamic University Malaysia in 2011 and 2017, respectively. He has authored or co-authored numerous research papers published in international journals and conferences. His current research interests include RF modeling and simulation, 5G radio resource management, and rain attenuation analysis.