ABSTRACT The growing tendency of wind energy technology usage has induced researchers to seek more studies on the improvement of wind energy harvesting systems with highly reliable power injected into the electric grid. The amount of extracted wind energy by a wind turbine depends on the accuracy of the maximum power point tracking (MPPT) algorithm associated with the control scheme of the wind energy conversion system (WECS). This paper aims to present a novel development of MPPT algorithm based on parabolic prediction techniques (PPT) for variable speed wind turbines (VSWT) so as to achieve maximum wind power extraction and efficiency enhancement. The developed PPT-MPPT algorithm uses parabolic convex functions to estimate the parabola wind turbine output curve and locate the maximum power point on that curve. Simultaneously the algorithm establishes a systematic procedure for adjusting the concavity and the optimal part of the estimated parabola curve to make sure that the proposed technique is in continuous convergence. The feasibility of the developed PPT-MPPT algorithm has been validated under rapid and random changing wind speed profiles via the MATLAB/Simulink environment. The performance of the proposed PPT-MMPT algorithm is evaluated by comparing the simulation finding to those obtained using the benchmark perturb and observe (P&O) algorithms. The simulation outcomes affirm that the proposed PPT-MPPT algorithm outperformed the other algorithms in terms of tracking efficiency and extracted power which can be regarded as an efficacious manner to improve the VSWT system.

INDEX TERMS MPPT algorithms, WECS, PMSG, VSWT, wind power, wind turbine, parabolic.
most wind turbine industries [6]. This is due to its several valuable features, such as harnessing maximum wind power, high efficiency, less power fluctuation, gearless construction and decreased mechanical stress [7]. The FSPC topology is made up of a machine-side rectifier (MSR) and a grid-side inverter (GSI) linked back-to-back via a DC-link capacitor and incorporated with control schemes named the MSR control scheme, maximum power point tracking (MPPT) algorithm, and GSI control scheme [8], [9], [10]. The development of advanced control schemes is a crucial point for achieving the optimal conversion efficiency from the wind and adhering to utility grid interconnection standards [11], [12], [13].

The MPPT algorithm is an essential part of this control scheme, as it is responsible for tracking the optimal rotational speed that results in optimally extracted wind power according to the prevailing wind speed [14]. Therefore, many MPPT algorithms have been developed and implemented in the recent literature, and they are typically classified as indirect MPPT algorithms (I-MPPT) and direct MPPT algorithms (D-MPPT) [15]. The I-MPPT class includes Power Signal Feedback (PSF), Optimum Torque Control (OTC) and Tip Speed Ratio (TSR) [16], [17], [18]. The TSR-MPPT algorithm has numerous advantages such as ease of use, high reliability, less ripple torque, and reduced output power fluctuation. However, it requires an accurate anemometer for continuously measuring a wind speed and prior knowledge about the characteristics of a wind turbine [19]. These requirements bring the system’s complexity as well as increase initial and ongoing maintenance costs [20]. Both the OTC-MPPT and the PSF algorithms require foreknowledge of the generator’s arithmetic paradigm, especially the torque-current relationship. Hence, the MPP is not obtained accurately due to turbine inertia, particularly under low-wind speed profiles [21], [22], [23].

Alternatively, the D-MPPT is comprised of three main algorithms: optimum relation-based (ORB), incremental conductance (IC) and perturb and observe (P&O) algorithms [23], [24], [25]. The P&O-MPPT algorithm is the most commonly used due to its advantages of being sensorless, requiring no prior knowledge about the turbine system and also can track the MPP as wind speeds fluctuate [26], [27], [28]. Nevertheless, it has the difficulty problem of choosing the right step size (SS) since a small SS improves the accuracy of the MPP but reduces the convergence speed. In contrast, a big SS leads to a quicker response but causes oscillation around the MPP. This oscillation causes a loss of power in the WECS. In addition, the P&O-MPPT algorithm suffers from misleading for a maximum power point in fast-changing wind speed [29], [30], [31], [32]. To address the shortcomings of conventional P&O MPPT algorithms and improve tracking efficiency, scholars have proposed several P&O-MPPT of Variable Step Size (VSS). In [33] an adapted P&O-MPPT technique of a big SS in the forwarding direction and small SS in the backward directions was developed so as to settle the slow speed-tracking problem. However, this work used an anemometer for measuring wind speed that in turn increases the cost, in addition to using a fixed forward step-size that creates undesirable oscillations around the MPP. In [34], a new approach combining the use of synthetic curves and ratios is introduced to adeptly adjust the SS according to power variations, estimated wind speed and generator rotational speed. Despite tracking performance being improved, the algorithm complexity is significantly increased. In [35], the authors presented an updated traditional P&O-MPPT algorithm in which the SS is altered according to the distance between the estimated and measured generator’s rotational speed. In spite of the fact that tracking speed has improved, this method is solely reliant on the first SS. In [36] and [37], an advanced P&O-MPPT algorithm of the multi-operation zone is proposed. In this approach, the power vs. rotating speed \((P - \omega)\) curve is divided into four zones. Consequently, the selection of the suitable SS is related to the closeness of the operating zone to the MPP. For the two zones close to the MPP, a small SS is applied. Otherwise, the algorithm uses a big SS. However, this strategy comprises a restricted operating zone, in addition to using an anemometer for measuring wind speed. Furthermore, choosing SS poses a significant challenge to reach proper and fast speed tracking with lesser oscillations. Moreover, the approach in [38] is developed to increase the applied SS number and operating zone via adopting a synthesized ratio that corresponds to the nominal optimal power. Nevertheless, the limits of the operating zone and associated SS are retained constant even when the wind speed changes. This in turn causes undesirable swinging around the MPP at low wind speed profiles. Therefore, there is still a need to develop a new effective MPPT algorithm that can get rid of the limitation of the existing algorithms and add more enhancement to the performances of WECS.

This work aims at introducing a new efficient sensorless MPPT technique that eliminates the limitation of the existing D-MPPT and I-MPPT algorithms as well as extracting the maximum wind power effectively. The proposed technique is developed based on the concept of the downward parabola curve and is named the parabolic prediction technique (PPT). Then, by a progressive renewal of the operating points and their corresponding parabola, the WT optimal rotational speed and the corresponding power can be obtained. The proposed PPT-MPPT algorithm has the following features and advantages over the existing MPPT algorithms:

- In comparison to the P&O-MPPT algorithms, the proposed PPT-MPPT algorithm instantly finds the maximum power point using parabolic function arithmetic. The properties and constraints of the estimated parabola shape for guaranteeing convergence conditions are easily marked from introductory arithmetic. This results in quicker MPPT hunting speed and eliminating oscillation of operating point around the MPP.
- To optimal-tune the predicted parabolic shape, a methodical adjusting approach has been introduced. Therefore, the possibility of incorrect tracking direction could be
totally eliminated. In contrast, the P&O-MPPT algorithm that some time loses the tracking path of the MPP.

- Locating the maximum power point at the convergence conditions only requires four sampling times.
- As compared to the TSR-MPPT, OTC-MPPT, and PFS-MPPT algorithms, the proposed PPT-MPPT algorithm proffers two main benefits: (1) no wind speed sensor is needed, and (2) no pre-knowledge of system characteristics is required, this will improve the WECS efficiency and decrease the associated cost.

To the best of the authors’ knowledge, introducing an MPPT algorithm based on PPT for a VSWT-PMSG system has not been addressed in the literature related to WECS.

II. DESCRIPTION AND MODELLING OF THE WECS

This section describes the configuration and mathematical model of WECS adopted in this investigation. The WECS, as indicated in Figure 1, is outfitted with a VSWT-PMSG and is connected to the UG via an FSPC and a filter. The FSPC is made up of an MSR and a GSI linked by an overvoltage protection capacitor as well as incorporated with three main control schemes namely, MPPT algorithm, MSR and GSI control schemes. In this configuration, the aerodynamic forces acting on the WT blades generate mechanical power which is converted to electrical power using the PMSG and then fed into the UG via FSPC as well as a filter to meet the grid’s framework.

A. WIND TURBINE AERODYNAMIC MODEL

The nominal available kinetic energy in the wind is modelled as follows [39], [40]:

\[ P_{wind} = 0.5 \rho A V_{wind}^3 \]  

(1)

where \( \rho \), \( A \) and \( V_{wind} \) denote the air density (kg/m\(^3\) ), the rotor blades swept region (m\(^2\) ), and the wind speed (m/s) respectively. However, due to physical constraints, the WT can only capture a part of the available wind energy [40]. The amount of captured power by WT is computed by Equation (2), [39], [40]:

\[ P_m = 0.5 \rho A V_{wind}^3 C_p(\beta, \lambda) \]  

(2)

The Equation (2) reveals that the captured power is a function of the power coefficient \( C_p \) and depends on TSR \( \lambda \) and pitch angle \( \beta \) as detailed in Equations (3)-(5), [39], [40], [41], [42]

\[ C_p(\beta, \lambda) = 0.22(\frac{116}{\lambda^3} - 0.3\beta - 5) e^{-15\lambda^5} \]  

(3)

with

\[ \frac{1}{\lambda} = (\frac{1}{\lambda_1} + 0.08\beta - \frac{0.035}{\beta^3 + 1}) \]  

(4)

The TSR \( \lambda \) represents the ratio of wind turbine rotational speed \( \omega_m \) of blade radius \( R \) to prevailing wind speed \( V_{wind} \), [39], [40], [41], [42], [43] which is:

\[ \lambda = \frac{\omega_m R}{V_{wind}} \]  

(5)

In order to harness the maximum wind energy, WT must be operated at optimal power coefficient \( C_{p, opt} \). This can be achieved by obtaining the optimal rotational for the corresponding wind speed. As can be seen in Figure 2, each wind speed has a unique rotational speed that leads to \( C_{p, opt} \).

B. PMSG MODEL

The PMSG converts mechanistic power into electrical power even at a low angular rotating speed. It has the features of high electrical power density, less copper loss due to the lack of field coils, and a low cost, [44]. The revolving reference frame’s electrical voltages \( dq-axis \) supplied by the PMSG are expressed as follows [41], [45]:

\[ v_{ds} = R_i i_{ds} + L_d \frac{di_{ds}}{dt} - \alpha_e L_q i_{qs} \]  

(6)

\[ v_{qs} = R_i i_{qs} + L_q \frac{di_{qs}}{dt} + \omega_e \psi_f + \omega_e L_d i_{ds} \]  

(7)

where \( i_{ds}, i_{qs}, v_{ds} \) and \( v_{qs} \) signify the PMSG’s stator currents and voltages. \( L_q, L_d \) symbolise inductances of the PMSG’s stator and \( R_i \) denotes the stator resistance. The magnetic
field and the electrical rotation velocity are represented by \( \psi_f \) and \( \omega_e \), respectively. The electrical angular velocity \( \omega_m \) is proportional to PMSG mechanical speed as a function of machine poles number \( P_n \) and is defined as in the following Equation [45]:

\[
\omega_m = P_n \omega_e
\]

The PMSG’s electromagnetic torque \( T_e \) is figured by the following equation [45], [46], [47]:

\[
T_e = \frac{3}{2} P_n \left( (L_d s - L_q s) i_d i_q - \psi_f i_q \right)
\]

Hence, the PMSG’s dynamic model formula is expressed as Equation (10), [45], [47].

\[
J \frac{d \omega_m}{dt} = T_e - T_m - D \omega_m
\]

where, \( T_m, D \) and \( J \) denote the mechanical torque the generator’s rotor damping coefficient and the moment of inertia respectively.

III. CONTROL SCHEMES OF FSPC

The VSWT-PMSG system is tied with UG terminals by an FSPC [48]. The FSPC includes three major control schemes namely the MPPT algorithm, the MSR, and the GSI as depicted in Figure 1. The MPPT algorithm tracks and provides the optimal angular rotating speed of the best wind power extraction [49], [50]. The MSR controller adjusts the turbine rotating speed according to the MPPT provided speed to acquire maximum wind energy, whereas the GSI control scheme regulates the terminal current, terminal voltage and DC-link voltage, according to the framework of UG. The control schemes of the FSPC including the MPPT algorithm, MSR and GSI are clarified in the subsequent sections, and our relevant work is detailed in [39].

A. MSR CONTROL SCHEMES

The MSR aims at maximising the output power of WT and fulfilling a unity power factor at the PMSG terminal. To accomplish this, efficacious cascaded control schemes are built for ensuring optimal operation conditions. Frequently, the MSR’s control system consists of three control schemes: a speed regulator (SCA-PI-1) and two current control schemes (SCA-PI-2 and SCA-PI-3), as seen in Figure 1. The SCA-PI-1 adjusts the angular rotation speed of the PMSG to the MPPT algorithm’s appropriate reference speed. The SCA-PI-2 alters the \( q \)-axis stator current \( (I_q, ref) \) in accordance with the reference point \( (I_q, act) \) provided by the SCA-PI-1, ensuring that the maximum power is delivered to the UG. Similarly, the SCA-PI-3 is used to keep the \( d \)-axis stator current \( (I_d, ref) \) at the zero set point \( (I_d, ref) \) in order to achieve unity power factor operation. The output signal of both SCA-PI-3 and SCA-PI-2 \( (V_{a,b,c,ref}) \) are transformed into an abc frame, \( V_{abc,ref} \), by employing \( \theta r \), which is got from the PMSG rotation speed. The \( V_{a,b,c,ref} \) signals are then compared to a 1.65 kHz triangular carrier frequency to generate IGBT pulsing signals for the MSR [39].

B. GSI CONTROL SCHEME

The linkage of the VSWT-PMSG to the utility grid is committed via a GSI. To guarantee compliance with UG criteria, cascaded vector schemes based on SCA-PI are created for GSI, as revealed in Figure 1. The GSI control scheme is responsible for two main jobs: the exterior SCA-PI-4 controller is used to control the DC-link capacitor voltage to its set point, while the SCA-PI-5 and SCA-PI-6 based interior control loops are used to manage the quadrature and direct currents \( (I_d \) and \( I_q) \). For guaranteeing that the GSI operates at a unity power factor condition, \( I_{q,ref} \) is assigned to zero. Consequently, the SCA-PI-6 \( (V_{q,ref}) \) and SCA-PI-5 \( (V_{d,ref}) \) output signals are converted into 3-phase frame signals \( V_{abc,ref} \) using the angle \( (\theta r) \). In this case, the PLL scheme retrieves the angle \( (\theta r) \). Finally, pulse firing for the IGBT inverter is generated by comparing the carrier signal frequency to the \( V_{a,b,c,ref} \) signals [39].

C. DC-LINK PROTECTION SCHEME (DCLPS)

In conditions of electrical grid trouble, the GSI is unable to integrate obtained wind energy into the utility grid because of an abrupt voltage drop on the grid [39]. The voltage drop...
induces an intense rise in DC-link voltage and an unstable power system between the grid side and the WECS. The excess energy could harm the inverter and the DC-link capacitor [45]. As a result, DCLPS is committed for protecting the WECS and keeping the DC-link voltage within allowable limits as appointed in Figure 1. In this configuration topology, a relay and a braking unit are outfitted with the DC-link as a protection mechanism [51]. When the DC-link voltage surpasses the permitted limit, the relay triggers the braking unit. Accordingly, the brake units avoid DC-link overvoltage by channelling excess power to a resistor, that is then dispersed as heat.

### D. MPPT CONTROL SCHEME

In WECS, the wind turbine power output changes accordingly to the prevailing wind speed profile and the angular rotational speed of the turbine blades. Where each wind turbine under a certain wind speed has a single optimal rotational \( \omega_{m,\text{opt}} \) speed that contributes to optimal WT operating and harnessing the maximum wind energy. To accomplish this, it is needed to integrate an MPPT algorithm with the WECS control schemes. The MPPT algorithm hunts the optimal angular rotational speed \( \omega_{m,\text{opt}} \) at a provided wind speed and delivers the information to the MS control schemes. Thereafter, the MSR controller forces the WT to rotate according to the speed given by the MPPT algorithm. In the I-MPPT such as (TSR-MPPT) algorithm, the angular rotational speed \( \omega_{m,\text{opt}} \) of the WT of any given wind speed can be obtained by Equation (11), [14], [19].

\[
\omega_{m,\text{opt}} = \frac{V_o \lambda_{\text{opt}}}{R}
\]  

Equation (11), [14], [19].

Locating the optimum rotational speed, \( \omega_{m,\text{opt}} \), utilising this way is simple, however, it mandates a particular wind speed measurement that is complex to get. The idea of seeking the optimum angular WT rotational speed without consideration for wind speed measurement is more trustworthy and promising. As a result, the tracking strategy based on D-MPPT algorithms such as P&O algorithms has recently become very popular. The P&O algorithm can be classified into two broad categories based on the SS used, which can be a fixed step size (FSS) or a variable step size (VSS) as detailed in the following subsection [52].

1) FSSP&O-MPPT ALGORITHM

The FSSP&O-MPPT algorithm is a mathematical approach used to search for the peak point of a given function. It is widely applied in WECS to get the optimal operating point that maximizes the extracted energy. The concept of this technique is that the algorithm perturbs a variable control in a certain direction by a step size and observes the captured power variation. The main disadvantage of the FSSP&O-MPPT technique is the difficulty of choosing the right step size since a small step improves the accuracy of the MPP but reduces the convergence speed. In comparison, a big step size leads to a quicker response but causes oscillation around the MPP. This oscillation causes power loss in the WECS [53]. For this reason, the VSSP&O-MPPT has been proposed by many researchers.

2) VSSP&O-MPPT ALGORITHM

A VSSP&O-MPPT algorithm is intended to eliminate the deficiencies of the FSS &O-MPPT approach by creating a balance between tracking speed and oscillation challenge. The operating principle of the VSS P&O-MPPT is that the algorithm divides that \( P - \omega \) curve into multiple zones and each has a certain SS. This strategy is efficient for tracking speed, nevertheless, it uses wind speed information to define the curve which is in turn considered as the main limitation of the I-MPPT algorithms. Besides, the number of operating zones is limited and associated SS must be carefully tuned. Therefore, the development of a new MPPT algorithm that is not reliant on dividing the \( P - \omega \), hence picking a certain perturbing SS or measuring wind speed is still required [54].

### IV. PROPOSED PPT-MPPT ALGORITHM

The proposed work aims to develop a new MPPT algorithm for the wind conversion system based on the parabolic prediction technique (PPT). The developed algorithm is intended to address the most significant issues of the existing power extraction algorithms. The concept of this algorithm comes from the observation that the wind turbine power vs. rotational speed \( (P - \omega) \) curve has a parabolic shape, characterised by a single maximum point for each wind speed [55], [56], [57], [58]. Therefore, strategies that are used to find the vertex of a parabolic curve can be applied to search the MPP of a wind turbine.

#### A. FUNDAMENTAL CONCEPT OF PPT

PPT is a parabola fitting technique used to find a maximum point (vertex) of a parabola curve based on three given points on that curve. One point must be taken from one side of the curve and two-points are taken from the other side of the curve as revealed in Figure 3. The standard formula, given by Equation (12), can be used to describe any point on the parabola curve [59], [60], [61].

\[
y = f(x) = ax^2 + bx + c
\]  

where a, b, and c are numerical coefficients and x is an unknown variable. The maximum point of the parabola curve is called the vertex. By deriving the standard formula and making the first derivative equal to zero, the vertex of the

![Figure 3. Parabola curve estimation.](image-url)
parabolic function can be calculated as follows [62], [63], [64]:

\[ f(x) = 2ax + b = 0 \]  
\[ 2ax + b = 0 \]  
\[ x = -\frac{b}{2a} \]

To find the value of vertex, the numerical coefficients \((a, b)\) are obtained from solving the corresponding equations of the three points \((x_1, f(x_1)), (x_2, f(x_2))\) and \((x_3, f(x_3))\) as follow [62], [63], [64]:

\[ f_1(x) = ax_1^2 + bx_1 + c \]  
\[ f_2(x) = ax_2^2 + bx_2 + c \]  
\[ f_3(x) = ax_3^2 + bx_3 + c \]

\[
\begin{bmatrix}
0 \\
1 \\
2
\end{bmatrix}
\begin{bmatrix}
x_1^2 \\
x_2^2 \\
x_3^2
\end{bmatrix} =
\begin{bmatrix}
0 \\
x_1 \\
x_2
\end{bmatrix} \times
\begin{bmatrix}
f_1(x) \\
f_2(x) \\
f_3(x)
\end{bmatrix}
\]

\[ \begin{bmatrix}
a \\
b \\
c
\end{bmatrix}
\]

\[ = \begin{bmatrix}
x_1^2 & x_1 & 0 \\
x_2^2 & x_2 & 0 \\
x_3^2 & x_3 & 0
\end{bmatrix}^{-1}
\begin{bmatrix}
f_1(x) \\
f_2(x) \\
f_3(x)
\end{bmatrix}
\]

B. OPERATION PRINCIPLE OF PPT-MPPT ALGORITHM

The proposed PPT-MPPT algorithm is developed to operate in two phases: Convergence Phase (CP) and Polynomial Interpolation Phase (PIP). In the CP, the algorithm estimates the parabolic output curve of wind turbine using three reference rotational speed and their corresponding powers \((\omega_1, P_1), (\omega_2, P_2)\) and \((\omega_3, P_3)\). To have a good MPPT result, \((\omega_2, P_2)\) must be higher than \((\omega_1, P_1)\) and \((\omega_3, P_3)\), as shown in Figure 4. Usually, the initial three points are not satisfied, therefore, a systematic shifting procedure must be performed for having the convergence and making the power \((P_2)\) as the highest. For the convergence procedure, the algorithm first sends three rotational speed \((\omega_1, \omega_2, \text{and } \omega_3)\), between which is an interval time \((dt)\) with the same value. Simultaneously, the extracted power of each rotational speed is measured and stored. Following that, the algorithm checks the locations of the three rotational speed and their powers on the curve to perform one of the following cases:

First case: when \(\omega_1 < \omega_2 < \omega_3\) and the measured power \(P_2\) is the highest output power. In this case for \(\omega_1 < \omega_2\) and \(P_2 > P_1\), the derivatives, \(P' (\omega_1)\) and \(P' (\omega_2)\), are positive (at the uphill side of the output curve of a wind turbine) as shown in Figure 4 (a). On the other hand, for \(\omega_2 < \omega_3\) and \(P_2 > P_3\), the derivative \(P' (\omega_2)\) and \(P' (\omega_3)\) are negative (at the downhill side of the power output curve of a wind turbine), as shown in Figure 4 (b). This means that the three given rotational speed satisfy the convergence condition. With help of the mathematics 1st derivative which state that, if \(P' (\omega)\) varies from positive to negative on the interval \(\omega_1\) and \(\omega_2\), then a \(\omega_{\text{max}}\) location is between \(\omega_1\) and \(\omega_3\) and can be found by using PIP.

Second case: when the \(\omega_1 < \omega_2 < \omega_3\) and the measured power, \(P_3\), is a present largest output power. In this case, the derivatives, \(P' (\omega_1), P' (\omega_2)\) and \(P' (\omega_3)\), are positive (at the uphill side of the power curve of a wind turbine). This means that the three measured powers do not satisfy the convergence condition. Hence, extra consideration must be imposed to have a successful convergence condition. In this case, a shifting procedure is performed in such a way that the rotational speed \(\omega_1, \omega_2, \text{and } \omega_3\) are increased by a step size \((\Delta \omega)\), until the measured power, \(P_2\), becomes the highest. After it is ensured the measured power at \(\omega_2\) is always the highest, the PIP is applied. The concept of rotational speed adjustment to the right is illustrated in Figure 5.

Third case: when the \(\omega_1 < \omega_2 < \omega_3\) and the measured power, \(P_1\), is the highest output power. In this case, the derivatives, \(P' (\omega_1), P' (\omega_2)\) and \(P' (\omega_3)\), are negative (at the downhill side of the power curve of a wind turbine). This means that the three measured powers do not satisfy the convergence conditions. Consequently, the shifting procedures to the left must be performed in such a way that the rotating speed \(\omega_1, \omega_2, \text{and } \omega_3\) are decreased by a step size \((\Delta \omega)\), until the measured power, \(P_2\), becomes the highest as shown in Figure 6. Once making sure that the measured power \(P_2\) is the highest, the PIP is applied.

In the PIP, the algorithm uses the information of the three satisfying points to create equations of the estimated parabolic curve as follows:

\[ P_1 = a\omega_1^2 + b\omega_1 + c \]  
\[ P_2 = a\omega_2^2 + b\omega_2 + c \]  
\[ P_3 = a\omega_3^2 + b\omega_3 + c \]
Based on the facts that the MPP can be reached when the first derivative of a parabolic equation is equal to zero, the maximum rotating speed ($\omega_{\text{max}}$) which produces the optimum MPP ($P_{\text{max}}$) can be reached from the following formulas:

\[
\frac{dP}{d\omega} = 2a\omega + b = 0 \quad (23)
\]

\[
\omega_{\text{max}} = -\frac{b}{2a} \quad (24)
\]

To find $\omega_{\text{max}}$, the parabolic coefficients, $a$ and $b$, can be obtained by solving the equations (20)-(22) as follows:

\[
\begin{bmatrix}
a \\
b \\
c
\end{bmatrix} = \begin{bmatrix}
\omega_1^2 & \omega_1 & 0 \\
\omega_2^2 & \omega_2 & 0 \\
\omega_3^2 & \omega_3 & 0
\end{bmatrix}^{-1}
\begin{bmatrix}
P_1 \\
P_2 \\
P_3
\end{bmatrix}
\]

\[
a = \frac{\omega_1 \times (P_2 - P_1) + \omega_2 \times (P_1 - P_3) + \omega_3 \times (P_3 - P_2)}{(\omega_1 - \omega_2) \times (\omega_1 - \omega_3) \times (\omega_2 - \omega_3)}
\]

\[
b = \frac{\omega_1^3 \times (P_1 - P_2) + \omega_2^3 \times (P_3 - P_1) + \omega_3^3 \times (P_2 - P_3)}{(\omega_1 - \omega_2) \times (\omega_1 - \omega_3) \times (\omega_2 - \omega_3)}
\]

C. DYNAMIC RESPONSE OF PPT-MPPT ALGORITHM TO WIND SPEED VARIATIONS

The dynamic response of the developed PPT-MPPT algorithm under dynamic-changing in wind speed can be analyzed based on the effect of changes in wind speed on the measured power $P_2$ position. In case, the measured power point $P_2$ at the rotating speed $\omega_2$ remains the largest, as shown in Figure 8. This means that the change in wind speed has no effect on the convergence condition and the three measured power points are still satisfied to perform the PIP for finding $\omega_{\text{max}}$. Conversely, in case, the change in wind speed has an influence on the measured power points and changes the sorting patterns of $P_2$ ($P_2$ is not the largest measured power), the algorithm will give more time to the shifting procedure to rearrange the rotational speed.

The rotational speed should be shifted to the right if the values of power after changes in wind speed are on the left side as portrayed in Figure 9. Otherwise, the rotational speed should be shifted to the left when the values of power after a change in wind speed are on the right side, as depicted in

FIGURE 7. Flowchart of PPT-MPPT algorithm.

FIGURE 8. Wind speed variation with no effect on power arrangement.
The WECS configuration circuit illustrated in Figure 1 is composed of a wind speed sensor, the WECS itself, and the control system. The control system includes a sensor to measure wind speed, which is then fed into the controller. The controller modifies the rotational speed of the WECS to optimize power extraction. The control system includes a PI controller, which adjusts the rotational speed to maintain the optimal power extraction rate. The extracted power is then transmitted to the grid through the MPPT algorithm.

Figure 10. In the associated figures, the solid line represents the \((P - \omega)\) curve before the change in wind speed, while the dashed line refers to the \((P - \omega)\) curve after a change in wind speed.

V. SIMULATION RESULTS AND DISCUSSION

The WECS configuration illustrated in Figure 1 is constructed and simulated through the MATLAB/Simulink environment. The main goal of the simulation is to validate the feasibility of the proposed PPT-MPPT algorithm for the VSWT- PMSG connected to the grid. To confirm the effectiveness of the developed PPT-MPPT algorithm, the considered system has been evaluated under various wind speed circumstances. In addition, the simulation findings of the developed PPT-MPPT algorithm are compared to those of the CP&O and VSP&O algorithms so as to establish its superiority. The overall VSWT-PMSG simulation parameters and the PI controller gains of the considered system are optimally designed and furnished in [39]. The simulation time is chosen according to the wind speed variation scenarios.

A. EVALUATION UNDER RAPID CHANGE OF WIND SPEED

To check the performance of the proposed PPT-MPPT algorithm during sudden changes in wind speed, a wind speed profile that changes every five seconds at the rate of 2 m/s was applied as seen in Figure 11. Meanwhile, the optimal rotational speed, the tip speed ratio, the power coefficient, and the extracted power waveforms of the CP&O with a small and big SS, VSP&O, and the proposed PPT-MPPT algorithms, have been analysed and compared.

The analysis and comparison have been conducted via evaluating the performances of all MPPT algorithms in terms of oscillation rate, reaching time to optimal condition and WECS efficiency indices. The WECS efficiency is determined for each step changes during the entire period so as to confirm the dynamic performance of the developed control scheme. The efficiency \(\eta_{sys}\) is computed as the ratio of the extracted output power \(P_{ext}\) of the WECS to the nominal power \(P_{nom}\) using the formula of \(\eta_{sys} = \frac{\int_0^t P_{ext}(t) dt}{\int_0^t P_{nom} dt} \times 100\%\).

In this turn, Figure 12 (a) shows that with a small SS, the reaching time to optimal rotational speed is longer and the oscillation of operation point around the optimal value is smaller when the wind speed changes quickly. Alternatively, using a big SS leads to a faster reaching to the optimal rotational speed with large oscillations apparent when the peak value is attained. The VSSP&O algorithm reduces the reaching time but there are still some oscillations around the maximum point; at steady state speed because of the strategy used. In contrast, Figure 12 (a) proves that the developed PPT-MPPT algorithm has a faster reaching time to the optimal rotational speed with zero oscillations around the maximum point due to the features of the tracking mechanism. The magnified views of the Figure 12 (a) shows that the Proposed PPT-MPPT algorithm first sent three initial rotational speed and then performed shifting procedure to satisfy the convergence condition. Consequently, the optimal rotational speed that resulted in the maximum power is obtained by applying the PIP procedure. The outcome showed that with the PPT-MMPT algorithm, the optimal rotational speed for the wind speeds of 8, 10 and 12 can be reached at 39 msec, 25 msec and 10 msec respectively. Moreover, after the optimal value was reached, the oscillation issue was totally eliminated which in turn enhanced the overall system efficiency.

The comparison study including reaching time, oscillation rate around optimal value and efficiency of the proposed PPT-MPPT, CP&O and VSSP&O algorithms for wind speed step change of 8 m/s, 10 m/s and 12 m/s are provided and listed in Table 1, Table 2 and Table 3 respectively. In view of TSR, the outcomes shown in Figure 12 (b) confirmed that the proposed PPT-MPPT has succeeded in keeping the system...
TABLE 2. Comparison of proposed PPT-MPPT and other algorithms under rapid change of 10 m/s.

| MPPT Algorithm    | Step Size (p.u) | Reaching time (msec) | Oscillations rate (p.u) | Efficiency |
|-------------------|----------------|----------------------|-------------------------|------------|
| Small SS-P&O-MPPT | 0.005          | 348                  | 0.01                    | 93.05 %    |
| Big SS-P&O-MPPT   | 0.05           | 30                   | 0.05                    | 92.31 %    |
| VSSP&O-MPPT       | 0.01 ~ 0.03    | 147                  | 0.01                    | 93.96 %    |
| Proposed PPT-MPPT | $\Delta \omega$ | 25                   | 0                       | 97.80 %    |

TABLE 3. Comparison of proposed PPT-MPPT and other algorithms under rapid change of 12 m/s.

| MPPT Algorithm    | Step Size (p.u) | Reaching time (msec) | Oscillations rate (p.u) | Efficiency |
|-------------------|----------------|----------------------|-------------------------|------------|
| Small SS-P&O-MPPT | 0.005          | 311                  | 0.01                    | 93.92 %    |
| Big SS-P&O-MPPT   | 0.05           | 26                   | 0.1                     | 91.17 %    |
| VSSP&O-MPPT       | 0.01 ~ 0.03    | 95                   | 0.01                    | 94.74 %    |
| Proposed PPT-MPPT | $\Delta \omega$ | 10                   | 0                       | 98.78 %    |

FIGURE 11. Step change of Wind speed profiles.

FIGURE 12. System response to rapid change of wind speed. (a) Rotational speed. (b) TSR.

operating at the optimal TSR value of 10.65, better than CP&O and VSP&O regardless of wind speed changes. The enlarged image in 12 (b) indicates that the proposed control algorithm supports the WECS in returning to the optimal TSR and stability following a sudden change in wind speed more effectively than the other mentioned algorithms.

The power coefficient Cp is a crucial indicator of the WECS conversion efficiency. In this study, the MPPT algorithm must maintain the Cp at the optimal value of 0.44 regardless of the wind speed change to convert the whole available wind energy into mechanical power. Zoomed views in Figure 13 (a), reveals that the big SS-P&O and PPT-MPPT algorithms attain the optimal Cp (0.44) faster than both the small SS-P&O and the VSSP&O-MPPT algorithms. Though, the big SSP&O has high steady-state oscillations that have a negative impact on the converted mechanical
power. Conversely, the proposed PPT-MPPT algorithm has a faster response with zero oscillations because of the effective tracking approach. For instance, at the step change of 10 m/s the $C_p$ descent period of the proposed PPT-MPPT was 20 msec (shorter) compared to the small SSP&O, VSSP&O and big SSP&O which take 291 msec, 139 msec and 29 msec respectively. Moreover, the proposed PPT-MPPT algorithm was able to reach the maximum power within 39 msec for the wind speed of 8 m/s, 25 msec for the wind speed of 10 m/s and 10 msec for the wind speed of 12 m/s. This indicates that the amount of captured wind power utilising the proposed PPT-MPPT algorithm under fast change wind speed is higher and more efficient compared to the other algorithms as portrayed in figure 13 (b).

To further demonstrate the performance of the proposed PPT-MPPT under rapid change of wind speed, the significant variables of GSI also have been analysed. The simulation outcomes of active and reactive power under the given wind speed profile for all algorithms are indicated in Figure 14. Figure 14 (a) indicates that when the proposed PPT-MPPT
is used, the integrated active power (AP) into UG is more precise and proximate to the nominal value than when other MPPT algorithms are applied. Besides, Figure 14(b) ascertains that when the proposed PPT-MPPT algorithms are involved into the control scheme, keeping the reactive power (RAP) at zero is more accurate and stable. According to Figure 14 details, the proposed algorithm more efficiently aids in delivering AP with excellent response and attaining RAP of a better damped with minimum fluctuation for unity power factor operation than the other schemes. To end the analysis assessment, Figure 15 visualizes the DC-link voltage ($V_{DCL}$) performance. The spotting shows that BSS-PO, SS-PO and VS-PO produce a maximum ripple $V_{DCL}$ of 0.034 p.u, 0.028 p.u and 0.030 p.u respectively. Whereas the ripple $V_{DCL}$ of PPT-MPPT is 0.018 p.u which indicates that the proposed PPT-MPPT algorithm has a less negative impact on

**FIGURE 16.** Wind speed profiles.

**FIGURE 17.** System response to rapid change of wind speed. (a) Rotational speed. (b) TSR.

**FIGURE 18.** System response to rapid change of wind speed. (a) $C_p$. (b) Mechanical power.
UG behavior. This is due to the non-use of the continuous perturbing concept for rotational speed during the tracking procedure.

**B. EVALUATION UNDER RANDOM CHANGE OF WIND SPEED**

The fluctuation and randomness of wind speed are significant challenges for the MPPT algorithms to encounter in relevant to WECS research environment. To evaluate the proposed PPT-MPPT algorithm robustness and performance under erratic wind speed variations, a randomized wind speed pattern defined in Figure 16 is utilized. It is varied at random between 8 and 12 m/s for 100 seconds to imitate a more natural wind speed profile in real life. The PPT-MPPT algorithm’s performance was compared to that of CP&O-MPPT and VSP&O-MPPT under identical conditions. The outcomes indicated in Figure 17 (a) proved that the PPT-MPPT was capable of tracking and generating the optimal PMSG rotational speed according to wind speed changes better than CP&O-MPPT and VP&O-MPPT algorithms. This instantly reflects on TSR as appears in Figure 17 (b) and confirms that the proposed PPT-MPPT algorithm outperformed the CP&O-MPPT and VSP&O-MPPT algorithms in keeping the system operating at optimal TSR value of 10.65. Alternatively, the proposed PPT-MPPT algorithm indicates optimistic outcomes by tracking the optimal Cp value of 0.44 compared with CP&O-MPPT and VSP&O-MPPT algorithms, as portrayed in Figure 18 (a) which in turn, immediately reflects on extracted wind power as exhibited in Figure 18 (b). Moreover, the magnified views in Figures 17 and 18 indeed confirmed that the TSR, Cp and extracted power using the proposed PPT-MPPT algorithm have a small variation even under the random wind speed change compared to other executed algorithms. The high performance of the Proposed PPT-MPPT algorithm is due to proper design which results in the rapid convergence speed to detect the optimal value in fewer iterations.

**VI. CONCLUSION**

MPPT algorithms associated with a control scheme of the WECS are a crucial part of extracting the maximum wind power and enhancing the system performance. This work has introduced a novel MPPT algorithm based on parabolic prediction techniques (PPT) for grid-connected VSWT-PMSG. The proposed algorithm seeks to address the most significant issues of the existing WECS MPPT algorithms as well as to achieve maximum wind power extraction and efficiency enhancement. The developed PPT-MPPT algorithm uses parabolic convex functions to estimate the parabola wind turbine output curve and locate the maximum power point on that curve. At the same time, the algorithm evolves a systematic approach for changing the concavity and optimal portions of the predicted parabola curve to ensure that the proposed scheme is in continuous convergence. The performance of the proposed PPT-MPPT algorithm has been evaluated under rapid and fluctuating wind speed profiles. Moreover, PPT-MPPT algorithm performance has also been compared with CP&O-MPPT and VSP&O-MPPT algorithms performances under the same operating circumstances. Simulation results verified that the PPT-MPPT algorithm outperforms the CP&O-MPPT and VSP&O-MPPT algorithms in terms of oscillation rate, reaching time to optimal condition and efficiency indices. The notable performance of the proposed PPT-MPPT algorithm is due to the inspired development which relies on the developer’s knowledge.

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