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RESEARCH ARTICLE OPEN ACCESS

HIGHLY EFFICIENT POWER CONDITIONING TOPOLOGY FOR MAXIMUM ENERGY EXTRACTION FROM WIND POWER SYSTEM USING HILL CLIMBING SEARCH-MPC APPROACH

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ABSTRACT

This article proposes a high-gain and high-efficiency power conditioning topology for grid connected wind energy system (WES) based on Hill Climbing Search (HCS) algorithm and a fixed frequency Model Predictive Controller (MPC) to maximize the energy harvest and control the DC/DC switched inductor boost converter (SIBC) to achieve high performance regardless of wind speed variations. In this study, the MPC is based on minimizing the difference between the reference and prediction currents, which is computed to select the switching state of the SIBC converter. The feasibility of the proposed SIBC converter and HCS-MPC scheme is verified in a variety of dynamic conditions through dSPACE DS1104-based experiments on a 3 kW wind energy conversion system prototype. Outcomes show that the suggested control mechanism follows the maximum power point (MPP) with less power fluctuations.

I. INTRODUCTION

The low conversion efficiency of wind turbine is an obstacle to the growth of WESs. The MPPT algorithm ensures that the maximum available wind energy is harnessed from the WES. Many MPPT methods have been suggested over the past few decades, and the relative merits of these various approaches are discussed in [1, 2].

An effective MPPT controller and converter can exploit available energy to significantly reduce the amount of installed WESs. Considering the MPPT techniques listed in [1], candidate techniques include P&O [3, 4] and hill climb searching (HCS) algorithms [5]. Each approach has certain advantages and disadvantages for the present application. HCS algorithm is a well-known technique with relatively good performance [6]. However, HCS algorithm cannot always converge to the true maximum power point (MPP). In addition, HCS algorithm is relatively slow, which limits its ability to track transient environmental conditions.

The main contribution of this study is to improve the HCS algorithm performance by predicting the error two-steps ahead in horizon of time through the MPC technique. The proposed MPC method consists of two-stage. The first stage is a HCS algorithm used to generate the necessary reference current that achieves the MPP. The model predictive control (MPC) constructs the second stage. It is based on the optimization of the cost function that determines the switching action for the SBIC switch. Adding MPC improves the performance of the MPPT control and gives faster response and better operation in case of fast environmental changes without requiring expensive sensing and communications equipment. The SIBC is chosen as a DC/DC boosting stage converter. It is controlled using two-steps MPC-MPPT algorithm. The main advantages of the SIBC are high boosting gain, lower switching losses. With this topology, the 50 V DC-input voltage can be boosted to 600 V with 12 DC/DC conversion gain ratio and efficiency reaches approximately to 92.5%.

These surveys show that SIBC topologies are more efficient, lighter, less bulky and less costly than the conventional DC/DC boost converters. In the WESs, grid-connected inverters are required to help convert the DC power to AC power in a single conversion stage [7, 8]. Numerous inverter circuits can be used for wind power conditioning system (PCS) [9]. For small-scale distributed renewable energy generation systems, single-phase utility interactive inverters are of particular interest [10]. This type of application normally requires a power level lower than 5 kW [11]. These inverters commutate at high frequencies and thus eliminate the low frequencies harmonics, smaller filters are used and the cost and the physical size are reduced. Moreover, the power factor created by these types of inverters could be controlled and the losses on the grid-side are thus reduced.

Consequently, the performance of the inverters connected to the grid depends largely on the control strategy applied. A suitable control of these inverters is needed to get an efficient energy transfer. Therefore, many methods for the current control of grid connected single-phase inverters have been developed. These methods include the use of the proportional integral (PI) controller [12], proportional resonant (PR) controller [13], repetitive based controller [14], deadbeat controller [15], fuzzy controller [16], and predictive controller [17]. Although, the latter has the advantage of outstanding current regulation, higher power factor, lower current harmonic distortions and fast dynamic response during the transient conditions, but demands more computing resources and requires a good knowledge of system parameters. Aiming at overcoming these disadvantages of predictive controller, an improved predictive current controller (IPCC) has been developed in this paper for single-phase full bridge grid connected inverters and has been verified through experimental tests.

This article is structured as follows: Section 2 provides a detailed description of the proposed WES, including SIBC and single-phase inverter. Section 3 presents the improved HCS-MPPT algorithm. Section 4 presents the experimental results and findings and their discussion, along with a comprehensive analysis of the MPPT tracking performance in terms of recovery time, response time, efficiency and energy yield. Finally, Section 5 concludes the article with a summary of findings.

II. SYSTEM TOPOLOGY STRUCTURE

The configuration of the proposed WCS is depicted in Figure 1. The system consists of two stages. The first stage is a high-gain switched inductor with voltage multiplication boost converter to provide high-gain, high-efficiency and the DC source required by the single-phase voltage source inverter. The second stage is a single-phase full bridge inverter is used to inject a sinusoidal current into the grid with low harmonic distortion as possible.

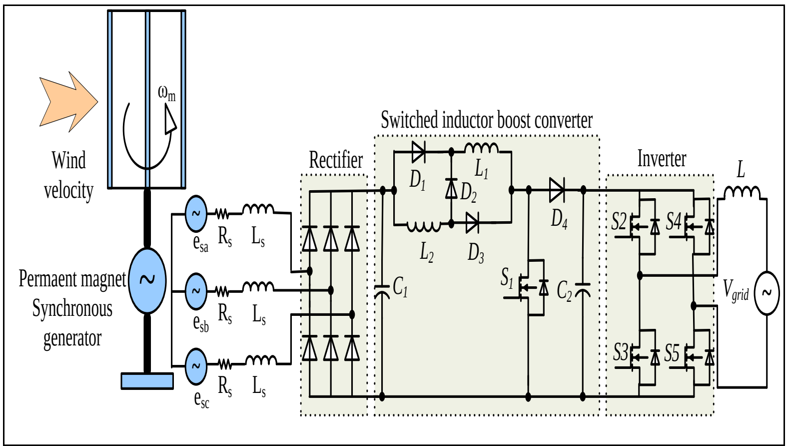

Figure 1: Configuration of the proposed wind energy system.
Source: Authors, (2025).

III. SUGGESTED CONTROLLER DESIGN

III.1 IMPROVED HCS-MPPT ALGORITHM

In this part, a maximum power tracker controller by using MPC will be presented for the SIBC in order to operate the wind turbine at the optimal power point until wind changes. The main goal to using the MPC technique in the proposed HCS-MPPT algorithm is to increase the response of the control of MPPT on WESs when there is abrupt change in the environmental conditions such as wind speed, because predictions of the future values of the system variables gives the advantages of fast reference tracking. The proposed HCS-MPPT algorithm is developed in such a manner that it sets a reference current corresponding to the peak power of the wind turbine by predicting the error at next sampling time before applying the switching signal to the SIBC.

III.2 HCS-MPPT USING FIXED FREQUENCY MPC

A discretization of the SIBC model is required for the implementation of the HCS-MPPT algorithm. By using the Euler forward approximation, the derivative of the input current (I_{in}) and input voltage (V_{in}) can be approximately discretized as follows:

$$\begin{cases} \dfrac{dI_{in}}{dt} = \dfrac{I_{in}(n+1) - I_{in}(n)}{T_s} \\ \dfrac{dV_{in}}{dt} = \dfrac{V_{in}(n+1) - V_{in}(n)}{T_s} \end{cases} \quad (1)$$

Where T_s is the sampling time. The discretization of the SIBC equations can derive from a state-space model (2) when the switch is turned ON as follows:

$$\begin{bmatrix} I_{in}(n+1) \\ V_{in}(n+1) \end{bmatrix} = \begin{bmatrix} 1 - \frac{T_s}{L}\left(\frac{R_L}{2} + R_{on}\right) & \frac{T_s}{L} \\ 0 & 2 \end{bmatrix} \begin{bmatrix} I_{in}(n) \\ V_{in}(n) \end{bmatrix} + \begin{bmatrix} 0 \\ -1 \end{bmatrix} \begin{bmatrix} V_{in}(n-1) \\ V_d \end{bmatrix} \quad (2)$$

When the switch is turned OFF:

$$\begin{bmatrix} I_{in}(n+1) \\ V_{in}(n+1) \end{bmatrix} = \begin{bmatrix} 1 - \frac{T_s}{L} R_L & \frac{T_s}{2L} \\ 0 & 2 \end{bmatrix} \begin{bmatrix} I_{in}(n) \\ V_{in}(n) \end{bmatrix} + \begin{bmatrix} 0 & -\frac{T_s}{L} & -\frac{T_s}{2L} \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{in}(n-1) \\ V_d \\ V_0 \end{bmatrix} \quad (3)$$

As a good approximation to reduce the number of sensors, the predicted value of input voltage can be expressed as:

$$V_{in}(n+1) \cong 2\,V_{in}(n) - V_{in}(n-1) \quad (4)$$

Previous work has suggested the addition of a second stage of MPC for even better system performance and model accuracy [18]. Therefore, Eqs. (2) to (4) are adjusted to get Eqs. (5) and (6) for two-stage MPC:

$$\begin{bmatrix} I_{in}(n+2) \\ V_{in}(n+2) \end{bmatrix} = \begin{bmatrix} 1 - \frac{T_s}{L}\left(\frac{R_L}{2} + R_{on}\right) & \frac{T_s}{L} \\ 0 & 2 \end{bmatrix} \begin{bmatrix} I_{in}(n+1) \\ V_{in}(n+1) \end{bmatrix} + \begin{bmatrix} 0 \\ -1 \end{bmatrix} \begin{bmatrix} V_{in}(n) \\ V_d \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} I_{in}(n+2) \\ V_{in}(n+2) \end{bmatrix} = \begin{bmatrix} 1 - \frac{T_s}{L} R_L & \frac{T_s}{2L} \\ 0 & 2 \end{bmatrix} \begin{bmatrix} I_{in}(n+1) \\ V_{in}(n+1) \end{bmatrix} + \begin{bmatrix} 0 & -\frac{T_s}{L} & -\frac{T_s}{2L} \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{in}(n) \\ V_d \\ V_0 \end{bmatrix} \quad (6)$$

The cost function for the MPC algorithm is calculated with the consideration that the switch of the SIBC is turned "ON" and "OFF" it is given as:

$$g_{s=1,0} = \left| I_{in}(n+2) - I_{ref} \right| \quad (7)$$

The flowchart in Figure 2 illustrates all the main steps of the modified HCS-MPPT algorithm by using the proposed MPC method.

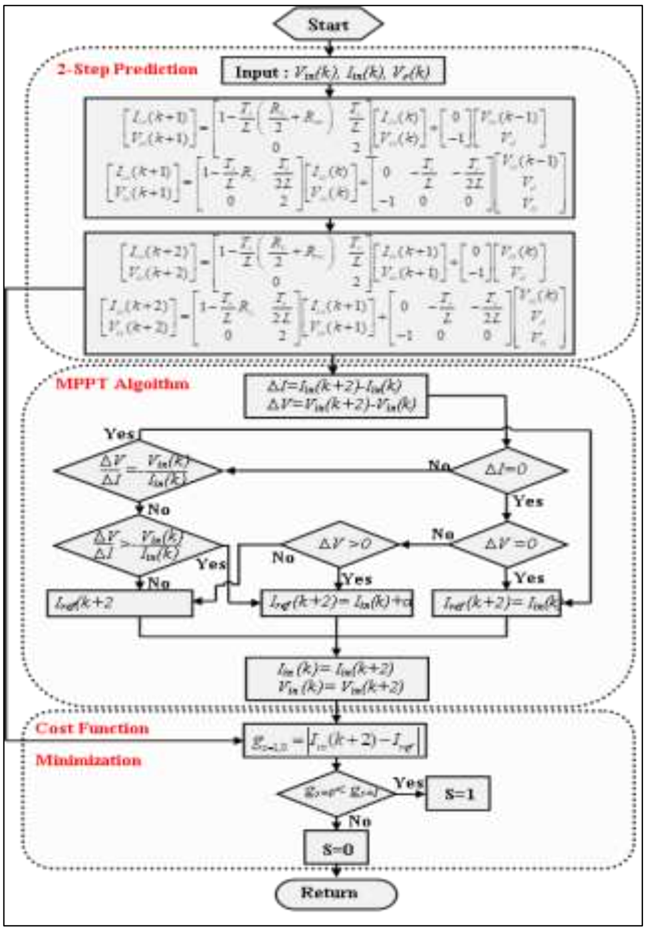

Figure 2: Proposed HCS-MPPT using MPC method.
Source: Authors, (2025).

The cost function assures the tracking of predicted input current from the reference provided by the HCS-MPPT algorithm. Comparison of cost function for different switching states of SIBC determines the control actions for the following time instant. Figure 3 shows the implemented of modified MPPT control scheme to the proposed SIBC.

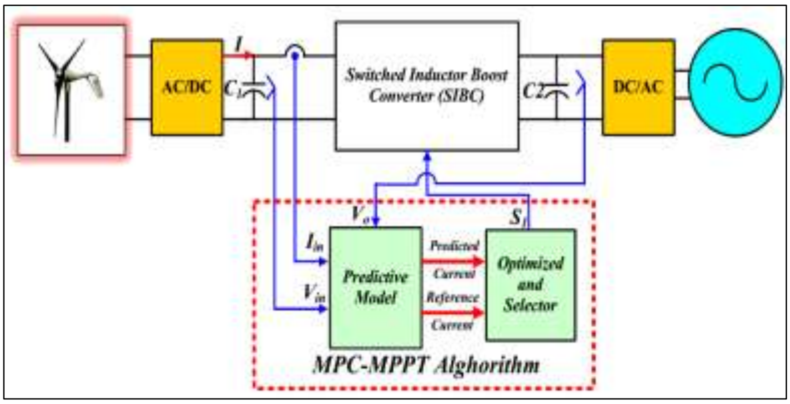

Figure 3: The proposed WES implementing HCS-MPPT using MPC method.
Source: Authors, (2025).

IV. EXPERIMENTAL RESULTS

To verify the performance of the proposed MPC-MPPT algorithm for the SIBC, a prototype of grid connected WES based on a small PMSG is developed as shown in Figure 4.

Figure 4: Photograph of the experimental setup.
Source: Authors, (2025).

Figure. 5 shows the experimental result of the system using the proposed MPC-MPPT algorithm. In this test, the algorithm goal is to track the maximum power operating point of the WES and the wind speed has changed in several steps. As can be seen from Figure 5 the turbine shaft speed is continuously matched to the wind speed in such a way that it is extracted maximum power out of the wind. The DC-input current of SIBC is controlled according to the MPPT strategy and can be better regulated to achieve the optimum reference current during wind speed step changes.

Also, the power conversion coefficient C_p is kept constant, and varies in a relatively small range around its optimal value of 0.47, which means that the wind turbine tracks maximum power from the wind. The mechanical torque changes accordingly to accommodate the variations in the wind speed. The mechanical power had small fluctuations phenomenon, but the value of the wind turbine power would back to the best value soon. It is noticed that the mechanical input power is slightly greater than the electrical power production due to the system losses.

The DC-link voltage response is completely robust with perfect rejection of wind speed disturbances and is maintained within the variation of 2%. Note also that only active power is delivered to the grid when the PI controller reaches its steady state value. The armature current (I_{dc}) is variable and depends on the mechanical power variations, thus the armature current is changed as the wind speed changes. The obtained results confirm that the proposed MPC-MPPT algorithm of the SIBC works properly and quite able to track the maximum wind power of the wind generation system effectively according to an increase/decrease in the wind speed.

This verifies that the tracking performance of the proposed MPC-MPPT algorithm is very good.

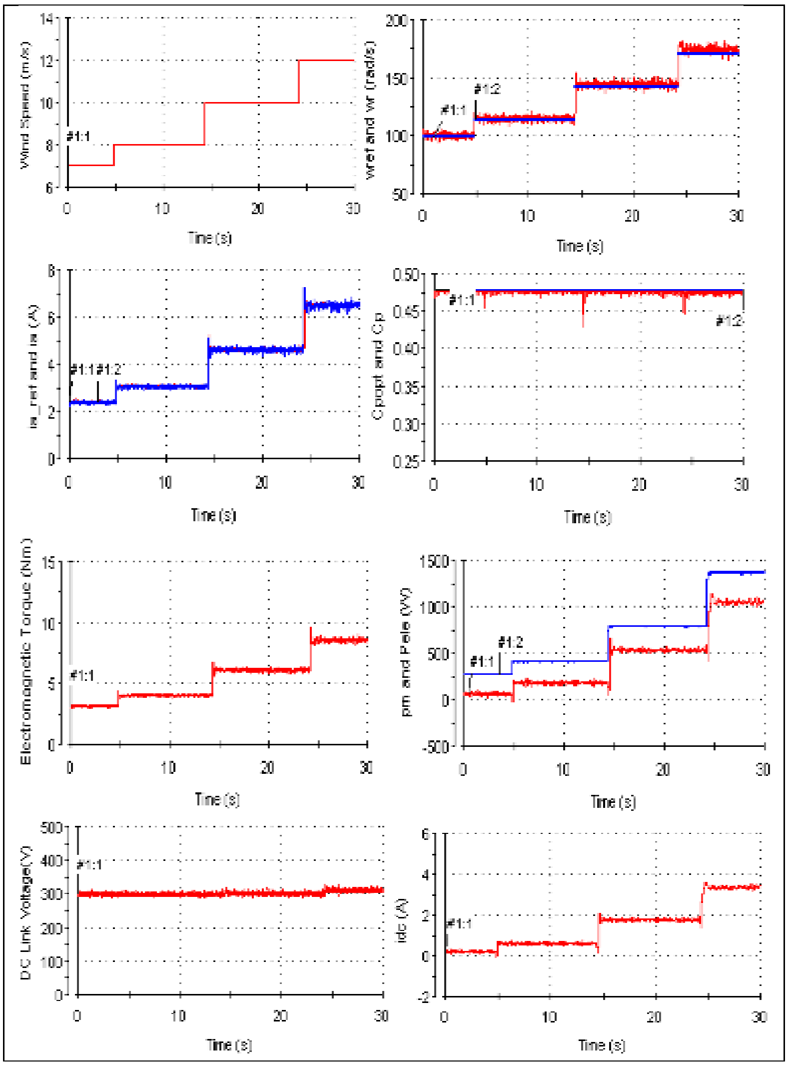

Figure 5: Dynamic response of the proposed WES using HCS-MPPT algorithm.
Source: Authors, (2025).

Figure 6 shows the tracking performance comparison between three typical MPPT algorithms: the Tip-Speed Ratio (TSR) algorithm [19, 20], the P&O algorithm [21], and the proposed MPC-MPPT algorithm. It can be seen from Figure 6 that every MPPT algorithm works properly, i.e. successfully tracks MPP. The proposed MPC-MPPT algorithm was found to be the fastest in achieving the MPP. The recovery time (t_r) upon wind speed change was also faster for the proposed MPC-MPPT algorithm. The dynamic response for algorithms based on proposed MPC-MPPT and TSR is relatively similar. In comparison, the P&O algorithm was found to be the slowest algorithm. Therefore it can be concluded that the robust tracking performance is achieved using the proposed MPC-MPPT algorithm under the wind speed variation.

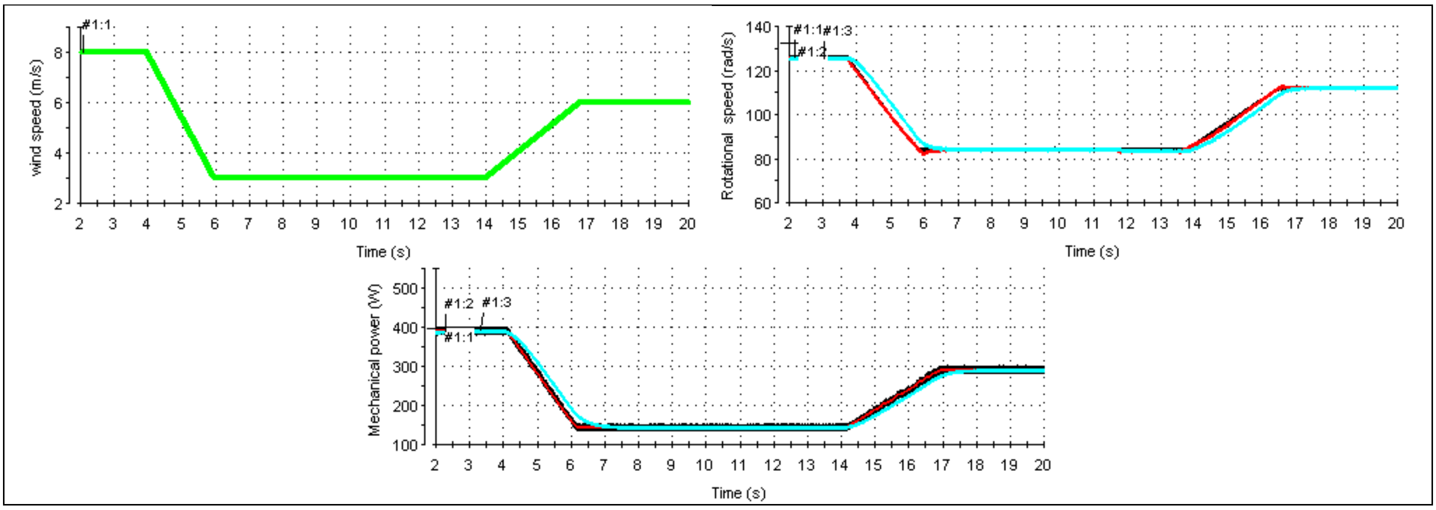

Figure 6: MPPT tracking performance: MPC-MPPT (Black), P&O (Cyan), and TSR (Red).
Source: Authors, (2025).

The comparisons of the three typical algorithms considering the efficiency (η) and energy yield (E) are summarized in Table 1 Based on results and analysis, the proposed MPC-MPPT algorithm reached the highest value of power conversion coefficient (C_p). It was followed by the TSR algorithm, with the average value of C_p being 0.4627. The P&O algorithm was found to be the least efficient method.

Table 1: Summary of performance of three MPPT algorithms.

Method	C_p	t_s(s)	t_r(s)	E(W)	η(%)
MPC-MPPT	0.4785	0.0247	0.0007	734.5	96.48
TSR	0.4627	0.0885	0.0024	665.9	90.42
P&O	0.4123	0.2478	0.0371	597.4	80.44

Source: Authors, (2025).

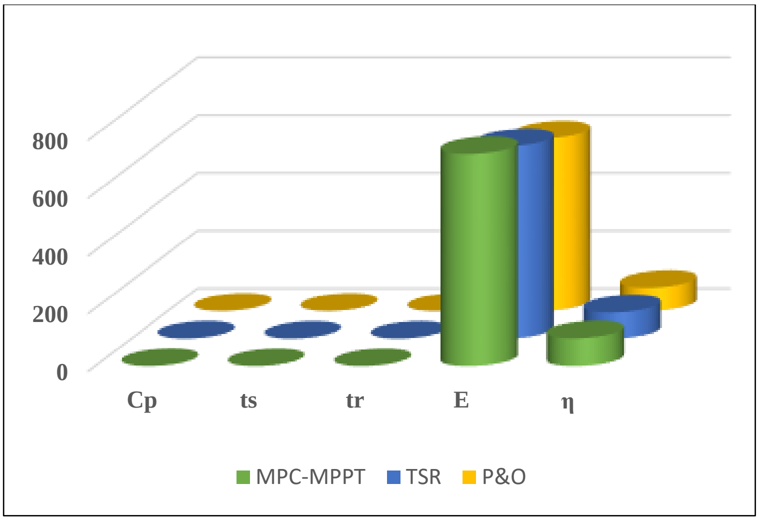

Figure 7: Comparisons of the three typical algorithms.
Source: Authors, (2025).

V. CONCLUSIONS

In this paper, an efficient power conditioning system for grid connected wind energy applications was introduced. The proposed system can potentially reduce the cost and size of wind turbine generator systems. A switched inductor boost converter (SIBC) is a totally novel technology, it has been used as DC/DC boosting stage converter due to its inherent features such as high DC/DC conversion ratio and better efficiency. Hence, MPPT techniques based on HCS algorithm employing a MPC method is proposed to extract maximum power from the wind generator through the SIBC. Modifications applied to the traditional HCS algorithm enabled the proposed MPC-MPPT algorithm to interact quickly for rapidly varying wind conditions. Moreover, it has been shown that the proposed MPC-MPPT algorithm can be easily implemented with reduced hardware setup because only current and voltage sensors have been used. Therefore, neither the measurement of the wind speed nor the knowledge of the wind turbine characteristics is required. Then, three of the typical MPPT algorithms (TSR algorithm, P&O algorithm, and suggested MPC-MPPT algorithm) have been implemented practically. A comparison be-tween the MPPT algorithms has been carried out to demonstrate the ad-vantages of the proposed MPC-MPPT algorithm, the results have shown that the proposed MPC-MPPT algorithm is the most favorable featuring fast dynamic response, and accuracy under almost any conditions

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Z. A, B. B and N. H.
Methodology: Z. A and B. B.
Investigation: Z. A and B. B.
Discussion of results: Z. A, B. B and N. H.
Writing – Original Draft: Z. A and B. B.
Writing – Review and Editing: Z. A, B. B and N. H.
Resources: B. B.
Supervision: Z. A and B. b.
Approval of the final text: Z. A, B. B and N. H.

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