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OPTIMAL POWER TRACKING THROUGH NONLINEAR BACKSTEPPING STRATEGY OF A FIVE-PHASE PMSG BASED WIND POWER GENERATION SYSTEM

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Abstract- Modern nonlinear techniques have been widely used to control electrical power drives due to its ability to deal with high efficiency against systems with unstructured dynamics. Hence, in this study, a robust backstepping strategy with two loops is implemented to control a direct-driven five-phase Permanent Magnet Synchronous wind-power generating system. The two loops have the role of controlling both the speed of the studied generator with high inertia and the 5 produced current components, for the purpose of enhancing the extracted power rate from the wind, lowering the power losses during the wind turbine operation, improving the dynamic and static performances, and increasing the system robustness. In order to reveal the superiority of the studied control system, the efficiency result is compared to the performance of the classical PI and other nonlinear techniques in the field. The comparison shows that the BSC increases the efficiency of the system to 95.3%, in contrast to the traditional techniques that can provide only a percentage average of 86,2, when using a proportional-integral control loop.

Keywords: Backstepping Control, Variable-Speed Wind Energy Conversion System, Nonlinear Control, Maximum Power Point Tracking, Grid Control, Multi-Phase PMSG, Optimal Power Extraction, DC-Link Stabilization, Five-Phase Permanent Magnet Synchronous Generator.

1. INTRODUCTION

With the evolution in the energy flied, the world is approaching to new clean sources as the wind power technologies that gains the worldwide support as an eco-friendly and reliable electrical power supplier. Its contribution to the global climate is increased significantly in the recent years. In general, the wind power is the transformed wind kinetic energy to an electrical energy by using the wind turbines [1].

In order to guarantee an efficient energy conversion, The type of the installed generator is a critical matter. Hence, the PMSG is an electrical machine that provides better reliability, better efficiency, and lower weight with a gearless construction that eliminates the need for mechanical speed gearbox, and when it comes to the power needs with elevated capacitance, PMSG delivers an excellent efficiency rate [2]. Moreover, an important factor to judge about the generator effectiveness is the proportion of torque divided by turbine inertia, in the PMSG case this proportion is increased, which results an elevated maximum acceleration of the turbine/generator.

Against this background, a multiphase PMSG is presented as a strong choice to replace the conventional PMSG with three phases due to the different advantages as increasing the produced power, reducing the DC bus ripples, reducing component costs, without forgetting that the multiphase has a high fault tolerance ability to operate with a suitable effectiveness during troubles as open-phase and short-circuit faults. Furthermore, the multiphase PMSG provides can establish high torque output due to the big magnetic flux density [3]. On the other hand, the proposed model of the multiphase PMSG brings more nonlinear variables to the system design, therefore, the reliability and robustness becomes more affected to the change of parameters and load disturbances. To prevent this kind of drawbacks, the research field overrode the classical techniques due to its inadequate performance and poor accuracy because of the parameter tuning difficulty [4].

Consequently, in order to offer better dynamic response, implementing modern control strategies has been studied to control the wind turbine, as the Fuzzy-Logic controllers [5], the MPC control [6], the adaptive control, [7], and the SMC control [8], that extract the highest rates of efficiency. Reasoning from this fact, this study is focusing on designing a nonlinear robust solution by using backstepping control in order to control the proposed direct-driven five-phase Permanent Magnet Synchronous wind-power generating system. Since the backstepping Control is an excellent control technique that brings many advantages and benefits [9] [10]. This study puts insight into this technique to validate its efficiency in controlling an installed five-phase PMSG in a high-powered wind turbine, improving the system steadiness, and enhancing the optimal power tracking ability.

The BSC results in this study are compared to other control techniques to confirm the strong point of the proposed approach and the provided advantages in terms of speed of tracking and robustness.

This paper is presented in the form of six sections: 1st section gives a general introduction. Second Section provides the general system proper model. Section 3 details with the generator side control by constructing the suggested backstepping control laws, with an overall analysis to ensure a high rate of accordance connecting the speed loop and current loop, since the proposed generator contains several variables and an extended number of phases compared to the conventional 3-phase generator. Forth Section displays the grid side converter control. Section 5 brings a detailed discussion the collected results. The final section concludes the study.

2. DESIGNING OF WECS

In this paper, a variable wind turbine that is coupled by a five-phase PMSG is interconnected with the utility grid by using two high power converters and resistor–inductor circuit network, in order to guarantee DC-link stabilization and an optimal power injection into the utility.

2.1. Architecture of the variable wind turbine

By operating the wind turbine under the wind effect, a mechanical energy is produced, it is assigned in this study by the following equation [11]:

$$P_{tr} = \frac{1}{2}.\rho A.V_w^3.C_p(\beta\lambda) \tag{1}$$

where,
C_p is the power coefficient,
λ is the tip speed ratio (*TSR*) that equals $\lambda = R.\omega_m / V_w$
ρ is the atmospheric density,
V_w is the velocity of the wind,
A is the Sweep Area of Turbine Blades
β is the pitch angle

The turbine mechanical torque is expressed as [11]:

$$T_m = P_m / \omega_m \tag{2}$$

2.2. Five-Phase PMSG Modeling

Applying the expanded Park's Transformation, the d-axis & q-axis vectors of the five-five PMSG voltages is stated in the synchronous frame as [8] [12]:

$$\begin{bmatrix} V_{d1} \\ V_{q1} \\ V_{d2} \\ V_{q2} \end{bmatrix} = \left[R_s\right] \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} + \begin{bmatrix} L_{d1}\dfrac{d\psi_{d1}}{dt} - \omega_e\psi_{q1} \\ L_{q1}\dfrac{d\psi_{q1}}{dt} + \omega_e\psi_{d1} \\ L_{d2}\dfrac{d\psi_{d2}}{dt} - 3\omega_e\psi_{q2} \\ L_{q2}\dfrac{d\psi_{q2}}{dt} + 3\omega_e\psi_{d2} \end{bmatrix} \tag{3}$$

where, $V_{d1}, V_{q1}, V_{d2}, V_{q2}$ are the stator voltages, i_{d1}, i_{q1}, i_{d2}, i_{q2} are the dq-axis current components, R_s is the stator resistance, $\psi_{d1}, \psi_{q1}, \psi_{q2}, \psi_{d2}$ express the dynamics of the flux linkage in the generator stator, L_{dq12} is the inductances, ω_e defines the machine electrical speed.

Considering the uniform-airgap of the PMSG in this study, then $L_d = L_q = L_s$, therefore, the components of flux-linkage are set as the following :

$$\begin{cases} \psi_{d1} = L_d i_{d1} + \psi_{pm} \\ \psi_{q1} = L_q i_{q1} \\ \psi_{d2} = L_d i_{d2} \\ \psi_{q2} = L_q i_{q2} \end{cases} \tag{4}$$

where, ψ_{pm} is the rotor permanent magnet flux-linkage.

The mechanical dynamics of the studied machine can be formulated as [11]:

$$\dot{\omega}_m = \frac{T_e}{J} - \frac{T_m}{J} - \frac{f\,\omega_m}{J} \tag{5}$$

where,
f express coefficient of friction.
T_m express Mechanical torque.
J express Rotational Inertia.

The designed five-phase PMSG electromagnetic torque can be indicated by the following [10]:

$$T_e = \frac{5}{2}p\left[\psi_{d1}i_{q1} - \psi_{q1}i_{d1} + 3\psi_{d2}i_{q2} - \psi_{q2}i_{d2}\right] \tag{6}$$

By setting i_{d1}, i_{d2}, and i_{q2} to zero, the third harmonic current component and Joule losses can be removed. Then, the electromagnetic torque can be assigned as:

$$T_e = 5/2\,p.\psi_{pm}i_{q1} \tag{7}$$

where, (p) is the number of poles.

3. GENERATOR SIDE BACKSTEPPING CONTROL

3.1. Control Overview

The overall approach to control the proposed wind turbine is shown in Figure 1. The essential goal of generator side converter control is guaranteeing the maximum power tracking (P_m) when the turbine is exposed to a variable wind profile. Hence, the five-phase PMSG is controlled to reach the optimal characteristics, through manipulating the turbine and drive it toward the Power Coefficient peak $(C_{p\max} = 0.48)$.

To reach this characteristic, (TSR) is controlled to be fixed around the optimal rate $(\lambda_{opt} = 8.1)$. Figure 2 details the relationship that connects (C_p) & (TSR).

The generator optimal velocity is determined as:

$$\omega_{m\_opt} = \lambda_{opt}.V_w / R \tag{8}$$

Hence, the rated produced power using the wind turbine can be written as:

$$P_{tr\_\max} = \frac{1}{2}.\rho.S.\left(R.\frac{\omega_{m\_opt}}{\lambda_{opt}}\right)^3.C_{p\max} \tag{9}$$

The integred five-phase PMSG in this study is the key component in WECS for converting the mechanical power to an electrical power, for its many beneficial features in contrast to the classical synchronous machine.

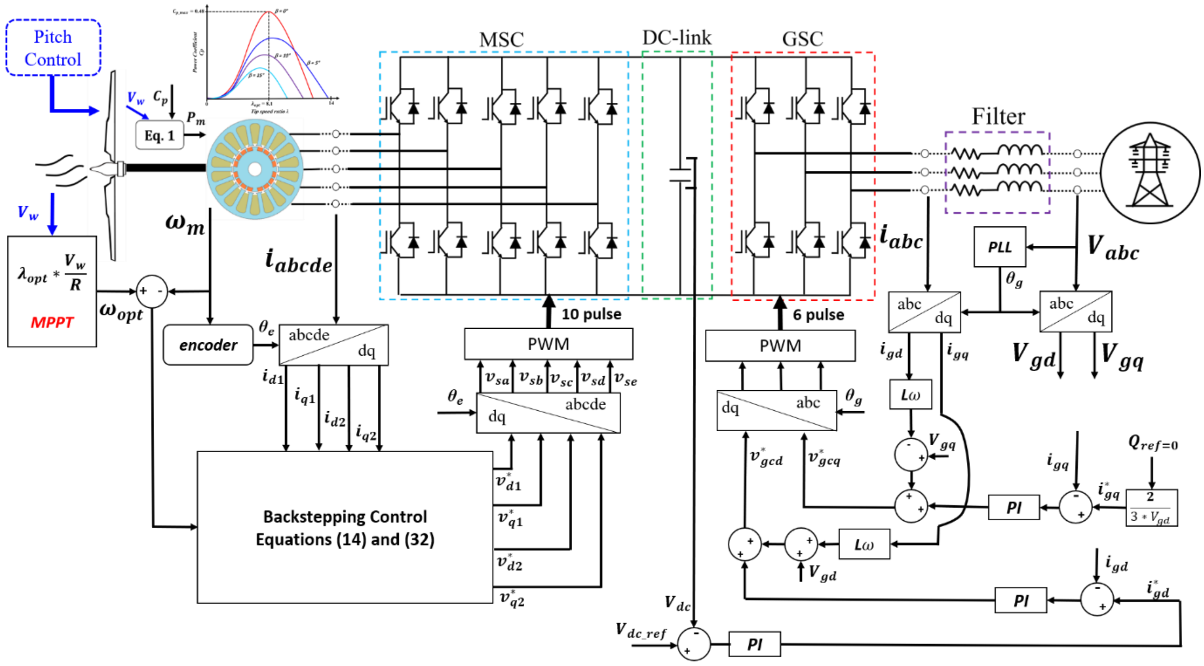

Figure 1. System control configuration [8]

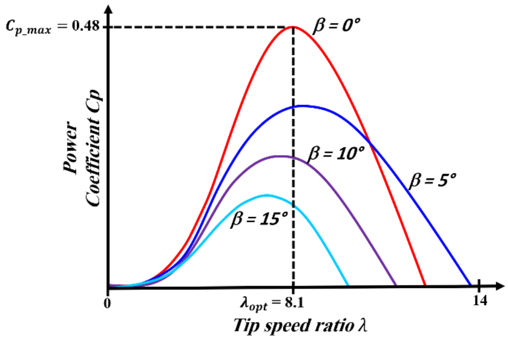

Figure 2. Function curve connecting C_p and *TSR* (λ) [8]

With the aim to control the studied multiphase generator, two loops are considered, the 1st loop has the role of controling the rotor speed and ensure that it pursues the optimal reference at that time. The output of the first loop is used to define the virtuel control. Thereafter, the second loop had the role of controlling the four dq- axis current elements of the five-phase PMSG by generating the voltage vectors references as the real controls of the generator side converter.

3.2. Backstepping Control Strategy

BSC approach is conditional on Lyapunov stability approach, with multistep construction, at each step, a virtuel references is constructed for the next step as stabilizing function and the convinient Lyapunov candidate is then produced to validate the stability of the system, the operation extend til the final command function is determined

Step 1: Designing Speed Loop Based Backstepping Technique

With the objective to achieve an optimal speed control, the tracking error in Equation (10) must be vanished rapidly from every starting point.

$$e_\omega = \omega_{m\_opt} - \omega_m \tag{10}$$

where, (ω_{m_opt}) is the reference speed, and (ω_m) is the estimated actual speed.

By using Equations (5) and (7), then the speed error dynamics is formulated as:

$$\dot{e}_\omega = \dot{\omega}_{m\_opt} - \dot{\omega}_m = -\frac{1}{J}\left[-f\,\omega_m + T_m - \frac{5p\psi_{pm}}{2} i_{q1}\right] \tag{11}$$

The Lyapunov function is selected to ensure the system stabilization as [13]:

$$V_1 = \frac{1}{2} e_\omega^2 \tag{12}$$

The time derivative of Lyapunov candidate in Equation (12) is expressed as:

$$\dot{V}_1 = e_\omega \dot{e}_\omega = -k_\omega e_\omega^2 + \\ + \frac{e_\omega}{J}\left[-T_m + f\,\omega_m + k_\omega J e_\omega + \frac{5p\psi_{pm}}{2} i_{q1}\right] \tag{13}$$

with $k_\omega > 0$

In conformity with Lyapunov stability condition, the derivative of V_1 must fulfill a negative value, to guarantee the convergence of tracking error to zero. Therefore, the currents $i_{d1,2}$ and $i_{q1,2}$ are considered as the virtual system inputs. Therefore, virtual control input i_{q1} is formulated as

$$i_{q1}^* = \frac{2}{5p\psi_m}\left[T_m - f\,\omega_m - k_\omega J e_\omega\right] \tag{14}$$

Thus, the time derivative of Lyapunov candidate becomes as:

$$\dot{V}_1 = e_\omega \dot{e}_\omega = -k_\omega e_\omega^2 < 0 \tag{15}$$

Consequently, the global asymptotic stability condition of the backstepping tracking control is reached using the designed dynamic rule i_{q1}^* in Equation (14).

Step 2: Designing the Five-Phase Current Loop Based Backstepping Technique

To reach the optimal tracking, the virtual control rules $[i_{q1}\ i_{d1}\ i_{q2}\ i_{d2}]$ are used to extract the real control rules $\left[v_{q1}\ v_{d1}\ v_{q2}\ v_{d2}\right]$. The five-phase PMSG current errors are formulated as the following:

$$e_{d,12}(t)=\left[i^*_{d,12}(t)-i_{d,12}(t)\right] \tag{16}$$

$$e_{q,12}(t)=\left[e^*_{q,12}(t)-e_{q,12}(t)\right] \tag{17}$$

By merging Equations (3) and (4) , then :

$$\frac{di_{d1}}{dt}=-\frac{R_s}{L_s}i_{d1}+\omega_e i_{q1}+\frac{1}{L_s}V_{d1} \tag{18}$$

$$\frac{di_{q1}}{dt}=-\frac{R_s}{L_s}i_{q1}-\omega_e i_{d1}-\frac{\psi_{pm}\omega_e}{L_s}+\frac{1}{L_s}V_{q1} \tag{19}$$

$$\frac{di_{d2}}{dt}=-\frac{R_s}{L_s}i_{d2}+3\omega_e i_{q2}+\frac{1}{L_s}V_{d2} \tag{20}$$

$$\frac{di_{q2}}{dt}=-\frac{R_s}{L_s}i_{q2}-3\omega_e i_{d2}+\frac{1}{L_s}V_{q2} \tag{21}$$

By using Equations (18), (19), (20) and (21), the time derivative of current errors can be expressed as:

$$\dot{e}_{d1}=-\frac{1}{L_s}\left[-R_s i_{d1}+L_s\omega_e i_{q1}+V_{d1}\right] \tag{22}$$

$$\dot{e}_{d2}=-\frac{1}{L_s}\left[-R_s i_{d2}+3L_s\omega_e i_{q2}+V_{d2}\right] \tag{23}$$

$$\dot{e}_{q2}=-\frac{1}{L_s}\left[-R_s i_{q2}-3L_s\omega_e i_{d2}+V_{q2}\right] \tag{24}$$

$$\dot{e}_{q1}=\frac{di^*_{q1}}{dt}-\frac{1}{L_s}\left[-R_s i_{q1}-L_s\omega_e i_{d1}-\psi_{pm}\omega_e+V_{q1}\right] \tag{25}$$

Equation (25) can be developed by using Equations (10) and (14) as the following:

$$\begin{aligned}\dot{e}_{q1}&=\frac{2\left[f-k_\omega J\right]}{5p\psi_{pm}}\dot{e}_\omega+\\&+\frac{1}{L_s}\left[R_s i_{q1}+L_s\omega_e i_{d1}+\psi_{pm}\omega_e-V_{q1}\right]\end{aligned} \tag{26}$$

Moreover, assisted by Equations (14) and (17), the speed error dynamics in Equation (11) is reformulated as:

$$\dot{e}_\omega=\frac{1}{J}\left[-k_\omega J e_\omega-\frac{5p\psi_{pm}}{2}e_{q1}\right] \tag{27}$$

Thus, Equation (26) became:

$$\begin{aligned}\dot{e}_{q1}&=\frac{2\left[f-k_\omega J\right]}{5pJ\psi_{pm}}\left[-k_\omega J e_\omega-\frac{5p\psi_{pm}}{2}e_{q1}\right]+\\&+\frac{1}{L_s}\left[R_s i_{q1}+L_s\omega_e i_{d1}+\psi_{pm}\omega_e-V_{q1}\right]\end{aligned} \tag{28}$$

A novel Lyapunov candidature is elected in order to control the system using the voltage vectors that are considered as the real control references:

$$V_2=\frac{1}{2}e_\omega^2+\frac{1}{2}e_{q1}^2+\frac{1}{2}e_{d1}^2+\frac{1}{2}e_{q2}^2+\frac{1}{2}e_{d2}^2 \tag{29}$$

Equation (29) derivative is developed as the following:

$$\dot{V}_1=e_\omega\dot{e}_\omega+e_{q1}\dot{e}_{q1}+e_{d1}\dot{e}_{d1}+e_{q2}\dot{e}_{q2}+e_{d2}\dot{e}_{q2} \tag{30}$$

Thus, using Equations (22), (23), (24), (27) and (28), the following equation is revealed:

$$\begin{aligned}\dot{V}_1&=-k_{q1}e_{q1}^2-k_{d1}e_{d1}^2-k_{q2}e_{q2}^2-k_{d2}e_{d2}^2-k_\omega e_\omega^2+\\&+\frac{e_{q1}}{L_s}\left[\begin{array}{l}\frac{2L_s}{5pJ\psi_{pm}}\left[f-k_\omega J\right]\left(-k_\omega J e_\omega-\frac{5p\psi_{pm}}{2}e_{q1}\right)\\+R_s i_{q1}+L_s\omega_e i_{d1}+\psi_{pm}\omega_e-V_{q1}+k_{q1}L_s e_{q1}\\-\frac{5L_s p\psi_{pm}}{2J}e_\omega\end{array}\right]+\\&+\frac{e_{d1}}{L_s}\left[R_s i_{d1}-L_s\omega_e i_{q1}-V_{d1}+k_{d1}L_s e_{d1}\right]+\\&+\frac{e_{q2}}{L_s}\left[R_s i_{q2}+3L_s\omega_e i_{d2}-V_{q2}+k_{q2}L_s e_{q2}\right]+\\&+\frac{e_{d2}}{L_s}\left[R_s i_{d2}-3L_s\omega_e i_{q2}-V_{d2}+k_{d2}L_s e_{d2}\right]\end{aligned} \tag{31}$$

where, $k_{q1},k_{d1},k_{q2},k_{d2}$ are positive constants.

With the aim to secure the studied system stability, (V_2) derivative must satisfy a negative value. Thus, five-phase PMSG reference control voltages are proposed as:

$$\begin{aligned}v^*_{d1}&=R_s i_{d1}-L_s\omega_e i_{q1}+k_{d1}L_s e_{d1}\\v^*_{q1}&=\frac{2L_s}{5pJ\psi_{pm}}\left[f-k_\omega J\right]\left(-k_\omega J e_\omega-\frac{5p\psi_{pm}}{2}e_{q1}\right)+\\&\quad+k_{q1}L_s e_{q1}-\frac{5L_s p\psi_{pm}}{2J}e_\omega+R_s i_{q1}+L_s\omega_e i_{d1}+\psi_{pm}\omega_e\\v^*_{d2}&=R_s i_{d2}-3L_s\omega_e i_{q2}+k_{d2}L_s e_{d2}\\v^*_{q2}&=R_s i_{q2}+3L_s\omega_e i_{d2}-V_{q2}+k_{q2}L_s e_{q2}\end{aligned} \tag{32}$$

4. GRID SIDE CONVERTER CONTROL

The GSC control is responsible for supervising the transmitted energy toward the interconnected electrical grid, and guaranteeing that is proportional to the load, by eliminating the reactive power and ensuring Unity Power Factor. The implemented control in this paper is the voltage-oriented control (VOC), through two series of control loops that are responsible for adjusting the DC link voltage, as well as forcing the dq-axis grid current components to follow their references.

With the aim to express the voltage equations of Utility Grid, dq-axis reference frame representation is used [8]:

$$\begin{bmatrix}V_{gcd}\\V_{gcq}\end{bmatrix}=\left[R_g\right]\begin{bmatrix}i_{gd}\\i_{gq}\end{bmatrix}+\begin{bmatrix}L_g\frac{di_{gd}}{dt}-L_g\omega_g i_{gq}\\L_g\frac{di_{gd}}{dt}+L_{dg}\omega_g i_{gd}\end{bmatrix}+\begin{bmatrix}V_g\\0\end{bmatrix} \tag{33}$$

V_g expresses the voltage element in direct axis.

i_{gd} , i_{gq} express the current elements.

L_g and R_g denote the resistor–inductor circuit network.

V_{gcd} , V_{gcq} denote the GSC voltage elements.

The objective of this control is to conserve the dc link voltage along a constant level, in addition to ensuring the flow of electrical energy into the grid with high effeciecy. .As shown in Equation (34) and (35) , active and reactive powers are controlled by controlling the dq-axis grid current elemetns respectively.

$$P = \frac{3}{2} V_{gd} i_{gd} \tag{34}$$

$$Q = \frac{3}{2} V_{gd} i_{gq} \tag{35}$$

5. SIMULATION RESULTS

The results of this study are extracted by using MATLAB/Simulink with the intention of validating the assumptions about the dominance of the suggested BSC strategy in enhancing the studied five-phase PMSG based variable wind turbine. The revealed advantages in terms of steady stat error, speed of tracking, robustness and efficiency are compared to the classical SMC and PI controllers. Moreover, the proposed system is associated with a healthy utility grid with the purpose of transmitting electrical energy with Unity power Factor. Thus, VOC control has been implemented in this paper. Additionally, the used PLL of the grid comes with a view to achieve the network synchronization. Table 1 exhibits the designed five-phase PMSG parameters.

Table 1. Wind turbine system parameters [8], [14]

Rated power	1.5 MW
Turbine radius (*R*)	32.06
Rated WT speed	9.42 rad/s
Stator resistance	3.17 mΩ
Stator inductance	0.395 mH
PM flux linkage	1.48 Wb
$C_{p\ max}$	0.48
Pole pairs	48
TSR	8.1
inertia moment	35 000 N.m
DC-link voltage	1150 V
Dc-link Capacitor	0.023 F
Grid side resistance	0.6 mΩ
Grid side inductance	0,165 mH
Grid voltage	575 V
Grid frequency	60 Hz

5.1. Set-Point Tracking Ability Examination Using Step Wind Profile

The First test of the proposed Backstepping control is implimented using under step change profile of wind speed as can be seen in Figure 3. The generator speed reaches its optimal value of (9.425 rad/s) whithin the rated wind speed of (12 m/s) after an average timing of (0.045 s), faster than the PI controller in reference [8]. Moreover, Figures 5 and 6 indicate the Mechanical power and the produced five-phase PMSG current, as documented, the current profile follows the wind speed path accurately, and the mechanical power is matching with the theorical optimal power. Therefoe the tracking requerement is achieved using the proposed BSC, and the system is fulfilling the best performance.

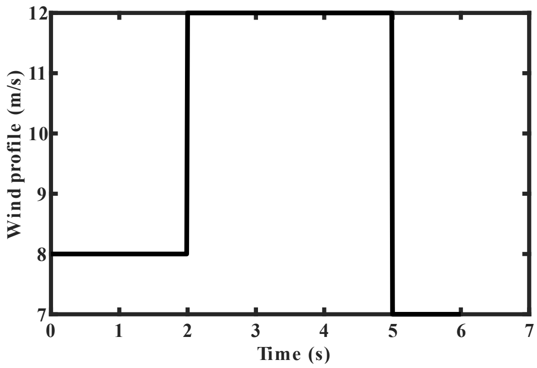

Figure 3. Wind speed

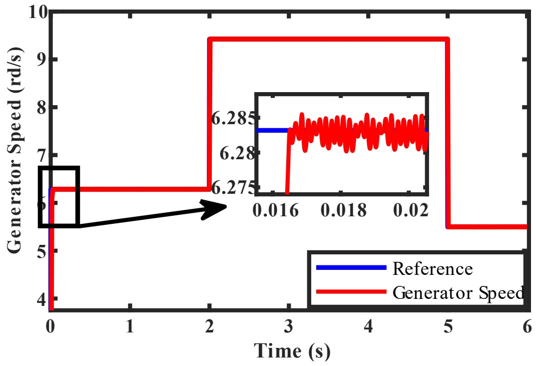

Figure 4. Generator speed

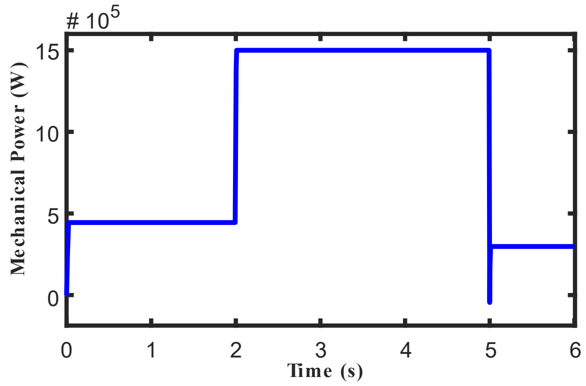

Figure 5. Mechanical power

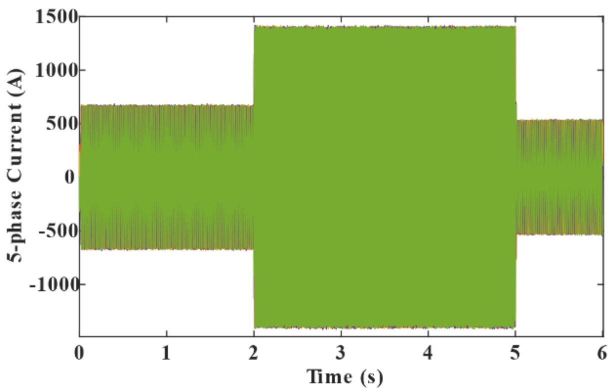

Figure 6. Generator five-phase current

5.2. Examination by Using Unpredictable Wind Speed Profile

With the aim to confirm the suggested Backstepping control ability, and discover the efficacy and robustness rate, another simulation test is conducted in this study under an unpredictable Wind speed input. The results are shown in the following figures.

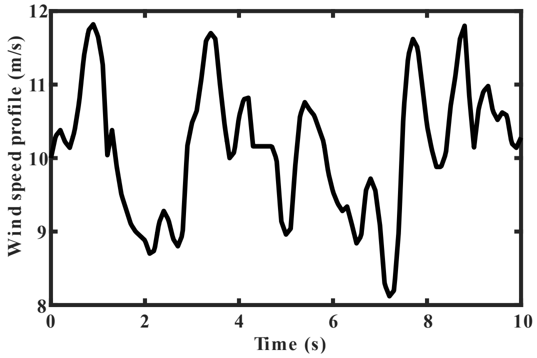

Figure 7. Unpredictable Wind Speed

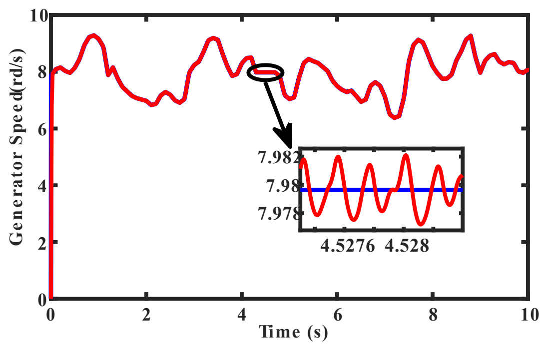

Figure 8. Generator Speed

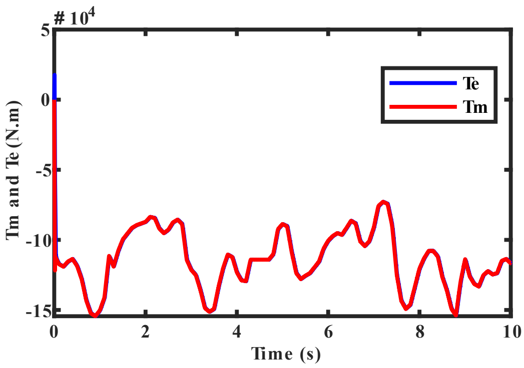

Figure 9. Mechanical & electromagnetic torques

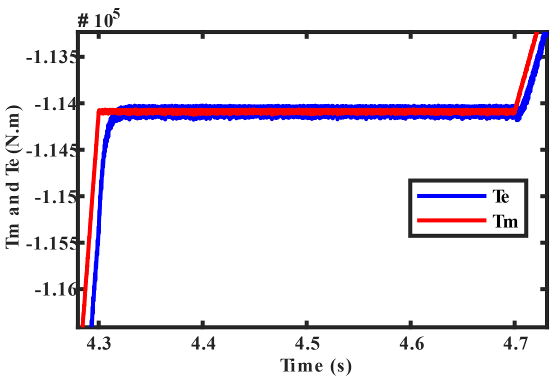

Figure 10. Close-up view of mechanical & electromagnetic torques

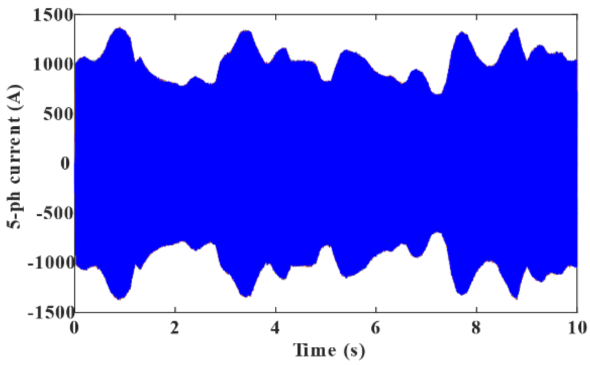

Figure 11. Five Generator five-phase current

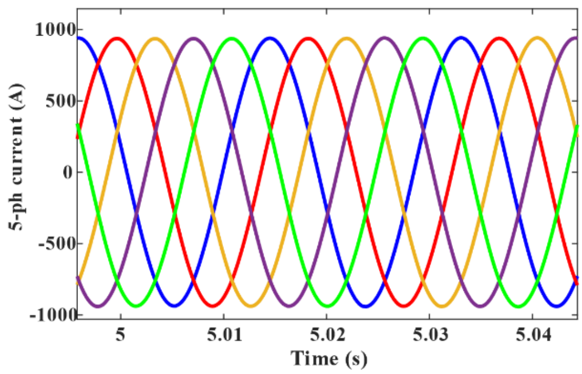

Figure 12. Close-up view of the five-phase PMSG current

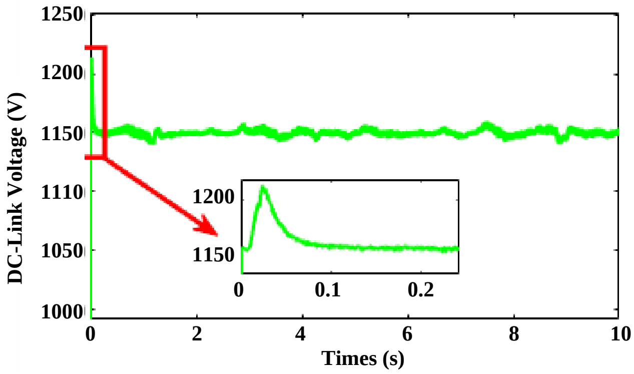

Figure 13. The DC-link Voltage

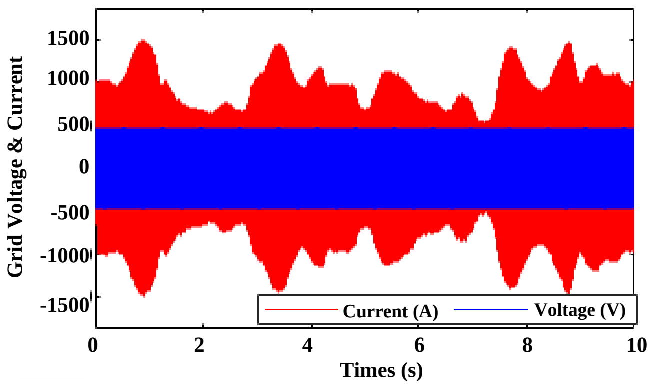

Figure 14. Grid current & voltage

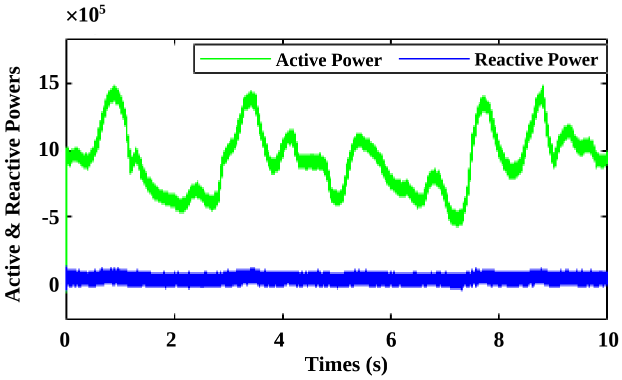

Figure 15. Injected power into the grid

The PMSG velocity is displayed in Figure 8. The generator speed (ω_m) is accurately tracking its desired reference (ω_{m_opt}) at any moment. Hence, the suggested BSC based MPPT technique, offers a high performance against the unpredictable conditions of wind speed, and the wind turbine is working with an excellent achievement. That is to say the transformed energy by the turbine is optimized and the Power-Coefficient (C_p) is adjusted to reach its optimal value during the proposed test in this paper. On the other hand, the electromagnetic and the mechanical torques are matching during the course of simulation as Figures 9 and 10 demonstrates. Furthermore, Figure 11 and 12 exhibit the five-phase PMSG current that is obviously following the wind speed path, with smooth and proportionate curves and the switching losses can be considered negligible. Accordingly, the suggested BSC is achieving an excellent performance with reference to the tracking error, response time, and robustness.

The proposed (VOC) to monitor the grid side converter delivers a suitable efficiency. As it can be seen in Figure 13, the DC-bus voltage is fixed around (1150 V), with a small overshoot value of (70 V). Moreover, the grid side control allows the injection of the three-phase currents into the grid with an acceptable quality and harmonic distortion rate, which can be easy to notice in Figure 14 that shows the grid current and voltage that are on phase.

Finally, the injected electrical power into the grid in this study reached a rate of efficiency of 95.3%. The injected active and reactive powers profiles are shown in figure 15. The first observation to make is that the reactive power is kept around zero value during the whole simulation as it is planned, and the active power is following the mechanical power smoothly with high precision, with the existence of some normal oscillations due the large-scale power producing.

In order to validate the assumptions, the collected results after applying the constructed BSC in this study are compared with the classical PI control and the conventional sliding mode control. Table 2 summarizes the performance comparison, which can confirm that the backstepping approach improves the extracted power from the wind and offers faster tracking timing, smaller losses and lower steady-state error. These outcomes validate the supremacy of the BSC over other control approaches

Table 2. Efficiency of the studied strategies in different research of literature

Technique	Efficiency	Response time	Static errors (%)	performance
PI Controller, [8]	86.2%	0.79 s	0.87%	Low
(SMC) strategy, [8]	91.14%	0.1 s	0.335%	Medium
Backstepping Control , (Main paper)	95.3%	0.045 s	0.2%	High

6. CONCLUSIONS

This research is concerned with integrating a nonlinear robust backstepping strategy, with the aim of controlling a high power five-phase PMSG, installed in a variable WECS, interconnected to a healthy grid. The proposed system architecture is detailed during the different sections of this paper. Two tests have been applied in this study to display the benefits of the BSC control. A first test using step change test is used to examine the tracking speed ability, then, an unpredictable profile of the wind speed is used to validate the entire system under the suggested BSC monitoring. The results are clearly at high rate of efficiency compared to other types of control in terms of speed, static error lowering and robustness. Moreover, the stability of backstepping control is ensured by applying Lyapunov function. The revealed results are matching with the proposed assumptions in this paper, which demonstrates that the BSC approach enhances the wind turbine performance, regardless the fast speed changes of the wind. Besides that, the grid side converter is controlled with high efficiency using the proposed grid control, and the active power flow is guaranteed with Unity Power Factor.

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