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ANALYSIS OF PERFORMANCE COEFFICIENTS IN MAXIMUM ELECTRICAL POWER EXTRACTION FROM STAND-ALONE WIND ENERGY CONVERSION SYSTEM

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ABSTRACT: Increasing performance and improving efficiency in maximum power extraction from Wind Energy Conversion Systems (WECS) is a quite important research topic. Today, in the large-scale WECS, it is widely aimed to extract the maximum mechanical power from the wind turbine using the Maximum Power Point Tracking (MPPT) unit. Similarly, it can also be targeted to achieve maximum mechanical power in small-scale WECS applications. However, losses occur in structural subsystems and electrical subunits located in WECS. Due to these losses, the overall system efficiency decreases and the characteristic of the system is also affected. The operation of these systems can also be performed via maximum electrical output power extraction, which is one of the most up-to-date ideas. Thus, the overall WECS rather than the wind turbine can be optimally controlled. Eventually, maximum electrical power tracking (MEPT) based designs can provide higher power extraction with higher efficiency than MPPT-based ones. In this paper, considering the system operating concepts with MPPT and MEPT for a stand-alone Permanent Magnet Synchronous Generator (PMSG) based WECS, the changes in performance coefficients at defined focus points in terms of system efficiency are evaluated. Technical and theoretical comparative analyzes are also made for each specific wind speed between 8m/s and 12m/s.

Keywords: *Maximum Electrical Power Tracking (MEPT), Maximum Power Point Tracking (MPPT), Performance Coefficients, Permanent-Magnet Synchronous Generator (PMSG), Wind Energy Conversion System (WECS)*

Şebeke-Bağlantısız Rüzgar Enerjisi Dönüşüm Sisteminden Maksimum Elektriksel Güç Eldesinde Performans Katsayılarının Analizi

ÖZ: Rüzgar Enerjisi Dönüşüm Sistemleri (WECS)'nden maksimum güç yakalanmasında performansın artırılması ve enerji verimliliğinin iyileştirilmesi oldukça önemli bir araştırma konusudur. Günümüzde büyük-ölçekli WECS'lerde Maksimum Güç Noktası Takibi (MPPT) birimi kullanılarak rüzgar türbininden maksimum mekanik gücün elde edilmesi yaygın olarak amaçlanmaktadır. Benzerce küçük-ölçekli WECS uygulamalarında da maksimum mekanik güce ulaşmak amaçlanabilir. Ancak WECS'de yer alan yapısal alt sistemler ve elektriksel alt birimlerde kayıplar meydana gelir. Bu kayıplardan dolayı tüm sistemin verimi düşer ve sistemin karakteristiği de ayrıca etkilenir. En güncel fikirlerden biri olan maksimum elektriksel çıkış gücünün yakalanması ile de bu sistemlerin çalışması gerçekleştirilebilmektedir. Böylece, rüzgar türbininden ziyade WECS'in tamamı optimal olarak kontrol edilebilir. Nihai olarak da Maksimum Elektriksel Güç Takibi (MEPT)'li tasarımlar MPPT'li tasarımlarından daha yüksek verimlilik ile daha yüksek gücün elde edilmesini sağlayabilmektedir. Bu çalışmada, şebeke bağlantısız Kalıcı Mıknatıslı Senkron Generatör (PMSG) temelli WECS için MPPT'li ve MEPT'li sistem çalışma konseptleri düşünülerek, sistem verimliliği açısından belirli odak noktalarındaki performans katsayılarının değişimleri değerlendirilmektedir. Ayrıca 8m/s ve 12m/s arasında her bir belirli rüzgar hızı için de teknik ve teorik olarak karşılaştırmalı analizler yapılmaktadır.

Anahtar Kelimeler: *Maksimum Elektriksel Güç Takibi, Maksimum Güç Noktası İzleme, Performans Katsayıları, Kalıcı Mıknatıslı Senkron Generator, Rüzgar Enerjisi Dönüşüm Sistemleri*

1. INTRODUCTION

With the increasing population, the quality of life and development level of societies, and technological advances in industrialization, the world's energy demand is increasing day by day (Dursun and Kulaksiz, 2020b). On the other hand, fossil fuel-based sources were widely used in power generation until recently. However, some serious social problems also arise due to the low energy efficiency of these resources, limited reserve capacity, decrease in usability, environmental pollution and greenhouse gas effect. However, low energy efficiency, limited reserve capacity and reduced availability of these resources cause environmental pollution and greenhouse gas effects, and thus serious social problems arise (Dursun et al., 2020; Kumar et al., 2018). Today, there is a great interest in renewable energy-based power generation systems using renewable energy resources such as solar, wind, hydroelectric, biomass and geothermal, which have attractive advantages to cope with these problems, and developed countries also make serious investments in such energy production systems (Lee and Kim, 2016). Among these energy resources, solar and wind attract more attention due to some of their advantages. In fact, while solar-based power generation systems were more popular in the recent past, this trend has now changed to wind-based power generation systems (Singh et al., 2022). The main reasons for this trend are that energy production can be made when the wind has aerodynamic flow regardless of day and night, and that wind energy is clean, infinite has zero-carbon emission and can provide greater power generation with less space occupation (Hussain and Mishra, 2016; Pranupa et al., 2022). Besides, it is known from the data of the Global Wind Energy Council (GWEC) that the global total wind power installation reached approximately 837GW with new installations in 2021 and has an annual growth of 12% (GWEC, 2022). Moreover, it is predicted among various scenarios that it can reach approximately 2100GW levels by 2030 and meet 20% of the world's needs (Pranupa et al., 2022).

Wind Energy Conversion System (WECS) is a device that mainly consists of wind turbine (WT), generator, power converter and controller units. While the kinetic energy of the wind is converted to mechanical energy by wind turbine, the conversion of mechanical energy into electrical energy is provided by the generator. Also, the electrical output suitable for consumer demand is regulated by the power converter and control units.

Various types of WECS structures have been proposed for the literature and used in industrial applications. Considering two different focuses, these classifications can be made in relation to WT orientation and WT operating speed type. Depending on the classification type of WT orientation, there are two broad families of wind turbines in the world today: vertical-axis WT (VAWT) and horizontal-axis WT (HAWT) systems. In the VAWT systems, axial rotation is perpendicular to the ground, while in HAWTs it is parallel to the ground (Hossain and Ali, 2015). Furthermore, VAWT systems are simpler in design and have the advantage of positioning the main equipment at ground level. However, it has a low tip speed ratio (TSR) and also has major disadvantages such as uncontrollable output power and low overall performance. On the other hand, three-blades (HAWTs) are widely used in modern industrial WECSs with the advantages of improved efficiency, controllability, high rotational speeds, lower mechanical stress and lower cost (Pao and Johnson, 2011).

WECSs are mainly divided into two types with the classification related to operating speed type; fixed-speed WECS and variable-speed WECS (Mousa et al., 2021). Fixed-speed WECSs are simple and cheaper, while variable-speed WECSs are more efficient thanks to the Maximum Power Point Tracking (MPPT) Control. Because the nature of the wind has a climatically non-linear and time-varying characteristic related to the flow of air. Therefore, the output power of WECS is also always fluctuating and variable (Nasiri et al., 2014). In addition, large fluctuations in power cause tensions and high mechanical stresses in the mechanical parts. Thus, fixed-speed WECSs can be operated in a very limited range, while variable-speed WECSs can be operated at optimal operating points in the whole wind speed range by full controllability in accordance with the nature of the wind, and higher energy can be captured from the flow of the wind (Hussain and Mishra, 2016).

Operating regions of WECS are classified into four regions by wind speed as shown in Figure 1 (Kumar and Chatterjee, 2016).

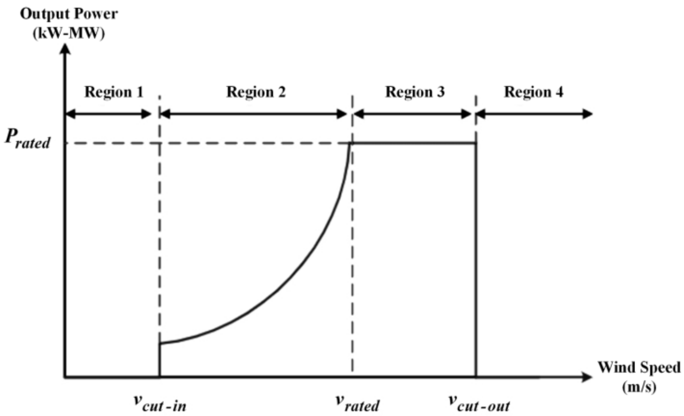


Figure 1. Operating Regions of WECS.

First one is Region 1 that represents wind speed is lower than cut-in wind speed (v_{cut-in}) and it is also known as the parking-mode. Power generation is not carried out in this region and grid-connected WECSs are disconnected from the utility grid. The section between the v_{cut-in} and rated wind speed (v_{rated}) is called as Region 2. Herein, various MPPT algorithms and control strategies are operated during a fixed pitch-angle, and WECS is controlled to capture as much power as possible. Region 3 is the section between the v_{rated} and the cut-out wind speed (v_{cut-in}) and the mechanical power generation is limited to its nominal value by performing stall control and pitch-angle control in here. Thus, damage to the turbine system is prevented at wind speeds above the v_{rated}. The last one is Region 4 where there are extreme wind speeds. To prevent damage from unsafe airflow, WECS is disabled by braking, and power generation is stopped. Grid-connected WECSs are also completely disconnected from the utility grid.

Examining the literature and industrial applications, it can be seen that various generator types are used in fixed-speed and variable-speed WECS structures depending on the development technologies over time. These generators can be listed as Squirrel Cage Induction Generator (SCIG), Wound Rotor Induction Generator (WRIG), Doubly-Fed Induction Generator (DFIG), Wound Rotor Synchronous Generator (WRSG) and Permanent Magnet Synchronous Generator (PMSG) (Chinmaya and Singh, 2018; Mousa et al., 2021; Vijayakumar et al., 2015; Yang et al., 2016; Yaramasu et al., 2015). Also, considering variable-speed WECS applications, power electronics converters are needed for controllability. In the SCIG-based WECS, while speed control can be provided at a limited level in fixed-speed applications, full variable-speed operation can be realized with a full-scale power converter. Nevertheless, it can still suffer from large mechanical stress. On the other hand, WRIG-based WECS can take place in semi-variable speed and full-variable speed applications regarding the used converter type. In the semi-variable speed operation, it suffers from high maintenance costs due to slip rings and brushes, and high initial investment costs due to an additional power converter. Also, external resistance causes losses and reduces reliability. Besides, full-variable speed operation is provided by a full-scale power converter. DFIG-based WECS can employ 30% semi-variable speed operation by needing a partial-scale power converter (Cheng and Zhu, 2014). However, due to the fact that slip rings and brushes require regular maintenance, their use in offshore wind farms is limited. Finally, the usage of PMSG-based WECS has attracted a great deal of attention worldwide with its advantages such as efficiency, reliability, fault ride through (FRT) compatibility, power density, low maintenance cost as well as direct-driven operation and no DC excitation current (Dursun and Kulaksiz, 2020b; Mousa et al., 2021). As a result of the mentioned advantages, various types of PMSGs related to phase number and generation power have also been developed and are used in small-scale, medium-scale, or large-scale WECS applications.

Many different types of converter structures can be used in WECS applications regarding the type of generator used. Some of these are back-to-back converter (BTBC) (Youssef et al., 2019), matrix converter (Barakati et al., 2009; Melício et al., 2010), rectifier and inverter (Yaramasu et al., 2015), rectifier and various DC-DC converters (Dursun and Kulaksiz, 2020b; Fathabadi, 2017; Hussain and Mishra, 2016). However, power converters are expected to meet several technical and operational requirements in order to achieve the desired type of application. These are initial cost, reliability, modularity and maintenance cost, efficiency, power quality, grid-code compliance, high-power density/small-weight and easy controllability (Yaramasu et al., 2015). Given merits and demerits, Power converters used in research and industrial applications are mainly of two types: BTBC structure and a combination of the rectifier and DC-DC converters. BTBC consists of two voltage source converters called the machine-side converter (MSC) and the grid-side converter (GSC) and is generally more advantageous for medium-scale and large-scale applications. On the other hand, uncontrolled rectifier and DC-DC boost converter (BC) are widely used in stand-alone and small-scale WECS applications with the merits of efficiency, simplicity, cost, and easy controllability. Therefore, this type of power converter is used in this paper.

Efficiency and higher power extraction are crucial issues for WECSs. An efficient WECS should be able to provide maximum power extraction by operating at a certain optimal point corresponding to each instantaneous changing wind speed over time. This type of operation is known in the literature as MPPT control or MPPT operation. Evaluating in general, MPPT operation consists of two parts: MPPT algorithms and MPPT controller designs. While the optimal operating point is determined by MPPT algorithms, WECS is brought to this operating point by appropriate switching of the power converter by MPPT controllers.

Examining the literature, it can be seen that different types of MPPT algorithms are utilized in WECS applications. Some of them are perturbation and observation (P&O) (Cheng and Zhu, 2014), modified P&O (Youssef et al., 2019), tip speed ratio (TSR) (Dursun and Kulaksiz, 2020a), power signal feedback (PSF) (Barakati et al., 2009), optimal torque control (OTC) (Ganjefar et al., 2014), optimum relation based (ORB) as well as incremental conductance (IC) (Kumar et al., 2018). Also, there are some structures in which these algorithms are hybridized. In addition, intelligent structures such as the fuzzy logic controller (FLC) (Yaakoubi et al., 2019), the neural network (NN) (Yin et al., 2020), and other soft computing-based MPPT algorithms are used. Besides, meta-heuristic-optimization algorithms using PSO and its derivatives have also been recently proposed for MPPT search.

In the MPPT controller design, which is the second subject, various techniques such as proportional-integral (PI) control, FLC, fractional-order PI, back-stepping, model-reference adaptive control and different sliding mode control types have been examined by researchers (Dursun and Kulaksiz, 2020b). However, all these mentioned structures have merits and demerits relative to each other. Therefore, unified framework designs created by hybridizing techniques have also been used in current studies (Dursun et al., 2020).

Traditionally, MPPT operation aims to achieve maximum turbine output mechanical power. However, losses occur in conversion units in WECS and situations that affect the efficiency are revealed. The system operating point is also affected. Therefore, among current perspectives, the maximum electrical output power tracking (MEPT) method becomes a more efficient structure (Fathabadi, 2017). It is aimed to achieve maximum efficiency and maximum power extraction at the end-point.

The main subject of this paper consists of detailed analysis of the changes in performance coefficients in both the MPPT operation and the MEPT operation for the stand-alone PMSG-based WECS. For each specific wind speed between 8m/s and 12m/s, the changes in the characteristics of the WECS are presented theoretically by investigating at different inspection points. Thus, changes in the power coefficient of wind turbine, power coefficient turbine-generator output, power coefficient of turbine-generator-rectifier output and power coefficient of turbine-generator-rectifier-converter output are expressed respectively.

Examining the literature, it can be seen that a similar analysis has been made for the vertical-axis WT based WECS structure in (Fathabadi, 2017). However, in this paper, entire analyzes are performed for the horizontal-axis WT based WECS. Thus, the results of the detailed analyzes in this study are included in the literature and constitute the main contribution of this paper. Nonetheless, the details of the algorithm and controller design for MPPT and MEPT operation fall outside the main focus of this study. Interested researchers can access the details of these parts from other studies of the author (Dursun et al., 2020; Dursun and Kulaksiz, 2020b).

The rest of this paper is presented as follows: In Section 2, the WECS configuration is given in detail. Similarly, Section 3 presents a detailed analysis of the changes in performance coefficients and discussion. Finally, conclusions are provided in Section 4.

2. WECS CONFIGURATION

The schematic diagram of the WECS configuration designed for this study is presented in Figure 2. This configuration basis on the small-scale stand-alone PMSG-based WECS, which consists of the wind turbine, PMSG, three-phase uncontrolled rectifier, connection capacitor, BC, load, MPPT algorithms, and SMC-based MPPT controller. Moreover, MPPT algorithms are presented in two different types, which are maximum mechanical power tracking (MMPT) and maximum electrical power tracking (MEPT). For such a configuration structure, MEPT operation provides economy and efficiency.

As can be seen from Figure 2, by taking some measurements from WECS, the MPPT algorithm is operated and thus the optimal operating point, which is BC reference voltage, is determined. Herein, the BC input voltage, BC reference voltage and BC output voltage are transferred to the MPPT controller. Moreover, the controller generates the switching signal of the BC to bring the WECS to the specified operating point to extract the maximum electrical output power. In addition, BC input voltage V_{in}, BC output voltage V_O and reference voltage V_{in_opt} (V_{ref}), which is the optimal operating point corresponding to maximum electrical output power, are indicated herein.

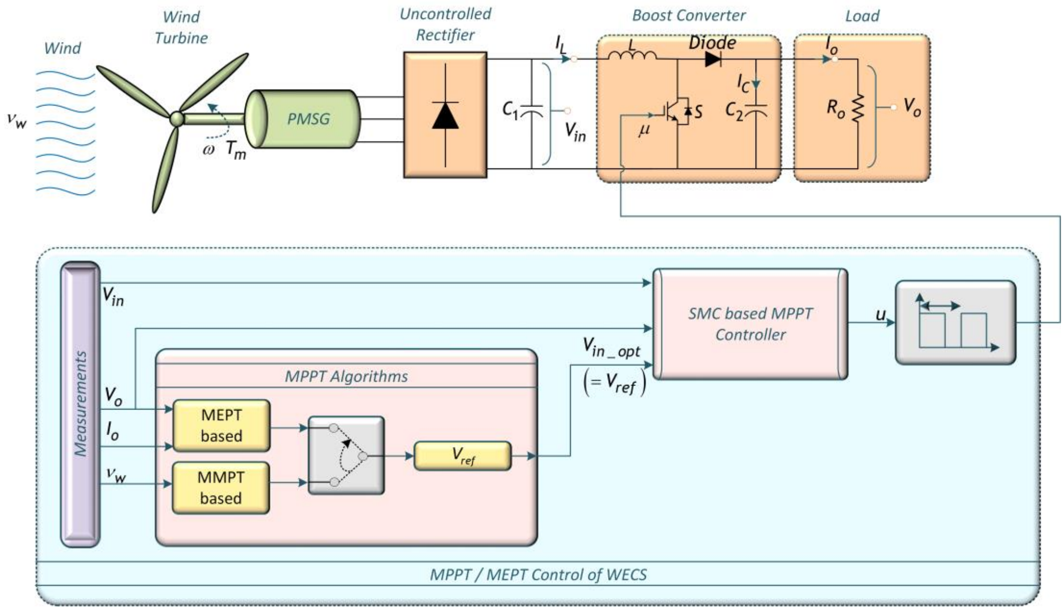


Figure 2. WECS Configuration.

The wind power (P_w) arising from the aerodynamic flow of the wind can be defined as given below.

$$P_w = 0.5\rho A v_w^3 \tag{1}$$

Besides, the mechanical power (P_m) extracted from the wind turbine can be expressed as:

$$P_m = C_p(\lambda,\beta)P_w = 0.5\rho A C_p(\lambda,\beta)v_w^{\ 3} \tag{2}$$

where v_w is the wind speed, ρ is the air density, A is swept area by blades of WT, $C_P(\lambda, \beta)$ is the power coefficient of WT, λ is the tip speed ratio and β is the pitch-angle of blades (β =0 for the MPPT operating region). Also, $C_P(\lambda, \beta)$ used in this paper can be denoted as follows:

$$\begin{aligned} C_p(\lambda,\beta) &= C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{-(C_5/\lambda_i)} + C_6\lambda \\ \lambda_i^{-1} &= (\lambda + 0.08\beta)^{-1} - 0.035(\beta^3+1)^{-1} \end{aligned} \tag{3}$$

where C_1-C_6 are specific parameters of WT. Variable-speed WECS should run at MPPT operation to obtain the maximum power while β =0, so that, $C_P(\lambda)$ depends only on λ, which is given as:

$$\lambda = \frac{\omega_m R}{v_w} \tag{4}$$

where R and ω_m are the radius and angular speed of WT, respectively. From here, considering the optimal values of λ_{opt} and C_{Pmax}, they can be calculated as 8.1 and 0.48 respectively, by way of differentiating to respect to λ. In addition, the C_P vs. λ characteristic of WT in this paper is shown in Figure 3. On the other hand, wind turbine output power (mechanical) vs. turbine speed characteristics for different wind speed conditions are presented in Figure 4. As can be inferred from here, there is a specific operating speed that extracts maximum mechanical power from the wind turbine for each wind speed.

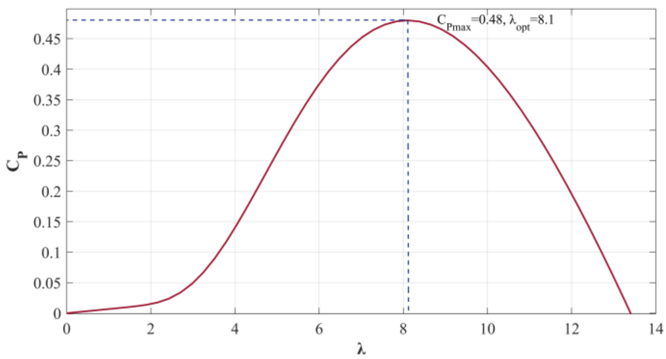


Figure 3. C_P vs. λ characteristic of WT.

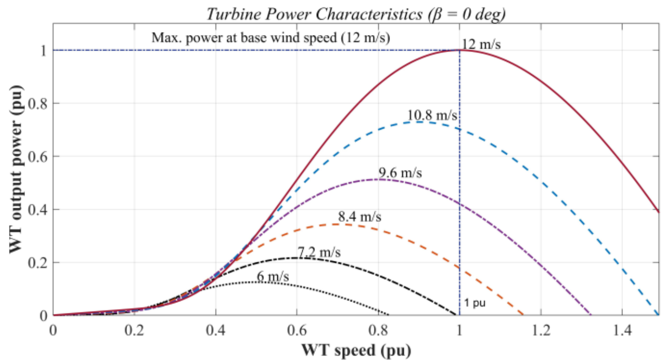


Figure 4. Wind turbine output power vs. turbine speed characteristics for wind speeds.

As it can be understood from the WECS configuration given in Figure 2, mechanical power extracted from the wind turbine is converted to electrical form over the generator and regulated by the converter unit and the controller, and then transferred to the load. Therefore, it should be taken into account that there are losses in electrical and mechanical components in the real world. Since losses also occur in structural subsystems and electrical subunits located in WECS. However, these losses in the generator and converter are not constant and change related to generator speed during the operation (Fathabadi, 2017). Also, the characteristic of the system is also affected by these losses. Considering the aforementioned, it would make it more reasonable to evaluate the MPPT searching on the end-point that is load-side. From here, the electrical output power on the load can be defined as below:

$$P_L = P_m \eta_{gen} \eta_{conv} \tag{5}$$

where, η_{gen} and η_{conv} express the efficiency of the generator and the power converter unit, respectively. Specifications for the WECS model are given in Table 1. In order to access more detailed information for BC and PMSG, interested researchers can examine references of (Dursun et al., 2020; Dursun and Kulaksiz, 2020b).

Table 1. Specifications for WECS.

	Description	Value	Description	Value	
WT	Optimal *TSR*	$\lambda_{opt} = 8.1$	Phase number	3	PMSG
	Maximum power coefficient	$C_{P\_max} = 0.48$	Stator Phase resistance	1 *ohm*	
	Pitch angle	$\beta = 0$	Armature inductance	L_d, L_q=0.00153*H*	
	Rotor Radius	$R = 2$	Inertia, *J*	0.013 *(kg.m²)*	
	The coefficients C_1 to C_6	C_1=0.5176 C_2=116 C_3=0.4 C_4=5 C_5=21 C_6=0.0068	Viscous damping, *F*	0.0425 *(N.m.s)*	
BC	Switching Frequency, f_{sw}	5 *kHz*	Inductor Resistance, R_L	0.15 *Ω*	
	Inductor, *L*	310 *µH*	Capacitor ESR, R_C	0.07 *Ω*	
	Capacitor, *C*	240 *µF*	Load Resistance, *R*	36 *Ω*	

3. PERFORMANCE COEFFICIENTS ANALYSIS AND DISCUSSION

In this section, the changes in performance coefficients during the system operating concepts with MPPT and MEPT for a stand-alone PMSG-based WECS are investigated. In addition, changes in the performance characteristics of the WECS are presented for each specific wind speed from 8 m/s to 12 m/s. Overall system modeling and all detailed analyses are carried out based on MATLAB/Simulink simulation environment and also given to validate the theoretically mentioned.

In this study, performance coefficients are acquired by evaluating them through four different focus points. These are C_P, C_{tg}, C_{tgr} and C_{tgrl}. Herein, C_P is the power coefficient of the turbine and C_{tg} is the turbine-generator power coefficient that is used by evaluating the efficiency of the turbine together with the PMSG generator. Moreover, C_{tgr} is the turbine-generator-rectifier power coefficient and the output of the rectifier is taken into account as the focus point. The last performance evaluation is made by examining the converter output. Thus, C_{tgrl} denotes the power coefficient of turbine-generator-rectifier-converter output. Therefore, these coefficients can be written mathematically.

Considering the losses on the generator, C_{tg} which defines the relationship between generator power and wind power, is as follows:

$$\begin{aligned} C_{tg} &= \frac{P_g}{P_w} \qquad ;\left\{P_g = P_m - P_{g\_loss}\right\} \\ C_{tg} &= \frac{P_m - P_{g\_loss}}{0.5\rho A v_w^3} \end{aligned} \tag{6}$$

where P_g indicates generator-output power and P_{g_loss} denotes power loses on the generator. From here, considering that the output of three-phase uncontrolled rectifier and filter capacitor is connected to the converter (BC), the input power of the converter P_{in_conv} and coefficient C_{tgr} are obtained as:

$$C_{tgr} = \frac{P_{in\_conv}}{P_w} \quad ;\left\{P_{in\_conv} = P_g - P_{rec\_loss}\right\}$$
$$C_{tgr} = \frac{P_g - P_{rec\_loss}}{0.5\rho A v_w^{3}} \tag{7}$$

Herein, C_{tgr} demonstrates the relationship between the input power of the converter and wind power by taking into account rectifier power loss. Furthermore, converter loss is variable according to the operating condition. From here, the output power of converter P_{out_conv} (P_L: power on load) is obtained by subtracting power loss on the converter P_{conv_loss} and C_{tgrl} can be written by relating as below:

$$C_{tgrl} = \frac{P_{out\_conv}}{P_w} \quad ;\left\{P_{out\_conv} = P_{in\_conv} - P_{conv\_loss}\right\}$$
$$C_{tgrl} = \frac{P_{in\_conv} - P_{conv\_loss}}{0.5\rho A v_w^{3}} \tag{8}$$

C_P, C_{tg}, C_{tgr} and C_{tgrl} vs. λ characteristics of used WECS are presented in Figure 5 (a-e) at different specific wind speeds from 8 m/s to 12 m/s. From here, it can be seen that C_P characteristics remain the same for whole wind speeds. Since it is a known fact that C_P characteristic occurs depending on the design of the turbine and has a unique structure. On the other hand, it can be inferred here that the other aforementioned characteristics don't reach their maximum values at the same λ values. Also, as the wind speed increases, the generator operating speed increases related to this situation. Thus, the characteristics of the performance coefficients are changed as a result of the increase and change in losses. In addition, it can be understood that maximum values of C_{tg}, C_{tgr} and C_{tgrl} characteristics decrease as the wind speed increases. For these specific wind speeds, obtained results through MMPT and MEPT-based control are given in Table 2, which is arranged in relation to this figure. According to this table, while λ is maintained at 8.1 in the MMPT-based implementation and, MEPT-based methodology by operating on the load-side keeps λ between about 8.7 and 9.2 for the determined wind speed range. Moreover, MMPT-based control aims to kept C_P at 0.48 while MEPT-based one intends to maximize the C_{tgrl}. Regarding to mentioned this perspective, data for C_{tgrl} and λ values, which correspond to the optimal operating point for both methodologies, listed in this table.

As can be understood from Equation in (8), C_{tgrl} indicates the relationship between the output power of the converter and wind power. Furthermore, it can be interpreted that C_{tgrl} is an indicator of the overall efficiency change of the whole WECS system. Besides, it can be seen that the MEPT-based one achieves a higher value of C_{tgrl} for all wind speeds compared to the MMPT-based one. Therefore, it can be understood that WECS is operated with higher efficiency and higher power extraction is obtained from the end-point.

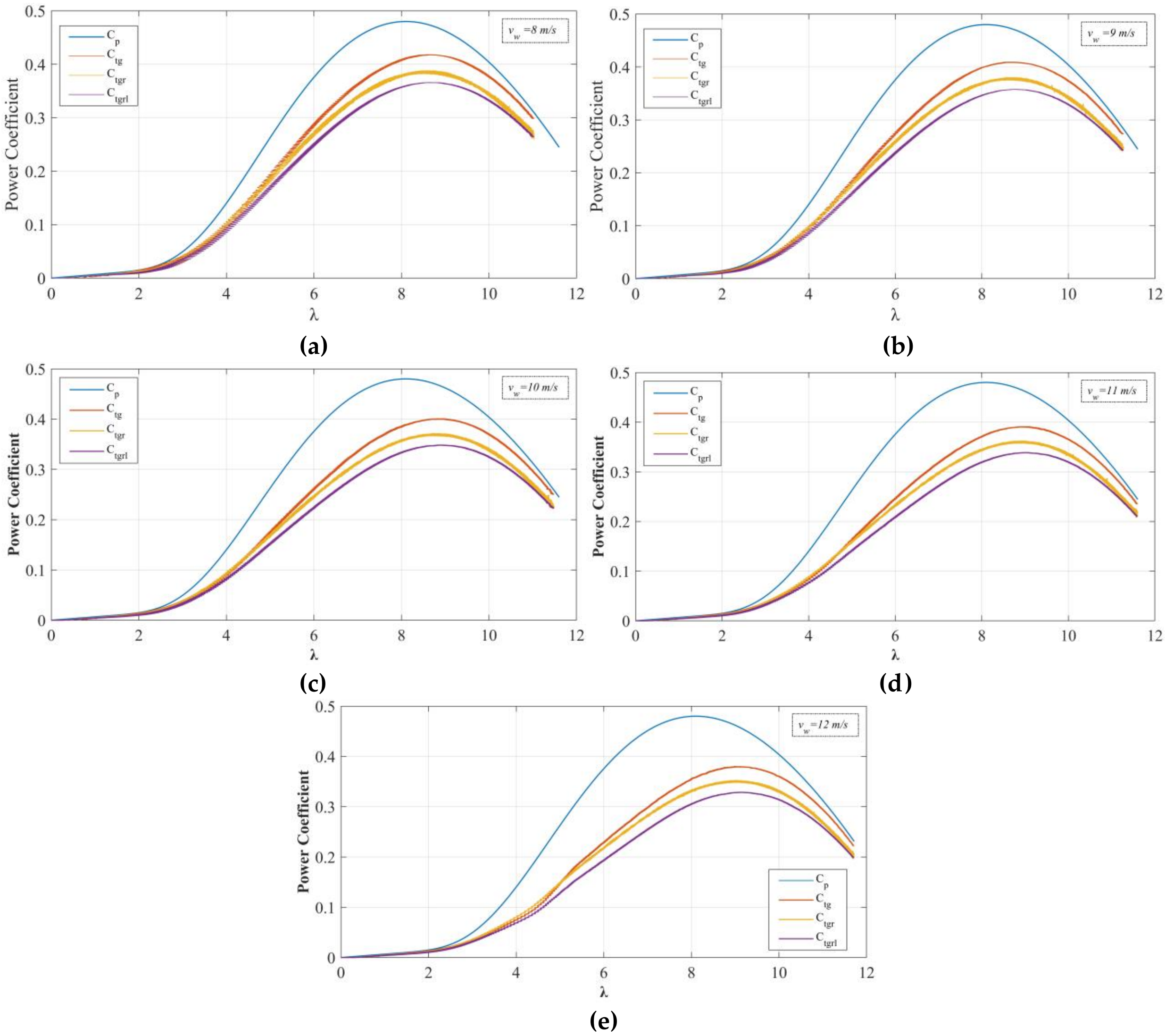


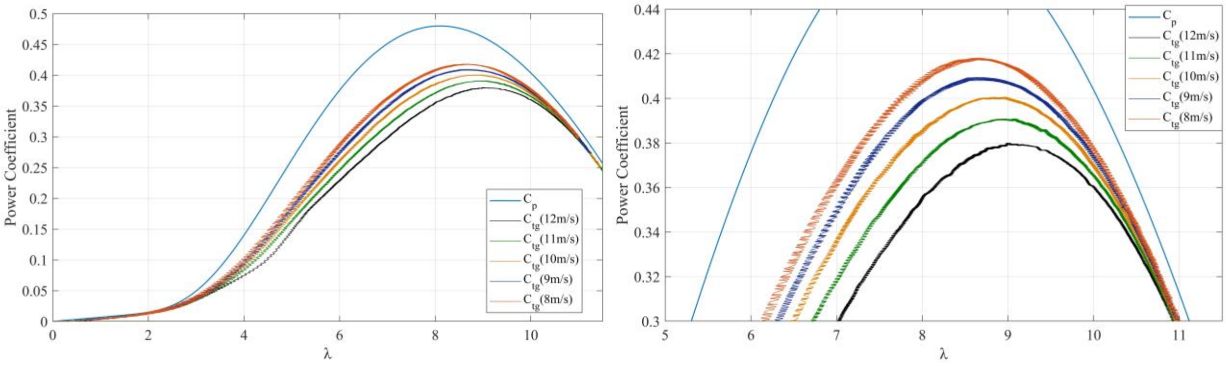
Figure 5. C_P, C_{tg}, C_{tgr} and C_{tgrl} vs. λ characteristics of WECS at different wind speeds. **(a)** Changes at wind speed 8 m/s. **(b)** Changes at wind speed 9 m/s. **(c)** Changes at wind speed 10 m/s. **(d)** Changes at wind speed 11m/s. **(e)** Changes at wind speed 12 m/s.

Table 2. Results of MMPT and MEPT control.

	MMPT			*MEPT*	
v_w	λ	C_P	C_{tgrl}	λ	C_{tgrl}
v_w=8 *m/s*	8.1	0.48	0.356	8.7	0.365
v_w=9 *m/s*	8.1	0.48	0.350	8.8	0.357
v_w=10 *m/s*	8.1	0.48	0.337	8.9	0.348
v_w=11 *m/s*	8.1	0.48	0.323	9	0.338
v_w=12 *m/s*	8.1	0.48	0.309	9.2	0.328

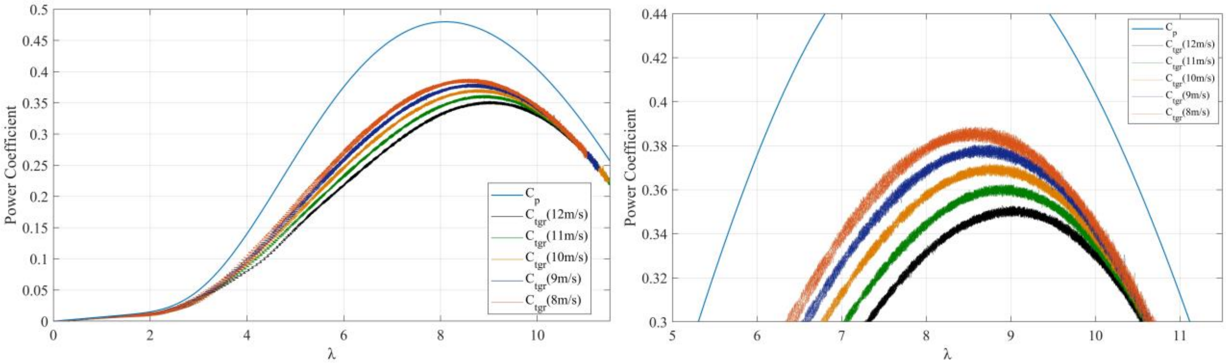
Besides, changes occurred these characteristics can be interpreted from another viewpoint and each one is compared in relation to every specific wind speed, which is demonstrated in Figure 6-8. Figure 6(a,b) presents changes in C_{tg} vs. λ characteristics with regard to all of the wind speed ranges and results in a zoomed-in view. Similarly, C_{tgr} vs. λ characteristics and zoomed results, and C_{tgrl} vs. λ characteristics and zoomed results are indicated in Figure 7(a,b) and Figure 8(a,b) respectively. Therefore, the change of the optimal operating points for each specific wind speed and also the maximum values of C_{tg}, C_{tgr} and C_{tgrl} can be expressed more clearly in Figure 6-8. In addition, the results and explanations presented for

Figure 5 can thus be clearer and more understandable. In Figure 6, it is seen that the maximum value of C_{tg} has decreased from approximately 0.418 to 0.380 as the wind speed increases from 8 m/s to 12 m/s. This situation arises in relation to the increase in the losses on the generator with the increasing operating speed. In addition, as mentioned before, a similar interpretation can be made for Figures 7 and 8. Investing from the end-point, it is understood from Figure 8 that the maximum value of and C_{tgrl} reduces from nearly 0.365 to 0.328 levels. On the other hand, maximum values of C_P, C_{tg}, C_{tgr} and C_{tgrl} coefficients in these characteristics for each specific wind speed are also listed in Table 3.



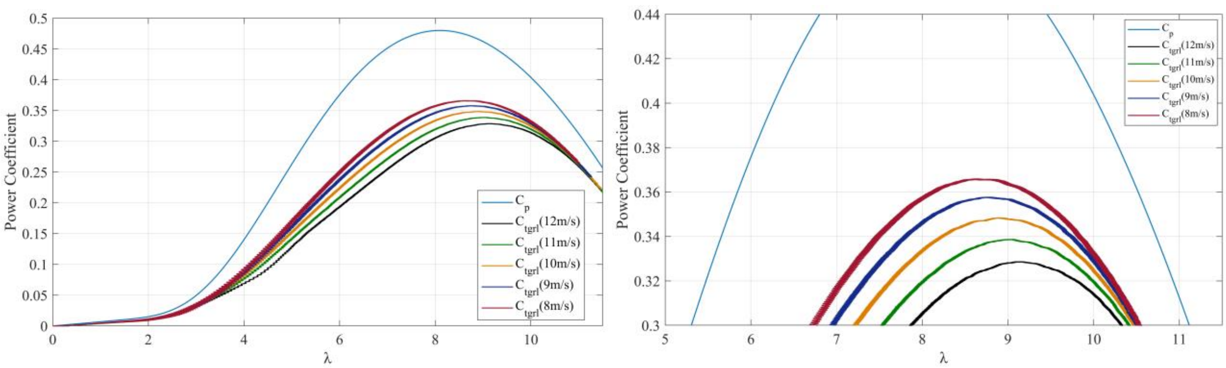
(a) **(b)**

Figure 6. **(a)** Changes of C_{tg} vs. λ characteristics at different wind speeds. **(b)** zoomed results.



(a) **(b)**

Figure 7. **(a)** Changes of C_{tgr} vs. λ characteristics at different wind speeds. **(b)** zoomed results.



(a) **(b)**

Figure 8. **(a)** Changes of C_{tgrl} vs. λ characteristics at different wind speeds. **(b)** zoomed results.

Table 3. Maximum values for C_P, C_{tg}, C_{tgr} and C_{tgrl}.

	C_P	C_{tg}	C_{tgr}	C_{tgrl}
v_w=8 m/s	0.48	0.418	0.386	0.365
v_w=9 m/s	0.48	0.409	0.377	0.357
v_w=10 m/s	0.48	0.400	0.368	0.348
v_w=11 m/s	0.48	0.391	0.360	0.338
v_w=12 m/s	0.48	0.380	0.353	0.328

4. CONCLUSION

In this paper, MMPT and MEPT-based system operating concepts are performed to extract maximum power from a stand-alone PMSG-based WECS. While maximum mechanical power is obtained by the MMPT-based implementation, maximum electrical output power extraction is carried out by the MEPT-based one. Therefore, losses that occur in structural subsystems and electrical subunits in WECS are taken into account by the second methodology and the overall WECS can be optimally controlled. Moreover, for the specific wind speeds from 8 m/s to 12 m/s, characteristics of performance coefficients and the occurred changes have been presented. Technical and theoretical analyzes are also carried out with comparison. Herein, obtained results with the simulation validation are put forward in detail. Also, λ, C_P and C_{tgrl} coefficients for MMPT and MEPT-based implementations are given both numerically and graphically. According to the obtained results, the maximum value of the C_{tgrl} coefficient decreases from approximately 0.356 to 0.309 with MMPT-based applications for this wind speed range. On the other hand, with the MEPT-based ones, the maximum value of the C_{tgrl} coefficient is nearly between 0.365 and 0.328. Therefore, it can be understood that WECS is operated with higher efficiency and higher power is extracted from the end-point with the MEPT implementation. The findings of this study indicate that loses or efficiency of each unit occurs changes on characteristics of the overall system. As a result, the performance characteristic that is viewed on the end-point is more different from the characteristic of C_P coefficient.

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