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Effects of WECS settings and PMSG Parameters in the Performance of a Small Wind Energy Generator

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***Abstract*— During recent years the market for small wind turbine generators (SWTG) has been continuously growing. In this context, the supply of components for this product has also been increasing. The main components of SWTG are the rotor, the generator and the wind energy conversion system (WECS), typically formed by a rectifier plus an inverter. The settings of WECS affect the SWTG behaviour, especially the parameters related with minimum and maximum voltages and the way in which the inverter power curve is established. In this paper, a method to calculate the inverter power curve of a STWG is presented, the impact of different types of curves is also evaluated.**

***Index Terms*-- Wind power generation, AC-AC power conversion, permanent magnet generators**

I. Introduction

Due to market expansion of this technology (SWTG), the study of its behaviour to improve its efficiency and performance is an important issue. Nowadays, the design and manufacture of the SWTG's tend to the use of permanent magnet synchronous generators (PMSG). In light if this, continuous studies have been carried out, mainly dealing with control and design methods [1,2,3,10].

PMSG's require wind energy conversion systems (WECS) that are used as interface between the generator (variable voltage and frequency) and the grid (fixed voltage and frequency).

There are several WECS configurations: with only diode rectifier and a inverter [1,2], with a DC/DC converter between rectifier and inverter [4,5,6], with a controlled rectifier [7,8], and with a controlled rectifier and a DC/DC converter [9]. However, the typical one is that composed by a rectifier, an inverter and dump load resistors as shown in Fig. 1. Dump loads are used to limit the AC voltage in the generator side or the DC voltage; they are usually connected or dimmed when a preset voltage value is achieved. In this configuration, most of the setting values are implemented in the inverter; the power curve values are one of the most important settings since they are directly related to the energy production.

A study based on SWTG's with PMSG is presented in this paper. It analyses the influence of PMSG parameters and WECS configuration in the energy production.

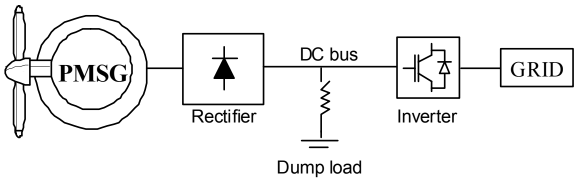

Fig. 1: General scheme of a wind turbine

II. System Description and Modelling

The power configuration of the analysed system is shown in Fig. 1. The wind turbine used in this work is a direct-drive system. The generator is connected to the network through a rectifier and an inverter (WECS). The torque produced by the wind turbine is used as the input torque to the PMSG, and the voltage produced by the PMSG is rectified and passed through an inverter to the network. A maximum power strategy is necessary to extract the maximum power out of the system. In this case, the maximum power strategy is implemented by means of the inverter power curve.

The main parameters of the simulated SWTG are summarized in TABLE I.

TABLE I. SWTG main parameters

ROTOR	
Type	Up-wind / fixed pitch
Number of blades	3
Diameter	2.8 m
GENERATOR	
Type	PMSG
Pole pairs	12
Nominal voltage / speed	230 V / 220 rpm
Power	6600 W
Steady-state resistance / inductance	1.63 Ω / 22.46 mH
No-load voltage at nominal speed	190.3 V
RECTIFIER	
Type	Full wave / diode
Power	7,2 kW
Efficiency	99,5%
Max. input voltage	400 V_{AC}
Dump load voltage	530 V_{DC}
INVERTER	
Efficiency	97%
Power	6 kW
Input voltage	50 – 560 V_{DC}

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A. *Wind power extraction*

The mechanical power (P_m) captured by the rotor can be calculated by the following equation:

$$P_m = \tfrac{1}{2}\rho A C_p(\lambda) v^3 \eta_{mec} \quad (1)$$

Where ρ is the air density (typ. 1,225 kg/m3), A is the area covered by blades' rotation, C_p is the power coefficient, v is the wind speed (m/s) and η_{mec} is the mechanical performance, which has been assumed to be constant in order to simplify the analysis.

The power coefficient depends on the tip speed ratio λ calculated with the following expression:

$$\lambda = \Omega R / v \quad (2)$$

Where Ω is the rotational speed (1/s) and R is the blade radius.

The relationship between Cp and λ is non-linear and for fixed pitch rotor can be modelled with the following equation [11]:

$$C_p = \tfrac{1}{2}\left(\frac{RC_f}{\lambda} - k_1\right) e^{-k_2 \frac{RC_f}{\lambda}} \quad (3)$$

Where C_f is a blade design constant, k_1 and k_2 are constant parameters. These parameters have been calculated from real data rotor behaviour, and the result is shown in Fig. 2.

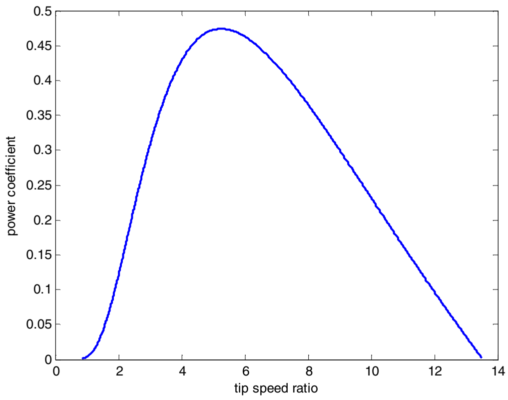

Fig. 2: Power coefficient curve

For each wind speed, it exists an optimum tip speed ratio λ_{opt} with its correspondent maximum power coefficient $C_{p,opt}$ (typ. 0.4-0.5), so the mechanical power has its maximum value $P_{m,opt}$ for that wind speed. From (1) and (2), the following equations can be obtained:

$$\Omega_{opt} = \lambda_{opt} v / R \quad (4)$$

$$P_{m,opt} = \tfrac{1}{2}\rho A C_{p,opt} v^3 = \tfrac{1}{2}\rho A R^3 \frac{C_{p,max}}{\lambda_{opt}^3} \Omega_{opt}^3 \quad (5)$$

This last equation establishes the well-known cubic relationship between rotational speed and mechanical power used to maximize wind power production (see Fig. 3).

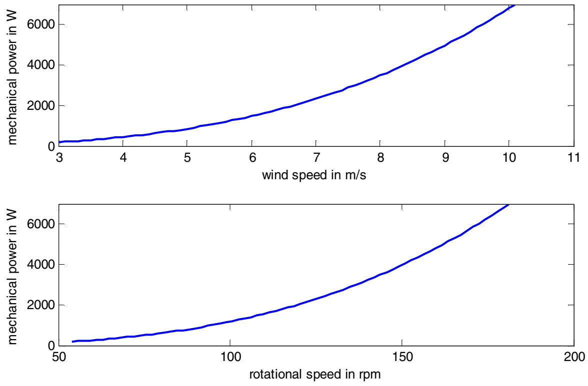

Fig. 3: Optimum mechanical power curves

B. *Permanent magnet synchronous generator (PMSG)*

Permanent magnet synchronous generators (PMSG's) are typically used in small wind turbines for several reasons (high efficiency, gearless, simple control…).

A simple steady-state model, as those used in other kinds of machines [13], has been chosen in order to evaluate the behaviour of these types of machines [14], with the following assumptions:

- Saturation is neglected;
- Internal voltage or back emf is sinusoidal (harmonic components are neglected);
- Eddy currents and hysteresis losses are negligible.

In this case, a single phase equivalent circuit (as shown in Fig. 4) can be used and the following equation determines the relationship between voltages and current:

$$\underline{E} = \underline{U} + (R_s + j\omega L_s)\underline{I} \quad (6)$$

Where $\underline{E}$ is the internal voltage, $\underline{U}$ is the voltage in the stator, $\underline{I}$ is the current delivered, R_s and L_s are the steady-state resistance and inductance respectively, and ω is the frequency of voltage and currents in the PMSG stator. In steady-state, frequency is related to rotational speed by means of the equation:

$$\omega = p\Omega \quad (7)$$

Where p is the number of pole pairs of PMSG.

Finally, the magnetic flux is supposed to be constant, thus, a linear relationship between rotational speed and no-load voltage is considered, so:

$$E = K_e \Omega \quad (8)$$

Where K_e is the relationship between E and Ω.

Fig. 4: PMSG equivalent circuit

C. *Wind energy conversion system (WECS)*

In the SWTG considered in this work, WECS is composed by a diode full-wave rectifier, dump load resistors and an inverter. Thanks to these elements, power extracted from wind can be delivered to the network in constant voltage and frequency conditions.

The rectifier has been developed using the relationship between the input RMS voltage U and the DC voltage U_{DC}:

$$U_{DC} = 3\sqrt{3}\sqrt{2}/\pi \, U \quad (9)$$

In the rectifier input, the phase shift between voltage and current is zero (cos φ = 1), so the following equations can be written:

$$\underline{E} = U + (R_s + j\omega L_s) I \quad (10)$$

$$E^2 I^2 = P_m^2 + \omega^2 L_s^2 I^4 \quad (11)$$

A current source equivalent has been used to model the inverter. Its main parameters are the DC voltage range and the power curve. Both parameters affect the wind energy production for a given rotor and the PMSG. Power delivered by the inverter can be written as:

$$P = 3UI\eta_{ele} \quad (12)$$

Where η_{ele} is the efficiency of WECS (inverter plus rectifier). In this paper η_{ele} has been assumed to be constant for the sake of simplicity. For example, in commercial inverters, efficiency values vary in the range 93%-0,97% for power values between nominal and one third of nominal power.

III. Power Curve Optimization

A. Inverter Power Curve

The inverter power curve relates an input variable (typ. rotor speed, DC voltage or frequency) with the desired inverter power output. Normally, frequency of the voltage in the PMSG side fr or DC bus voltage U_{DC} is used as input for the mentioned curve. In commercial inverters, this curve can be defined in several ways: typically by means of a polyline [3] or by a third degree polynomial [1,2,12]. In any case, inverter power curve must be designed to maximize the SWTG power production.

In certain inverters, the inverter power curve is divided into two parts: in the lower part the curve is linear and in the upper part the curve tends to be cubic (see Fig. 5). The upper high power part can be expressed with a set of polyline vertices (frequency-power or DC voltage-power):

$$\{(X_0, P_0); (X_0, P_0); \ldots; (X_n, P_n)\} \quad (13)$$

Where X is the input variable (fr or U_{DC}) and n the number of point. Another way to define the power curve is through the coefficients (a_0, a_1, a_2 and a_3) of a third degree polynomial expression:

$$P_{pol} = a_0 + a_1 X + a_2 X^2 + a_3 X^3 \quad (14)$$

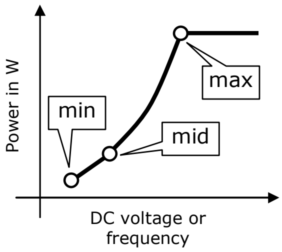

Fig. 5: Inverter power curve definition

So, the main inverter settings are:

- an inverter power curve defined with (13) or (14),
- a minimum DC voltage to start generation ($U_{DC,min}$),
- a middle DC voltage or power as a limit between the lower and higher power parts of the power curve parts,
- a maximum DC voltage or power when the power is fixed at the nominal value.

The upper part of the curve is closely related to the wind energy performance of SWTG, and the lower part is more related to the starting process of SWTG. This article focuses on the analysis of the impact that the upper part has on the energy production.

B. Power Curve Optimization

In large WTG's, an optimum power curve (as shown in Fig. 3) is usually used to define desired power production. In this instance, the inverter power curve can be defined as:

$$P_{opt} = K_{opt}\omega^3 \quad (15)$$

Where:

$$K_{opt} = \tfrac{1}{2}\rho A R^3 \frac{C_{p,max}}{p^3 \lambda_{opt}^3} \eta_{mec}\eta_{ele} \quad (16)$$

And P_{opt} is the optimum power delivered by the WTG. A similar equation can be found to relate power and DC voltage.

In SWTG, the cubic equation shown in (15) could not be the most appropriate due to the high impedance values of PMSG. The maximum mechanical power for a given wind speed could not imply the maximum electrical power. In this work, the maximum electrical power P_{max} delivered by the SWTG is obtained by using (3)(7)(8)(10) (12)(15) with an algorithm of maximization [16] in Matlab (Mathworks Inc., Natick, US). The result is shown in Fig. 6, where the curve called "opt." is that obtained from (15), and the curve called "max." is the one obtained with the optimization process mentioned above. Furthermore, the maximum wind speed v_{lim} at which the power delivered by the inverter can have the values given in (15) is calculated with the equation:

$$v_{lim} = K_e \sqrt{\frac{\lambda_{opt}}{RA\rho C_p \eta_{mec}} \frac{1}{3L_s} \frac{1}{p}} \quad (17)$$

For the data shown in TABLE I this value is 10.23 m/s, which implies an electrical power of approx. 4855W that is lower than the nominal one.

C. Power Curve Calculation: polynomial approximation

In the previous paragraphs, the maximum achievable power P_{max} has been obtained. This power can be used as reference for the inverter, so the maximum energy from wind can be captured. To be implemented in the inverter, this curve can be approximated by a third degree polynomial equation, as shown in Fig. 7. In order to be implemented in the inverter, the input values must be the frequency fr or the DC voltage U_{DC}. Through a least-squares based algorithm, the approximated polynomial curves can be calculated. The difference between the curves is quasi negligible, so the power achieved by the SWTG with this inverter power curve must be very close to the maximum one. For this reason, the polynomial approximation is here taken as a reference.

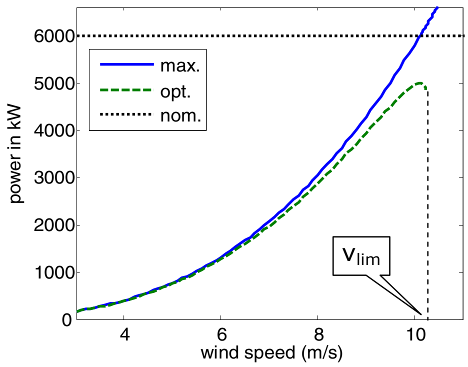

Fig. 6: Maximum power and optimum power curves

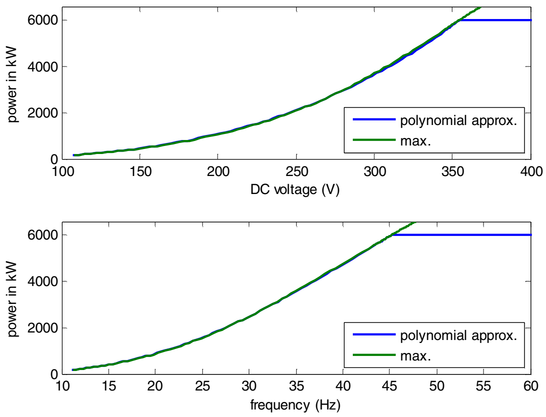

Fig. 7: Maximum power curve and its polynomial approximation.

D. *Power Curve Calculation: Polyline approximation*

In many commercial inverters for WECS, the power curve could be defined as a set of vertices of a polyline, as the number of vertices allowed for each inverter differs between manufacturers. The way to obtain these points and the size of the set determine the WECS behaviour. In this paper, an optimization method to obtain these points is presented. The process to get the optimum set of (X_i, P_i) vertices has the following restrictions:

1) All the vertices must form an increasing curve.

$$\begin{aligned} X_0 < X_1 < \ldots < X_n \\ P_0 < P_1 < \ldots < P_n \end{aligned} \tag{18}$$

2) Power associated to the last vertice must be the nominal one P_{nom}.

$$P_n = P_{nom} \tag{19}$$

3) The maximum distance d_i between each segment formed by the vertices {(X_i, P_i); (X_{i+1}, P_{i+1})} and the P_{max} curve must have a value lower than a given value $-d_{min}$ (see Fig. 9).

Finally, the polyline formed by the vertices (X_i, P_i) is approximated to the maximum power curve by a least-squares based algorithm with the restrictions mentioned above.

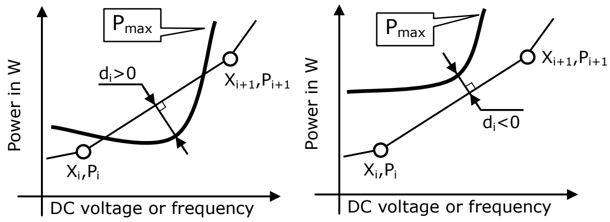

Fig. 8: Distance between P_{max} curve and the polyline defined by (X_i,P_i) vertices.

The resulting vertices, i.e., the polyline approximation of P_{max} curve, is shown in Fig. 9 for a set size of two vertices and using DC U_{DC} voltage as input. Similar results can be obtained using frequency fr as input.

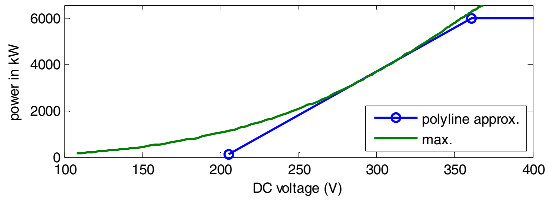

Fig. 9: Maximum power curve and its approximation by means a polyline defined by two vertices.

IV. Results

Once the inverter power curves have been obtained (polynomial and polyline approximation), they must be tested comparing their wind energy production in different wind regimes. With this aim, a probability distribution of Rayleigh has been used for wind speed [17].

Results are shown in TABLE II, where the resulting mean power production has been calculated for different mean wind speeds (3-9 m/s), using both the polynomial and the polyline approximation (with 2, 3 and 4 vertices). The mean power obtained whether it is done through the polynomial approximation of the inverter power curve or through the polyline one are also shown in the table. The difference between them is only significant when the wind speed is low (capacity factor < 0.2) and the number of vertices (N. points) used in the polyline approximation is two. In Fig. 10 the mean power ratio (mean power obtained with polyline approx. or with polynomial approx.) is presented when the number of vertices for the polyline approximation is only two.

TABLE II. Mean power results

Mean Wind Speed (m/s)	Polynomial approx.	Polyline approx.					
		N. points: 2		N. points: 3		N. points: 4	
	Mean Power (W)	Mean Power (W)	Diff.	Mean Power (W)	Diff.	Mean Power (W)	Diff.
3	278,48	252,78	-9,23%	277,75	-0,26%	278,48	0,00%
4	680,63	653,53	-3,98%	679,41	-0,18%	680,63	0,00%
5	1.235,16	1.211,40	-1,92%	1.233,72	-0,12%	1.235,16	0,00%
6	1.845,49	1.825,75	-1,07%	1.844,07	-0,08%	1.845,49	0,00%
7	2.415,04	2.398,83	-0,67%	2.413,74	-0,05%	2.415,04	0,00%
8	2.879,37	2.866,00	-0,46%	2.878,21	-0,04%	2.879,37	0,00%
9	3.208,93	3.197,81	-0,35%	3.207,92	-0,03%	3.208,93	0,00%

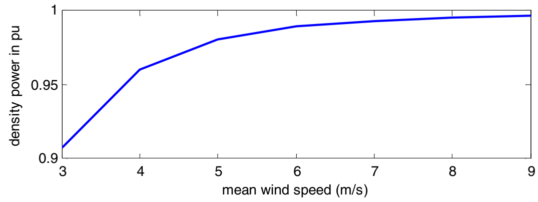

Fig. 10: Polyline Mean power referred to polynomial mean power

Apart from energy production, the working limits of the power curve are an important issue because they affect to the WECS dynamic behaviour (see TABLE III). The relationship between minimum and maximum values of DC voltages, or frequencies of the power curve is a measure of available capability of the inverter to follow the power curve. In this circumstance, the number of points of the polyline approximation is three; its behaviour is very close to that with the polynomial approximation.

TABLE III. VOLTAGE AND FREQUENCY LIMITS

	Polynomial approx.	Polyline approx.		
		N. points: 2	N. points: 3	N. points: 4
Vdc Min (V)	103	205	120	106
Vdc Max (V)	356	361	358	361
Vdc Max/Min	**3,5**	**1,8**	**3,0**	**3,4**
fr Min (Hz)	11,5	20,5	13,0	11,5
fr Max (Hz)	45,2	45,4	45,4	45,4
fr Max/Min	**3,9**	**2,2**	**3,5**	**3,9**

Another question that must be considered is how the WECS behaviour is affected by the variation of PMSG parameters. In this instance, variations of ±10% and ±20% have been assumed in the steady-state inductance L_s and in the internal voltage E (derived from the no-load voltage). The inverter power curves (fr-P and V_{DC}-P) obtained by polyline approximation (n. points: 2) are compared to the maximum available power P_{max} at different L_s and E values.

In Fig. 11 and Fig. 13 the resulting maximum power curves and the polyline power curve at different L_s and E values are shown. In these cases, DC voltage is used as input for the power curve. In Fig. 12 and Fig. 14 a similar analysis is shown but using frequency as input. These are the main conclusions:

- Polyline inverter power curve must be designed to manage PMSG parameters variations, because when P_{max} curve is lower than the polyline one, unstable situations can occur during SWTG operation.
- Variations on steady-state inductance L_s are more significant when frequency is used as input in the power curve.
- Variations on open voltage E are more significant when DC voltage is used as input in the power curve. In this case, to avoid unstable conditions the polyline power curve must be gently displaced to higher voltages.

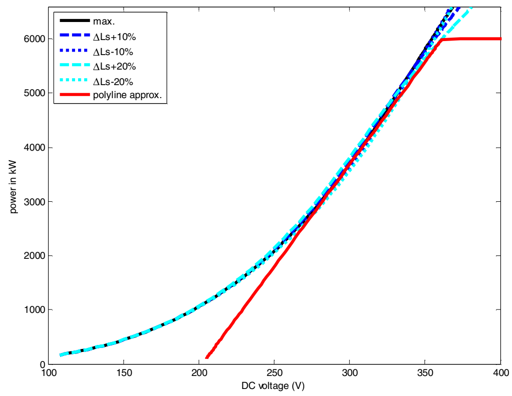

Fig. 11: Maximum power with L_s variations and polynomial power curve with DC voltage in the X-axis.

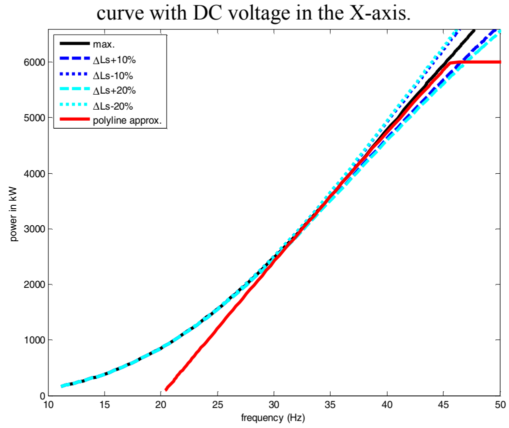

Fig. 12: Maximum power with L_s variations and polynomial power curve with frequency in the X-axis.

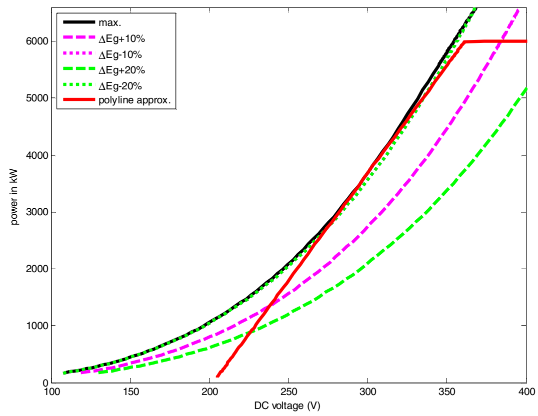

Fig. 13: Maximum power with E variations and polynomial power curve with DC voltage in the X-axis

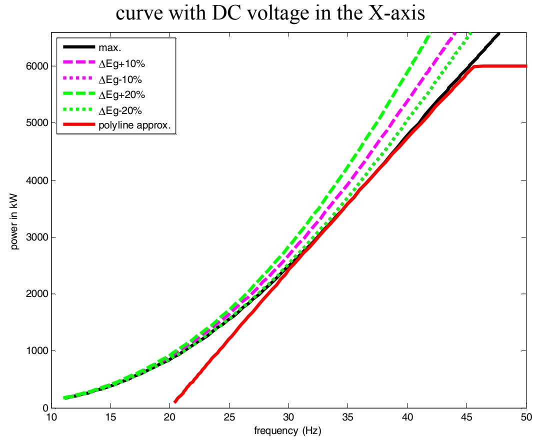

Fig. 14: Maximum power with E variations and polynomial power curve with DC voltage in the X-axis

V. CONCLUSIONS

Considered in this article are a SWTG with a WECS, which is formed by a rectifier, an inverter and dump load resistors. The paper is focused on how the power curve is implemented in the inverter, in order to optimize the wind energy production. Two methods of implementation are considered:

- a third degree polynomial function;
- a set of point, i.e., a polyline approximation;

Inverter power curve can have different variables as input; the most typical cases have been taken into account:

- Voltage in the DC bus is used as input for the power curve;
- The frequency in the PMSG side is used as input.

The polynomial approximation has been calculated using a least-squares based algorithm. For the polyline approximation an optimization method is proposed, that takes into account the distance between the maximum power curve and the proposed polyline approximation.

Using a third degree polynomial function a good agreement between maximum power curve and the approximated power curve is obtained. However, many commercial inverters do not use this method to implement its power curve; therefore, the curve is implemented by means of a polyline.

Once the approximated power curves to be implemented in the inverter have been obtained different analysis have been done. In a first step, the impact of the number of vertices used to define the polyline approximation is evaluated. This research indicates that for a number of vertices greater than two, the energy produced by the SWTG is almost the same than that created by the polynomial approximation.

The margin of input values (frequency or DC voltage) is also evaluated as function of the number of vertices. In this case, the behaviours of the polynomial and the polyline approximation are very close when the number of vertices is greater than three.

Finally, the impact of variation in the PMSG parameters is considered. This impact depends on which input the inverter power curve has. When the input is the DC voltage, the inverter curve must be gently displaced to avoid intercepting the maximum power curve, that may derive in an unstable behaviour. Thus, by using frequency as input for the inverter power curve, a more stable behaviour can be expected when changes on the PMSG parameters occur.

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