SWEPT AREA REGULATION FOR INCREASED ENERGY OUTPUT IN OFFSHORE WIND TURBINES

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ABSTRACT

Under the intrinsic variability of the wind speed and its exponential relationship with the rotor torque, the power control systems play an increasingly important role in terms of efficiency and stability in the modern and large wind turbines. The paper describes a power control system based on swept band area dimensional regulation (DBB) that it is particularly well suited for off-shore wind turbines. After an introduction of the modern power control strategies and revised their current limitations, the theoretical fundamentals of the new approach are formulated. The system operates jointly with pitch or active stall controls but dedicated to the low wind speed range. In this range, the dynamic pair of overlapping blade segments may increase or decrease their swept band areas aiming to reach a constant rated power output. With maximum total swept area larger and with minimum swept area lesser than the current wind turbines of the same class, the proposed control system may provide the rated power of the wind turbine in a broader wind speed range. Preliminary simulation results in the experimental offshore wind site of “Mar de Canarias” are presented. These results show an augmented annual energy yield that remarkably compensates the added complexity due to the incorporation of the new control system.

1.- INTRODUCTION

The wind turbines operate under the condition that the power contained in the wind exponentially depends on its speed. And the wind speed has intrinsic variability. This means that the turbine is working in one of these two regimens: under insufficient power when the wind speeds are low or in the second regimen of too much power when the wind speeds are high. The modern active control systems optimise the operation under those regimens through variation of the attack angle of the turbine blades [1]. At low speeds, the angle and pitch is adjusted to maximise the extracted power from the wind. On the other hand, the attack angle is tuned to discard the excess of power at high wind speeds. This is a modern and efficient approach to enlarge the total energy yield of the turbines under variable conditions of wind speed, something vital in any wind farm. However, this approach has one fundamental limitation: if the dimensions and blade profiles are designed for high efficiency at low wind speeds, these characteristics create difficulties for controlling the turbine under high wind speeds.

The output power of a wind turbine could be expressed in a very compact form by the following relationship:

$$P = Kp * A * V^3$$

where A is the swept area of the rotor, Kp is the global power coefficient that indicates the whole aerodynamic efficiency related to the swept area, and V is the wind speed. The modern active systems, such pitch control and stall control, modify the output power through Kp variations [2],[3],[4]. Thus, even though V rises and its cubic power reaches a very high value, P can be limited to a predefined value as low as the designer wants. Even a null value is obtained if Kp is set to zero.

On the other hand, at low wind speeds this coefficient is enlarged as much as possible to reach the aerodynamic blade limits, usually around 0.3. Further enlargement of this value for a wide range of wind speeds is an increasingly difficult task with limited results. It is much simpler to augment the swept area. So the designer choose larger rotor blades.

However, this way that works well with gentle breeze, it becomes a major problem with high wind speeds. Then the product of the cube of the wind speed by the swept area is too huge. Small variations of speed produce large power surges. The turbine enters into a dangerous operation state with high transitory mechanical efforts [5]. Even though at static regimens the power output is controlled well through Kp, at these conditions with high wind speeds and large swept areas, the Kp control is not enough for transients stabilisation. Then the safety of turbine is endangered. In these conditions, a recommended action is to stop the turbine.

Since the beginning of the modern wind turbine era, continuous research efforts for developing new control algorithms that smooth the transients and reduce its effects over the turbine [6] [7] [8] [9] [10] [11], or over the rotor blades [12] [13] [14] have been doing. Although there are unquestionable advances, if the designer wants that a wind turbine operates well under high wind conditions, smaller swept areas are selected [15]. Thus, the swept area is a key factor in the output power and its stabilisation; particularly in the wind speed operation range edges. In the next paragraphs we will see how the

swept area can be dynamically changed increasing at low wind speeds and reducing at high wind speeds [16].

2.- SWEPT BANDS

If the blade is divided into four segments, as it appears in figure 2.1, the total swept area is then distributed into four swept bands: A1, A2, A3, A4.

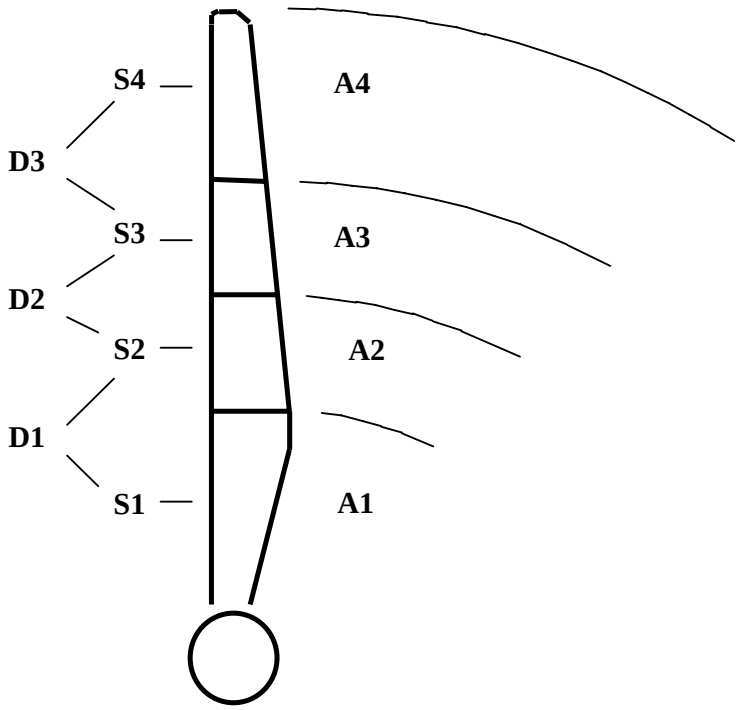

Figure 2.1 Wind turbine blade with four segments, three dynamic pairs and four swept bands at 100% of its rated values.

The modification of the band areas is achieved grouping the segments into dynamic pairs. For example, the segment S1 can be associated to S2 forming the dynamic pair D1. The segment S2 can be associated to S3 creating the dynamic pair D2 and so on. Within a dynamic pair, the segments may slide over overlapping their swept bands. Thus, the combined total swept band area may decrease or increase. The figure 2.2 illustrates the initial wind turbine example having three dynamic pairs D1, D2, D3 with their segments in an intermediate overlapped position.

In this condition, the output power of the wind turbine is expressed by the following equation:

$$P = (K'p_1 * A'1 + K'p_2 * A'2 + K'p_3 * A'3 + K'p_4 * A'4) * V^3$$

where A'1, A'2, A'3, A'4 are the new swept bands and $K'p_1$, $K'p_2$, $K'p_3$, $K'p_4$ the new power coefficient of each band. Although each segment has a defined aerodynamic profile, its power coefficient, resulted from the fluid pressure field, changes with its position. When the segments overlap, as it is shown in figure 2.2, there is a partial change of the power coefficients in the overlapped area, as well as, in the adjacent areas. In fact, the air pressure and air velocity distributions on the swept bands are influenced by the position of other segments, as well as, another remote elements such the nacelle or the tower.

Thus, when there is change in the relative position of segments within a dynamic pair there is change in the power coefficients of the swept bands. Because each swept band has different power coefficient, it is possible to modify and control the turbine output power by changing the distribution of the swept band areas without modifying the total swept area. Then the amount of displacement to the rotation axis of a segment is equal to the slide out to the periphery of another segment of a different dynamic pair. So, the rotor diameter and the total swept area keep unaltered but the turbine delivers a different output power. However, this approach has a limited range of control. The control effects are much more powerful if there is net change in the whole swept area. It is the case shown in figure 2.2 where it has been made a reduction in all swept band areas from their maximum. The total swept area now is 49% of its maximum. Individually, each swept band has an area of 50%, 40 %, 30% and 60% of its rated value.

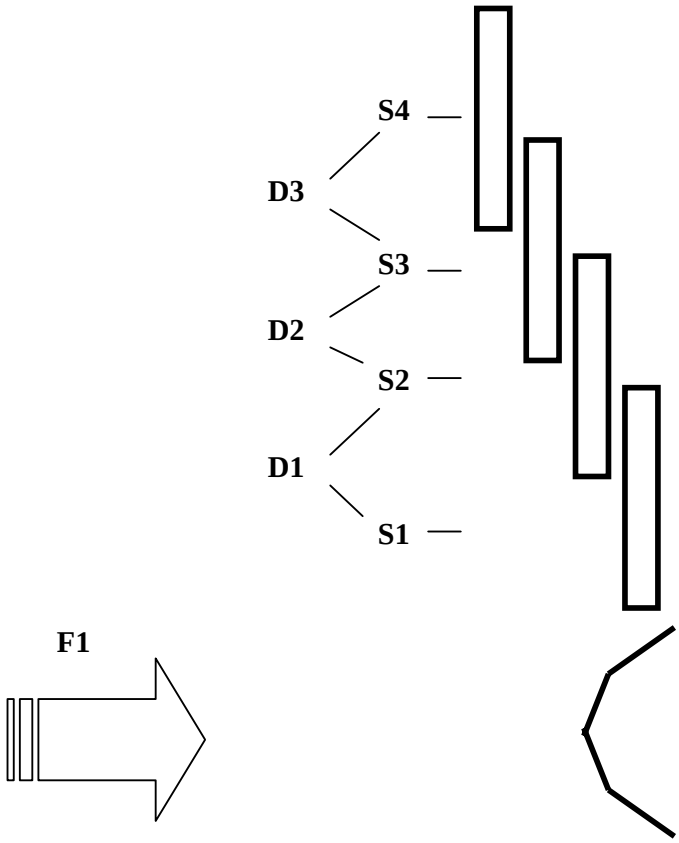

Figure 2.2. Wind turbine blade seen from a point of view normal to the airflow (F1). The three dynamic pairs (D1, D2, D3) have their segments (S1, S2, S3, S4) overlapped in intermediate positions. The swept band areas (A1, A2, A3, and A4) are close to 50%, 40%, 30% and 60% of their rated values.

3.- EXPERIMENTAL WIND SITE ASSESSMENT

In the preceding paragraphs it has been described the basic concepts of the DBB control (after the Spanish words "**D**imensional de las **B**andas de **B**arrido"). It estimated that the DBB control system increases its economic advantages with the size and power of the wind turbines, as well as, with the foundation costs. Aspects particularly relevant in offshore wind farms. So, in this document are presented the simulation results based on "Mar de Canarias"; an offshore experimental site in development stage. With very good wind resources (13.9 m/s average wind speed, 15.7 m/s, 2.23 scale and form Weibull factors at hub height), "Mar de Canarias" is located at the eastern coast of Gran Canaria island. On approximately 30 meter depth waters, two turbines are projected. The first one is a V120 turbine upgraded for delivering 5 MW. The second one is the same machine but with a DDB control system integrated as it is shown in Figure 3.1.

Firg.3.1. A design model of the second wind turbine with DBB control system for the "Mar de Canarias" experimental site.

The blades of the DBB control system are built with a dynamic pair of two segments S1 and S2. The segment S1 has a length of 55 meters and the segment S2 has 33 meters and its resulting power curve is represented by dashed line in Figure 3.2. This wind turbine starts its operation at 2.6 m/s wind speed. At this wind velocity, the operation is with the maximum area of the swept bands: 22,232 m^2. This large area keeps constant till the wind turbine reaches its rated power 5000 kW. Then, if the wind speed increases further, the control DBB slides the segment S2 over the S1, merging its swept bands and reducing the total swept area. This process continues till the swept band area of the segment S2 is completed merged into the swept band area of S1. At this point, the total wind turbine swept area reaches its minimum value of 9,075 m^2 and the wind speed is about 18.2 m/s. If the wind speed increases further, then the pitch control of the blades starts changing the attack angle. The pitch control remains regulating the output power till the maximum operation wind speed (29 m/s) is reached.

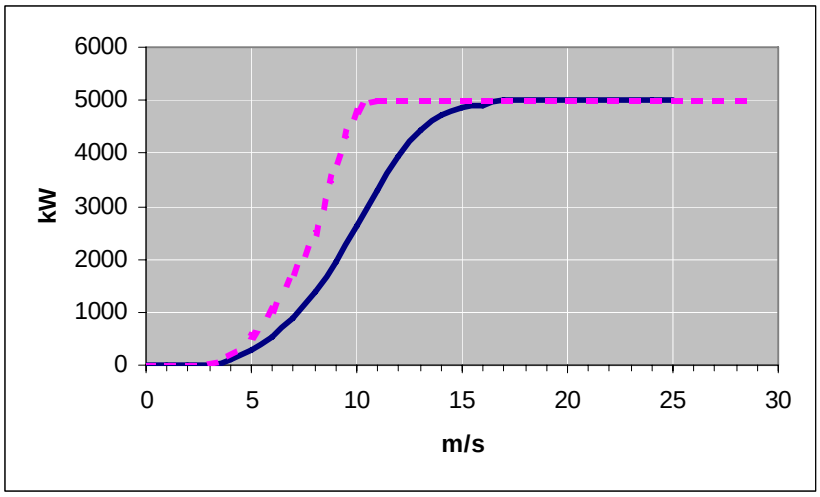

Figure 3.2. Power-speed curves of the two experimental 5 MW wind turbines. Turbine II equipped with DBB control system is represented by dashed line.

The power curves of both turbines seem to be rather similar, however when the energy productions of wind turbines are simulated emerge very significant differences. Thus, at "Mar de Canarias" wind experimental site we have found an annual production increment of 5,979 MW-h. The most impressive energy gain of the DBB control system is obtained in wind speeds around 10 m/s as illustrates the Table 3.3. These speeds belongs to the first range; one of the two ranges where differences between both turbines are found. This first range extends to wind speeds lower than 16 m/s and its estimated additional annual energy yield is 4,684 MW-h.; that is a 17.4 % of annual energy increment.

The second range is for wind speeds higher than 25 m/s. In this range, the DBB control system is able to generate 1,294 MW-h of extra energy. That is a 4.8 % increment of annual energy yield. A substantial amount but much less than the increment produced in the first range. So, in this location and with these turbines, is in the lower wind speed range where the biggest increase of annual energy is produced. This fact is significantly common, particularly in those wind farms with gusty winds. The turbines of those farms are designed to support transients of high wind speeds so they are less efficient operating in gentle breezes.

V(m/s)	Days	Turbine I MW-h	Turbine II MW-h	Increment MW-h
0	18	0	0	0
1	1	0	0	0
2	4	0	0	0
3	6	0	3	3
4	9	24	39	14
5	11	75	136	61
6	13	166	312	146
7	16	337	656	318
8	17	547	989	442
9	19	878	1,711	833
10	20	1,243	2,259	1,016
11	21	1,637	2,471	833
12	21	1,947	2,471	524
13	21	2,198	2,471	272
14	20	2,221	2,353	132
15	19	2,182	2,235	54
16	18	2,082	2,118	36
17	17	2,000	2,000	0
18	15	1,765	1,765	0
19	14	1,647	1,647	0
20	12	1,412	1,412	0
21	11	1,294	1,294	0
22	9	1,059	1,059	0
23	8	941	941	0
24	6	706	706	0
25	5	588	588	0
26	4	0	471	471
27	3	0	353	353
28	2	0	235	235
29	2	0	235	235
30	1	0	0	0

Table 3.3. Annual energy yield estimations of the 5 MW wind turbines at the experimental offshore site of "Mar de Canarias". Turbine II is equipped with DDB control system.

4.- CONCLUSIONS

Starting with basic concepts revision, the study has been focused on energy generation assessment of a new power control system in an experimental offshore site. According to the simulation results, the dimensional swept bands control system (DBB) increases the generation of energy at low winds speeds and allow a stable operation of the wind turbine till higher wind speeds. So the total annual energy yield of a wind turbine is significantly increased. In the projected experimental offshore location "Mar de Canarias", where this study has been performed, an annual energy increase of 22,2 % is expected to be reached.

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