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Experimental Study on the Hysteresis Properties in Operation of Vertical Axis Wind Turbines

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***Abstract*—**Hysteresis phenomenon has been observed in the operations of both horizontal-axis and vertical-axis wind turbines (HAWTs and VAWTs). In this study, wind tunnel experiments were applied to investigate the characters of hysteresis phenomena between the angular speed and the external resistance of electrical loading during the operation of a Darrieus type VAWT. Data of output voltage, output current, angular speed of wind turbine under different wind speeds are measured and analyzed. Results show that the range of external resistance changes with the wind speed. The range decreases as the wind speed increases following an exponential decay form. Experiments also indicate that the maximum output power of wind turbines is always inside the range where hysteresis happened. These results provide an important reference to the design of output control system of wind turbines.

***Keywords*—**Hysteresis phenomenon, Angular speed, Range of external resistance

I. Introduction

WIND power is a rapidly developing technology. The world total installed capacity of wind turbines increased significantly year by year from one decade ago [1]. Topics of wind power generator for both HAWTs and VAWTs attract interest of many researchers. Many works [2]-[4] help to promote the output performance. These studies focus on the aerodynamic problems of wind turbines only. Mathematical models describing both aerodynamic and electric components of wind turbine [5]-[7] thus enable efficient and full analysis of the wind turbine behavior in different operating conditions, including transitions between different operating regimes.

Theoretical and experimental analyses [8] explained the hysteresis phenomenon appearing during the change of external resistance in the operation of HAWTs [5], [6] and VAWTs [7]. Their results also indicate the preferable working regimes of wind turbines are in the range of external resistance where the hysteresis effect appears.

To achieve an optimized output control of wind turbine systems we need more information on the hysteresis phenomenon. In this paper we follow the theoretical study [8] and apply wind tunnel experiments to investigate the characters and variations in the range of external resistance under different operation environments. A vertical axis wind turbine DS300 with Darrieus blades only is the testing device. Output voltage, output current, external resistance and angular speed of rotor are measured under different wind speeds.

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II. Hysteresis Penomenon

Fig. 1 illustrates the hysteresis phenomenon in operation of an H-type stand-alone Darrieus wind turbine system [8]: the behavior of the angular speed ω depends on the direction of change of the external resistance *R*. In the direction of external resistance increasing, the angular speed accelerates abruptly to a higher level as *R* is just larger than R_2. The angular speed does not decrease smoothly but drops to a very low level as *R* is just less than R_1 in the direction of external resistance decreasing. The trajectory is similar to the curve of magnetic hysteresis.

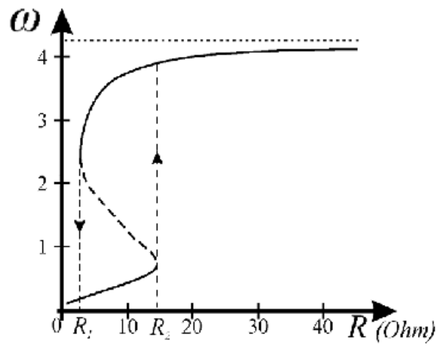

Fig. 1 Simulated relationship between external resistance and angular speed of H-type VAWT (from Fig. 4 in Dosaev *et al.* [8])

III. Wind Tunnel Experiments

The testing VAWT is originally a Savonius and Darrieus combination system. We took off the Savonius rotors to be a pure Darrieus turbine as shown in Fig. 2 to simplify the analysis of hysteresis effect.

Fig. 2 Darrieus type VAWT for wind tunnel experiments

Experiments are performed using the above three blades Darrieus VAWT with rotor diameter 1.24 m and rotor height 1.06 m under different fixed wind speeds from 4 m/s to 9 m/s. The external resistance first decreases monotonously step by step from infinity (open circuit) to almost zero. Output voltage, output current, angular speed and the fixed wind speed were recorded as the rotation reaches an equilibrium state for each resistance. Similar procedures are then performed for the external resistance increasing monotonously step by step form zero to infinity. Both the two procedures with resistance changing run for seven fixed wind speeds: 4, 4.5, 5, 6, 7, 8, and 9 m/s.

IV. Results

A. Range of External Resistance

Trajectories of angular speed changing with external resistance are analyzed first. Figs. 3, 4, and 5 are the hysteresis curves under wind speeds 5 m/s, 7 m/s and 9 m/s. The square spot and lines with blue color indicate the change of angular speed associated with decreasing of external resistance and those with red color are for increasing of external resistance. The three figures show that the range of external resistance becomes narrower as the wind speed larger.

We thus investigated how the range of resistance change with wind speeds. Fig. 6 shows all the critical values of external resistance correspond to sudden change of angular speeds. The upper boundary is resistances for angular speed accelerated abruptly (R_2). The lower one is resistances for angular speed decelerated abruptly (R_1). The blue line in the center of shaded range is the average resistance. We also found that the upper boundary drops more significantly than the lower boundary. Ranges of external resistance calculated by R_2 - R_1 for different wind speeds are listed in Table I.

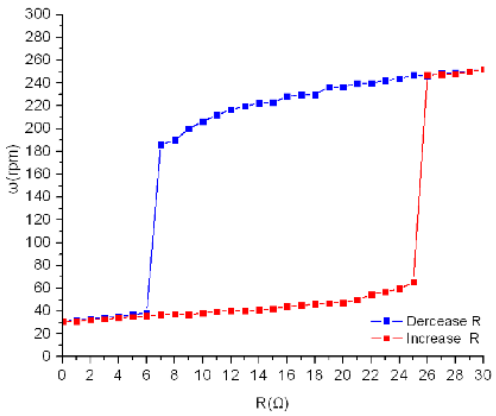

Fig. 3 Hysteresis relationship between angular speed (ω) and external resistance (R) for wind speed 5 m/s

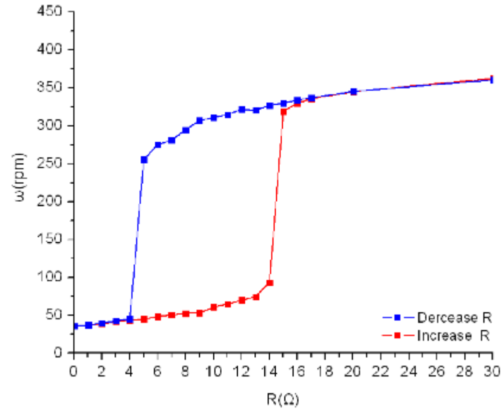

Fig. 4 Hysteresis relationship between angular speed (ω) and external resistance (R) for wind speed 7 m/s

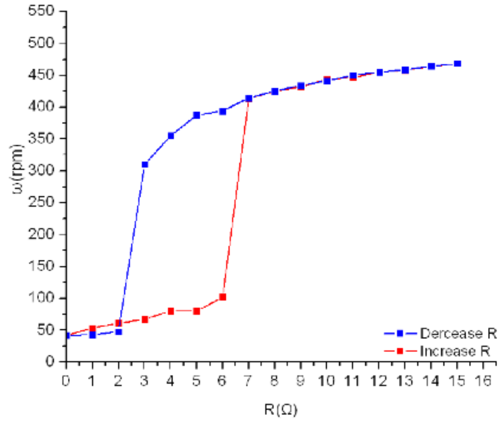

Fig. 5 Hysteresis relationship between angular speed (ω) and external resistance (R) for wind speed 9 m/s

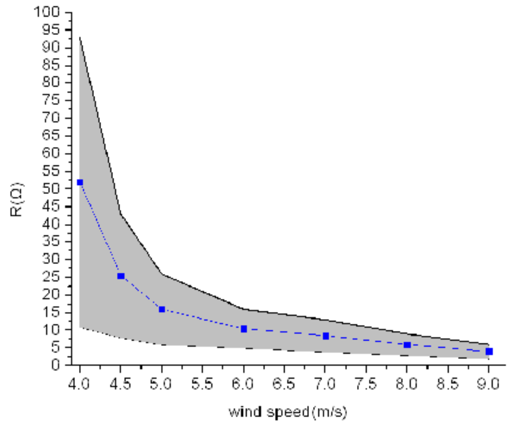

Fig. 6 Critical values of external resistance correspond to sudden change of angular speeds

TABLE I
CRITICAL VALUES OF EXTERNAL RESISITANCE

Wind Speed (m/s)	R_2 (Ω)	R_1(Ω)	R_2 - R_1 (Ω)
4	93	11	82
4.5	43	8	35
5	26	6	20
6	16	5	11
7	13	4	9
8	9	3	6
9	6	2	4

To describe the relationship between the range of resistance and wind speed, an exponential decay curve as shown in Fig. 7 is obtained using the minimum chi square fitting. The line with circle is measured data and the dotted line is fitting result. It proposes that the range exponentially decays with the change of wind speed. The fitting curve can be represented as the following equation.

$$R_r = 7.16777 + 16092800 \exp(-V / 0.34167) \qquad (1)$$

where R_r is the range of resistance and V is wind speed.

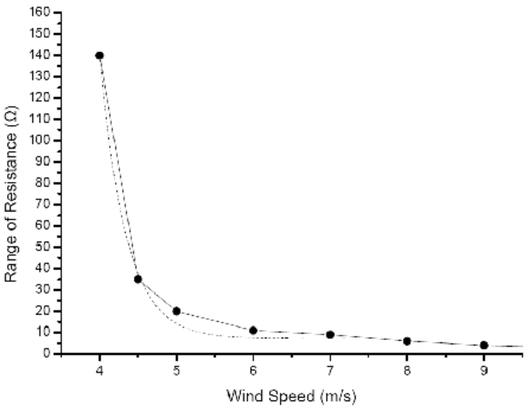

Fig. 7 Range of external resistance changes with wind speed and the fitting curve (dotted line)

B. Location of Maximum Output

All the measured output voltage and current data are applied to calculate the output power of wind system. Trajectories of output power change with the external resistance under wind speed 5 m/s, 7 m/s, and 9 m/s are shown in Figs. 8, 9, and 10 respectively. Lines with blue color indicate the change of output power associated with decreasing of external resistance and those with red color are for increasing of external resistance. These figures show that the hysteresis ranges of output power are the same as those of angular speed. It indicates the angular speed dominates the output power of wind turbines.

Figs. 8, 9, and 10 also show that the maximum output power points are found always inside the range where hysteresis effect appeared. These points move more closely to the drop down point under lower wind speed. It indicates wind systems are easier to stop by extra loading under low wind speed conditions.

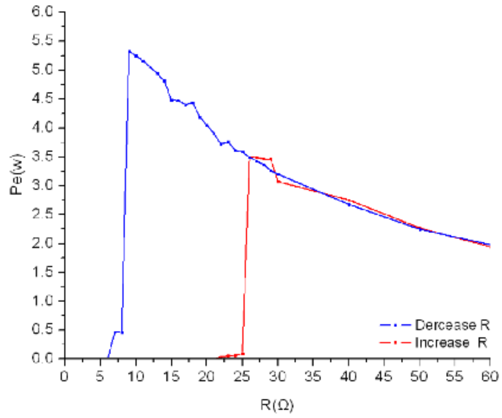

Fig. 8 Fig. 10 Hysteresis relationship between output power (Pe) and external resistance (R) for wind speed 5 m/s

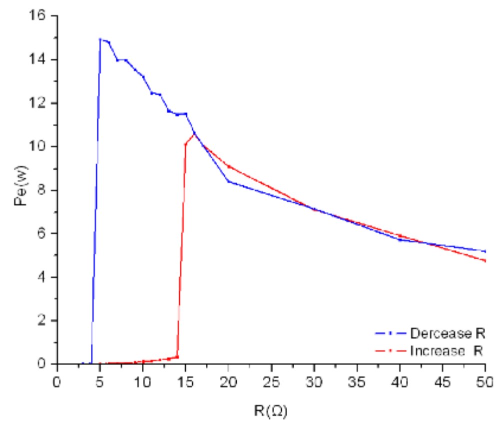

Fig. 9 Fig. 10 Hysteresis relationship between output power (Pe) and external resistance (R) for wind speed 7 m/s

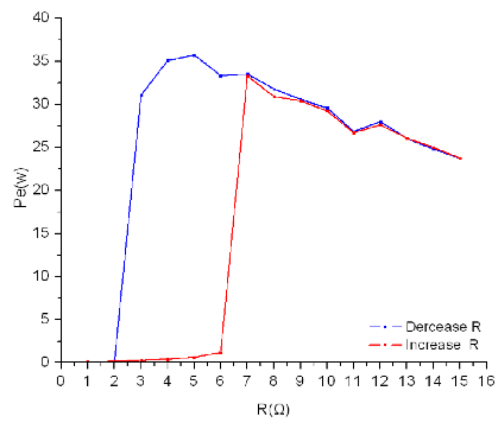

Fig. 10 Hysteresis relationship between output power (Pe) and external resistance (R) for wind speed 9 m/s

Based on the character of output power curves, it suggests the wind system is better to start with large external resistance (more than R_2 at least) to achieve a high level angular speed and then decreases the external resistance to some optimal value to slow down angular speed and obtain the maximum output power.

V. Summary

We investigated the hysteresis effect in operation of a small Darrieus type vertical axis wind turbines using wind tunnel experiments. The characters are consistent with the theoretical studies [5]-[8]. The analyses on the hysteresis range of external resistance and location of maximum output power are listed as the followed.

1) The range of external resistance changes with the wind speed. The range almost exponentially decays with the increase of wind speed.
2) The maximum output power points are always inside the range where hysteresis effect appeared. These points move closer to the drop down point under lower wind speed.
3) The best operation to obtain the maximum output power is to start rotating with a large external resistance (more than R_2) to achieve a high level angular speed and then decreases the external resistance to slow down the angular speed to enter the hysteresis region.

The above results provide useful parameters to the optimized design of output control system of wind turbines. Theoretical explanation on the variation of hysteresis range and location of maximum output are still absent. More studies are needed to understand the internal mechanism.

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