Development of a tornado proof pendulum safety system for a medium size wind turbine which turns the rotor out of the wind along an horizontal axis

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1 Introduction

Windmills with fixed rotors can be protected against too high forces and too high rotational speeds by turning the rotor out of the wind. This can be done around a vertical and around an horizontal axis. All present VIRYA windmills developed by Kragten Design turn out of the wind around a vertical axis and make use of the so called hinged side vane safety system.

Safety systems for water pumping windmills are described in report R 999 D (ref. 1). Water pumping windmills normally have fixed rotors and all safety system are working by turning the rotor out of the wind. However, electricity generating windmills can also be protected by turning the rotor out of the wind. In chapter 2 of R 999 D, the reasons are given why a safety system is necessary. These reasons are:

1 Limitation of the axial force or thrust on the rotor to limit the load on the rotor blades, the tower and the foundation.
2 Limitation of the rotational speed of the rotor to limit the centrifugal force in the blades, imbalance forces, high gyroscopic moments in the blades and the rotor shaft, to prevent flutter for blades with low torsion stiffness and to prevent too high rotational speeds of the load which is relevant for limitation of heat dissipation in a generator or for limitation of shock forces in the transmission to a piston pump.
3 Limitation of the yawing speed to limit high gyroscopic moments in the blades and the rotor shaft.

Almost all known systems are described shortly in chapters 3 and 4 of R 999 D. The three most generally used systems, the ecliptic system, the inclined hinge main vane system and the hinged side vane system are described in detail in chapter 7 of report R 999 D. Because report R 999 D is no longer available, the hinged side vane system is also described in several KD-reports. It is described in report KD 213 (ref. 2) for the VIRYA-4.2 windmill.

Every safety system has certain advantages and disadvantages. The main advantages of the hinged side vane safety system are:

1) It is simple and cheap.
2) It has a δ-V curve which is lying close to the ideal δ-V curve (see chapter 2).
3) The hinge axis is loaded only lightly and therefore simple door hinges can be used.
4) The vane blade is situated in the undisturbed wind and therefore a relatively small vane blade area is required to generate a certain aerodynamic force.
5) The moment of inertia of the head is large resulting in low yawing speeds and so large gyroscopic moments at high wind speeds are prevented.

The main disadvantages of the hinged side vane system are:

1) There must be a certain ratio in between the vane area and the vane weight if a certain rated wind speed is wanted. Therefore it appears to be difficult to make a large vane blade stiff enough. The hinged safety system is therefore limited to windmills with a maximum rotor diameter of about 5 m.
2) The system is sensible to flutter of the vane blade, if the vane blade and the vane arm is not made stiff enough. Flutter is suppressed effectively using a vane blade stop at the almost horizontal position of the vane blade
3) It is difficult to turn the head out of the wind permanently by placing the vane blade in the horizontal position because this vane blade is positioned far form the tower and far from the ground.

It is expected that the hinged side vane safety system can be used in regions with maximum wind speeds of about 35 m/s. The maximum wind speed which has been measured at the test side of Kragten Design is 26 m/s, so it is proven that the hinged side vane system works well at least up to this wind speed. But during hurricanes or tornado's, much higher wind speeds than 35 m/s may occur and it is expected that a windmill with a hinged side vane system will not survive extremely high wind speeds which may occur. If the tornado is predicted, the whole windmill can be laid down but this is only a realistic option for small windmills.

For a medium size windmill with a rotor diameter of about 10 m, laying down of the whole windmill in case of tornado's is probably too complicated and therefore it is investigated if a safety system can be designed with which the windmill can be protected also at extremely high wind speeds. It is assumed that the forces on the rotor are limited enough if the rotor can be placed and locked horizontally in the so called helicopter position. This requires turning of the rotor out of the wind along an horizontal axis. This system is used in some commercially available windmills but it has some important disadvantages if it is not properly designed. The main disadvantages are:

1) The weight of the rotor and the generator causes a moment around the hinge axis which varies sinusoidal. This weight is normally counterbalanced by a spring mechanism but it is difficult to design this mechanism such that the system functions stable at different wind speeds and that it results in an almost constant rotational speed and an almost constant rotor thrust at high wind speeds.
2) For most systems, the head starts to turn out of the wind above a certain wind speed and the head is pushed against a stop below this wind speed. If the rotor is far out of the wind at high wind speeds and if the wind speed is reduced suddenly, this results in turning back of the rotor with a rather large speed till the stop is reached. This results in large shock forces if the head movement is not damped.
3) The yawing movement of the head around the tower axis causes a gyroscopic moment which turns the rotor more in or out of the wind depending on the direction of rotation of the rotor and the head. So the yawing movement influences the safety system and the yawing movement must therefore be rather slow which can't be realised if only a small vane is used to keep the rotor in the wind.

Kragten Design did some research to a safety system which turns the head out of the wind along an horizontal axis already in 2003. This research is given in report KD 175 (ref. 3, in Dutch). The given system was not build and tested, mainly because of disadvantage no. 2. In chapter 3, a safety system will be described which turns the head out of the wind along an horizontal axis but which has no stop at the position of the head for low wind speeds.

2 The ideal δ-V curve

Generally it is wanted that the windmill rotor is perpendicular to the wind up to the rated wind speed V_{rated}, and that the rotor turns out of the wind such that the rotational speed, the rotor thrust, the torque and the power stay constant above V_{rated}. It appears to be that the component of the wind speed perpendicular to the rotor plane determines these four quantities. The yaw angle δ is the angle in between the wind direction and the rotor axis. The component of the wind speed perpendicular to the rotor plane is therefore $V \cos\delta$. The formulas for a yawing rotor for the rotational speed n_δ, the rotor thrust $F_{t\delta}$, the torque Q_δ and the power P_δ are given in chapter 7 of report KD 35 (ref. 4). These formulas are copied as formula 1, 2, 3 and 4.

$$n_\delta = 30 * \lambda * \cos\delta * V / \pi R \quad \text{(rpm)} \qquad (1)$$

$$F_{t\delta} = C_t * \cos^2\delta * ½\rho V^2 * \pi R^2 \quad \text{(N)} \qquad (2)$$

$$Q_\delta = C_q * \cos^2\delta * ½\rho V^2 * \pi R^3 \quad \text{(Nm)} \qquad (3)$$

$$P_\delta = C_p * \cos^3\delta * ½\rho V^3 * \pi R^2 \quad \text{(W)} \qquad (4)$$

These four quantities stay constant above V_{rated} if the component of the wind speed perpendicular to the rotor plane is kept constant above V_{rated}. So in formula:

$$V \cos\delta = V_{rated} \quad \text{(for } V > V_{rated}\text{)} \qquad (5)$$

It is assumed that the rotor is loaded such that it runs at the design tip speed ratio λ_d. If the wind speed is in between 0 m/s and V_{rated}, the n-V curve is a straight line through the origin. The F_t-V and the Q-V curves are then parabolic lines and the P-n curve is a cubic line.

Formula 5 can be written as:

$$\delta = \text{arc cos } (V_{rated} / V) \qquad (°) \qquad (6)$$

This formula is given as a graph in figure 1 for different value of V / V_{rated}. The value of δ has been calculated for V / V_{rated} is respectively 1, 1.01, 1.05, 1.1, 1.25, 1.5, 2, 2.5, 3, 4, 5 and 6.

The rated wind speed V_{rated} is chosen on the basis of the maximum thrust and the maximum rotational speed which is allowed for a certain rotor and a certain generator. Mostly V_{rated} is chosen about 10 m/s. For the chosen value of V_{rated}, figure 1 can be transformed into the δ-V curve for which V (in m/s) is given on the x-axis. If it is chosen that V_{rated} = 10 m/s, figure 1 becomes the δ-V curve if all values on the x-axis are multiplied by a factor 10.

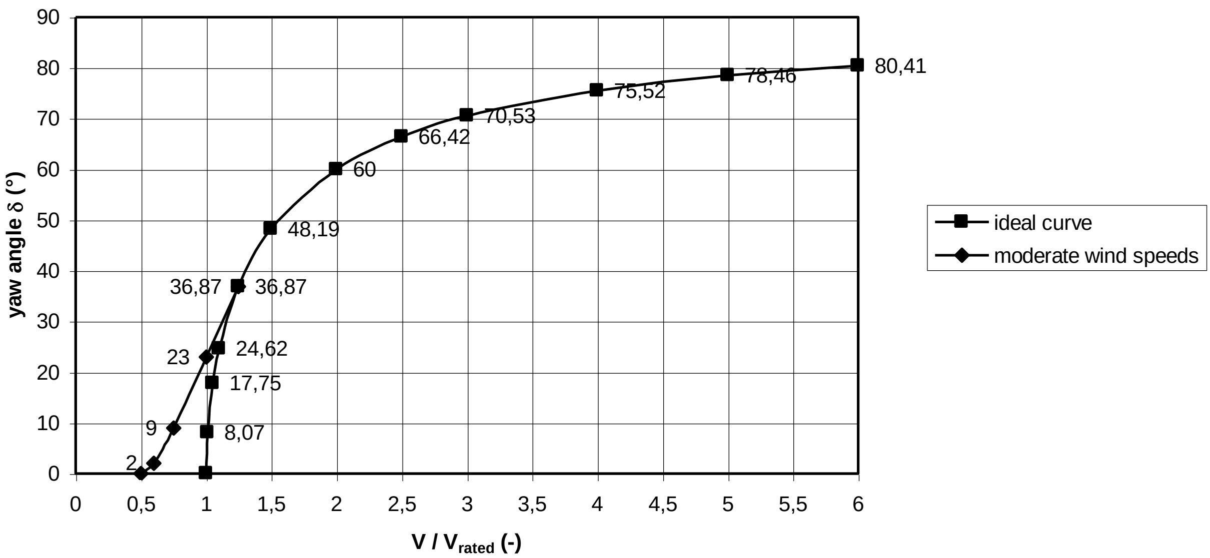

fig. 1 the δ-V/V_{rated} curve for the ideal safety system

In figure 1 it can be seen that the rotor is perpendicular to the wind for (V / V_{rated}) < 1 but that the required change in δ is very sudden if V / V_{rated} is a very little higher than 1. So even if one would have a safety system which theoretically has the ideal δ-V curve, in practice this curve will not be followed because the inertia of the system prevents sudden changes of δ around V / V_{rated} = 1. So the system will turn out of the wind less than according to the ideal δ-V curve. This will result in a certain overshoot of the rotational speed and the thrust.

For high values of V / V_{rated}, a certain increase of V, and therefore a certain increase of V / V_{rated}, requires only a relatively small increase of δ. It is therefore much easier to follow the theoretical δ-V curve at high wind speeds.

Because of this effect, it is practically impossible to follow the ideal δ-V curve for wind speeds lower than about 1.25 * V_{rated} and the practical δ-V curve must therefore start increasing already at a much lower wind speed than the theoretical rated wind speed. An example of a practical δ-V curve for moderate wind speeds is also given in figure 1. Even for this practical curve for moderate wind speeds and for the ideal curve for values of V / V_{rated} > 1.25, there will be a certain overshoot of n and F_t because of inertia effects.

3 Description of the pendulum safety system

The safety system is called the pendulum safety system because the whole assembly of rotor, head and balancing weights is swinging on top of the tower like the pendulum of a clock. The horizontal hinge axis is intersecting with the tower axis The eccentricity e in between the rotor axis and the hinge axis is taken larger than the rotor radius R and the place of the hinge axis can therefore be chosen such that it is lying in the rotor plane.

On a yawing fast running rotor there is a thrust force $F_{t\delta}$, working in the direction of the rotor shaft and a side force $F_{s\delta}$ working in the direction of the rotor plane. This side force is giving no moment around the hinge axis if the hinge axis is lying in the rotor plane. The side force can therefore be neglected concerning the balance of moments around the hinge axis. On a yawing fast running rotor there is also working a so called self orientating moments M_{so} which has a tendency to decrease the yaw angle. This moment is maximal for a yaw angle of about 30° and it partially neutralises the moment which is produced by the thrust. However, if the eccentricity is taken very large, like it is done for the pendulum safety system, the self orientating moment is very small with respect to the moment caused by $F_{t\delta}$ and the self orientating moment can therefore also be neglected. So the whole aerodynamic moment of the rotor M_{rotor} around the hinge axis is now only caused by the rotor thrust $F_{t\delta}$. M_{rotor} is given by:

$$M_{rotor} = F_{t\delta} * e \qquad \text{(Nm)} \qquad (7)$$

(2) + (7) gives:

$$M_{rotor} = C_t * \cos^2\delta * ½\rho V^2 * \pi R^2 * e \qquad \text{(Nm)} \qquad (8)$$

Apart from the aerodynamic moment M_{rotor}, there is also a moment working around the hinge axis which is caused by the weight of the rotor, the generator, the swinging parts of the head and the balancing weights. All these parts together result in a total weight of the swinging parts G, acting at the centre of gravity which is laying at a certain radius r_G from the hinge axis. The centre of gravity also has a certain position with respect to the rotor plane and this position depends on the position of the balancing weights.

As the eccentricity e is chosen very large, the balancing weight must be large and the value of r_G will be rather large too. It is assumed that two balancing weights are used and that each balancing weight is mounted to an arm which is swinging along the upper part of the tower. Now the rotor can be compared to the sail of a sail boat and the balancing weights can be compared to the keel. For a sail boat the sail is vertical if there is no wind but this seems to be not the optimum condition for the pendulum safety system because this will result in power reduction for wind speeds where it is not yet necessary. After some investigation it is found that the system is more optimal if the rotor has a negative yaw angle of 20° if the wind speed is 0 m/s. This angle is called the pre-angle ε = 20°. So the position of the centre of gravity of the swinging parts of the head has to be chosen such that the centre of gravity is lying exactly below the hinge axis for δ = -20°. The clock wise angle in between the horizon and the rotor axis is called δ.

If the rotor moves backwards because of the rotor thrust, the centre of gravity will move forwards. The clock wise angle in between the vertical and the line through the centre of gravity and the hinge axis is called α. In figure 2 all values are given for an angle δ = 10° corresponding to an angle α = 30°. The real balancing weights and the arms are not given in this figure. Only the resulting weight G is given in the centre of gravity. It is clear that:

$$\alpha = \delta + \varepsilon \qquad (°) \qquad (9)$$

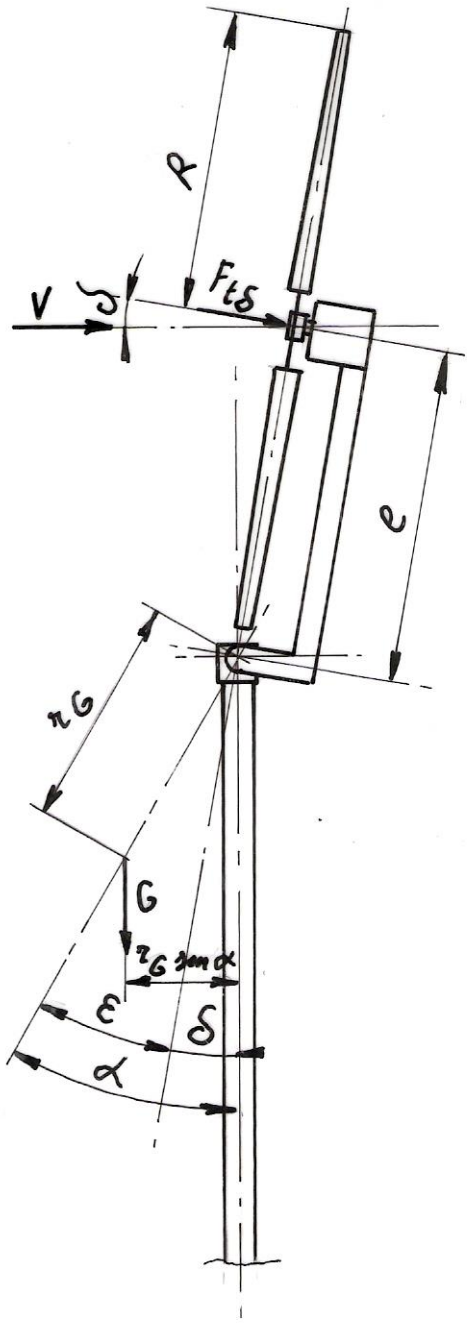

fig. 2 The pendulum safety system for $\delta = 10°$ belonging to $V = V_d$

The weight G causes a moment around the hinge axis M_G which is given by:

$M_G = G * r_G * \sin\alpha$ (N/m) (10)

(9) + (10) and $\varepsilon = 20°$ gives:

$M_G = G * r_G * \sin(\delta + 20°)$ (N/m) (11)

Now it is assumed that the whole system is working quasi stationary, so dynamic effects are neglected. For this condition there must be balance of moments around the hinge axis so:

$M_{rotor} = M_G$ (12)

(8) + (11) + (12) gives:

$C_t * \cos^2\delta * ½\rho V^2 * \pi R^2 * e = G * r_G * \sin(\delta + 20°)$ (13)

This is a rather simple formula and with this formula it is possible the derive the δ-V curve of the pendulum safety system if some of the parameters are chosen. To explain this procedure first some wind speeds are defined.
V_0 is called the wind speed for which V = 0 m/s. For $V = V_0$, $\delta = -20°$ and $\alpha = 0°$.
V_d is called the design wind speed. V_d is defined as the wind speed for which $\alpha = 30°$. With formula 9 and $\varepsilon = 20°$ it is found that $\delta = 10°$ for $V = V_d$. With formula 4 it can be calculated that the power reduction for $\delta = 10°$ is only a factor 0.9551 and so this reduction is only low for the design wind speed. With formula 10 it can be calculated that M_G is half the peak value for $\alpha = 30°$. So M_{rotor} is also half the peak value for $\alpha = 30°$.
V_{rated} is called the rated wind speed. V_{rated} is defined as the wind speed for which M_G and so M_{rotor} is maximal. With formula 10 it can be calculated that M_G has a maximum for $\alpha = 90°$ corresponding to $\delta = 70°$.

Next a certain assumption of V_d has to be made. For the time being it is assumed that $V_d = 7$ m/s. So all parameters are chosen such that $\delta = 10°$ for V = 7 m/s. Formula 13 can be written as:

$C_t * ½\rho * \pi R^2 * e / (G * r_G) = \sin(\delta + 20°) / (V^2 * \cos^2\delta)$ (14)

Substitution of $V = V_d = 7$ m/s and $\delta = 10°$ in formula 14 gives:

$C_t * ½\rho * \pi R^2 * e / (G * r_G) = \sin 30° / (49 * \cos^2 10°)$ or

$C_t * ½\rho * \pi R^2 * e / (G * r_G) = 0.010521$ (for $V_d = 7$ m/s) (15)

(14) + (15) gives:

$\sin(\delta + 20°) / (V^2 * \cos^2\delta) = 0.010521$ (for $V_d = 7$ m/s) (16)

Formula 16 can be written as:

$0.010521 * V^2 * \cos^2\delta = \sin(\delta + 20°)$ or

$V = \sqrt{\{(\sin(\delta + 20°) / (0.010521 * \cos^2\delta)\}}$ (m/s) (for $V_d = 7$ m/s) (17)

Next formula 17 is used to calculate V for different values of δ. It has been chosen that δ = -20°, -15°, -10°, 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80° and 90°. The result is given in table 1.

δ (°)	V (m/s)	cosδ	$\cos^2\delta$	$\cos^3\delta$	V * cosδ	$V^2 * \cos^2\delta$	$V^3 * \cos^3\delta$
-20	0	0.9397	0.8830	0.8298	0	0	0
-15	2.9797	0.9659	0.9330	0.9012	2.878	8.284	23.842
-10	4.1253	0.9848	0.9698	0.9551	4.063	16.505	67.053
0	5.7016	1	1	1	5.702	32.508	185.349
10	7	0.9848	0.9698	0.9551	6.894	47.522	327.603
20	8.3180	0.9397	0.8830	0.8298	7.816	61.096	477.545
30	9.8530	0.8660	0.75	0.6495	8.533	72.811	621.294
40	11.8436	0.7660	0.5868	0.4495	9.073	82.314	746.815
50	14.7027	0.6428	0.4132	0.2656	9.451	89.316	844.100
60	19.3498	0.5	0.25	0.125	9.675	93.604	905.606
70	28.5049	0.3420	0.1170	0.0400	9.749	95.028	926.645
80	55.7156	0.1736	0.0302	0.0052	9.675	93.604	905.610
90	∞	0	0	0	-	-	-

table 1 Calculated relation in between δ and V for V_d = 7 m/s

In table 1 the values for cosδ, $\cos^2\delta$, $\cos^3\delta$, V * cosδ, $V^2 * \cos^2\delta$ and $V^3 * \cos^3\delta$ are also mentioned. V * cosδ is an indication for the increase of the rotational speed (see formula 1). $V^2 * \cos^2\delta$ is an indication for the increase of the thrust and the torque (see formula 2 and 3). The value for δ = 70° is double the value for δ = 10°. $V^3 * \cos^3\delta$ is an indication for the increase of the power (see formula 4). In table 1 it can be seen that all these four quantities reach a maximum for δ = 70° which could be expected because for this situation α = 90° and this is the angle for which M_G has a maximum.

The values for δ as a function of V are given as the δ-V curve figure 3.

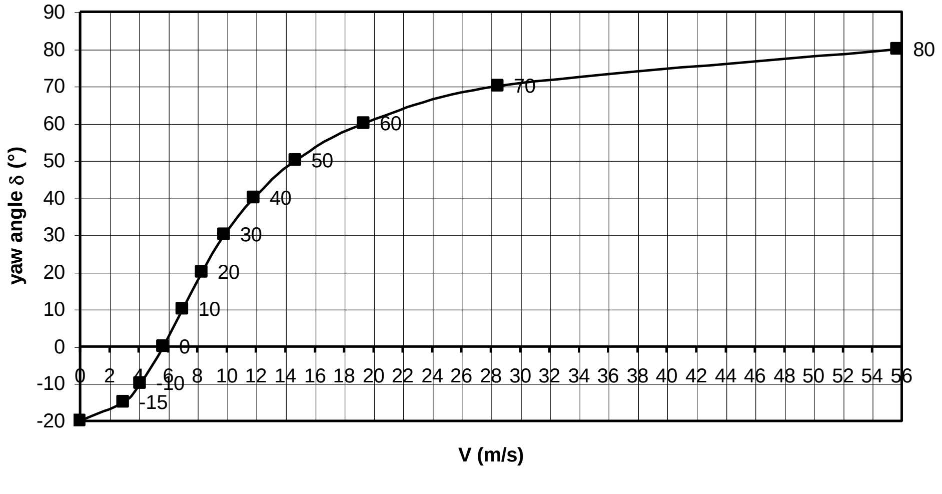

fig. 3 Calculated δ-V curve for the pendulum safety system for V_d = 7 m/s

If figure 3 is compared to the ideal curve and the curve for moderate wind speeds of figure 1, it can be seen that the δ-V curve for the pendulum safety system has about the wanted shape.

The most frequent wind speeds are normally lying in between about 4 m/s and 7 m/s, The yaw angle δ for these wind speeds is lying in between –10° and 10°. The power loss for yaw angles less than 10° is only small and this demonstrates the value of the pre-angle ε = 20°.

For the chosen value V_d = 7 m/s (at α = 30° and δ = 10°) it is found that the rated wind speed V_{rated} = 28.5049 m/s (at α = 90° and δ = 70°). For this rated wind speed, the maximum rotational speed and the maximum thrust are found and the rotor strength has to be calculated for this wind speed and this yaw angle. In table 1 and figure 3 it can be seen that a very large increase of the wind speed (from 28.5049 m/s up to 55.7156 m/s) is needed to increase the yaw angle from 70° to 80°. The helicopter position will never be reached for stationary conditions. However, hard wind gusts at hurricanes or tornados will cause swinging movements resulting in reaching δ = 90° for a short moment.

The system can make extremely large movements from about δ = -170° up to δ = 170° without the rotor touching the tower. So it is expected that stops for limitation of δ are not necessary. However, to make the system tornado proof, it must be possible to fix the movement at δ = 90°, so there must be a stop and a kind of clamp at this angle. This clamp can work automatically and it will lock the rotor at δ = 90°. If this has happened one has to unlock the system manually but as automatic locking will happen only during very high wind gusts, automatic locking is an acceptable option. It must be possible to turn the rotor to the helicopter position while standing on the tower at about 2/3 of the height. From this position it must also be possible to unlock the rotor from the helicopter position and as unlocking results in a big swing of the balancing weights, this must be done from a position when one can’t be hit by the swinging weights.

High upwards wind speeds may occur in the central part of a tornado, so the rotor may start rotating even if the safety system is locked in the helicopter position. However, the rotor will rotate backwards if the wind comes from below and the airfoil will therefore have a lot of drag which strongly limits the rotational speed and the thrust. So the rotor will survive large upwards wind speeds. But there may be extremely strong tornados which will not be survived.

The moment of inertia of all swinging parts of the head will be rather large because of the large eccentricity e. This limits the maximum yawing speed around the horizontal axis at high wind speeds and therefore the gyroscopic moment in the rotor shaft and the rotor blades will be limited too.

The calculated values of V * cosδ as a function of V are given in figure 4. This curve is an indication of the variation of the rotational speed.

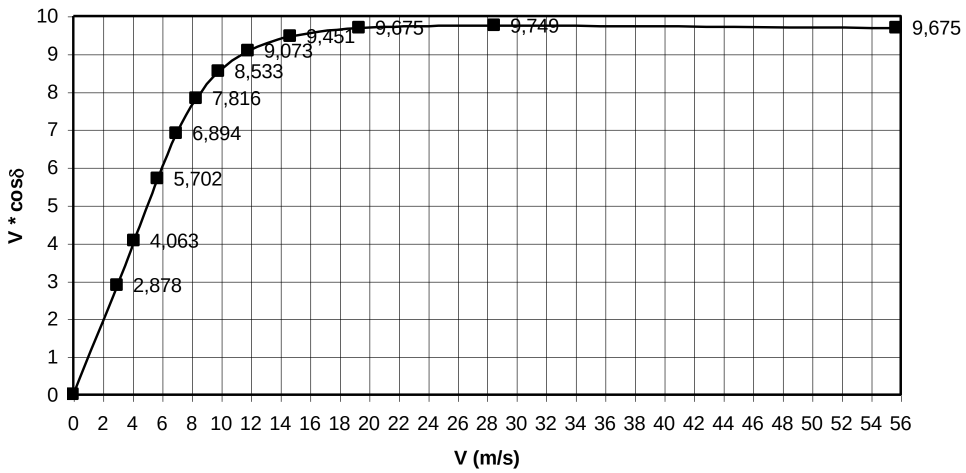

fig. 4 V * cosδ as a function of V for V_d = 7 m/s

In figure 4 it can be seen that the rotational speed is sharply limited and that it rises only a little above a wind speed of about 12 m/s.

The calculated values of $V^2 * \cos^2\delta$ as a function of V are given in figure 5. This curve is an indication of the variation of the thrust and the torque.

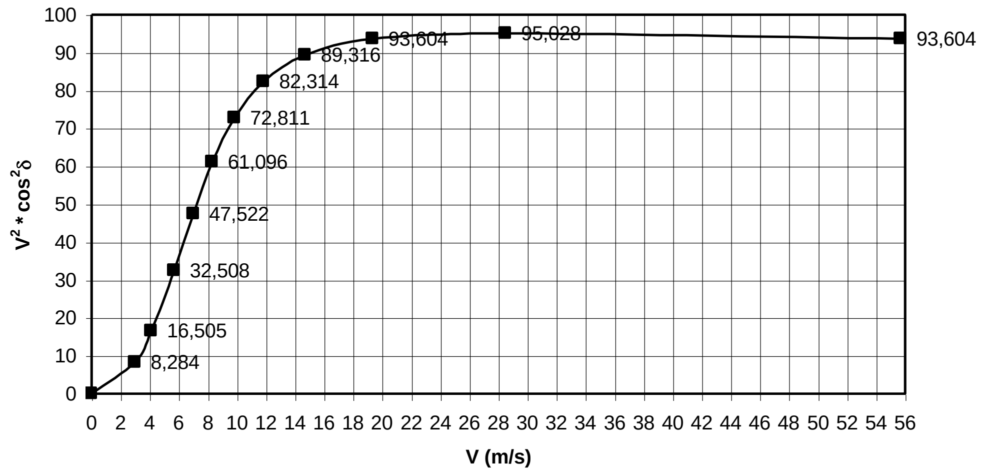

fig. 5 $V^2 * \cos^2\delta$ as a function of V for V_d = 7 m/s

In figure 5 it can be seen that the thrust and the torque are sharply limited and that they rise only a little above a wind speed of about 13 m/s.

The calculated values of $V^3 * \cos^3\delta$ as a function of V are given in figure 6. This curve is an indication of the variation of the power.

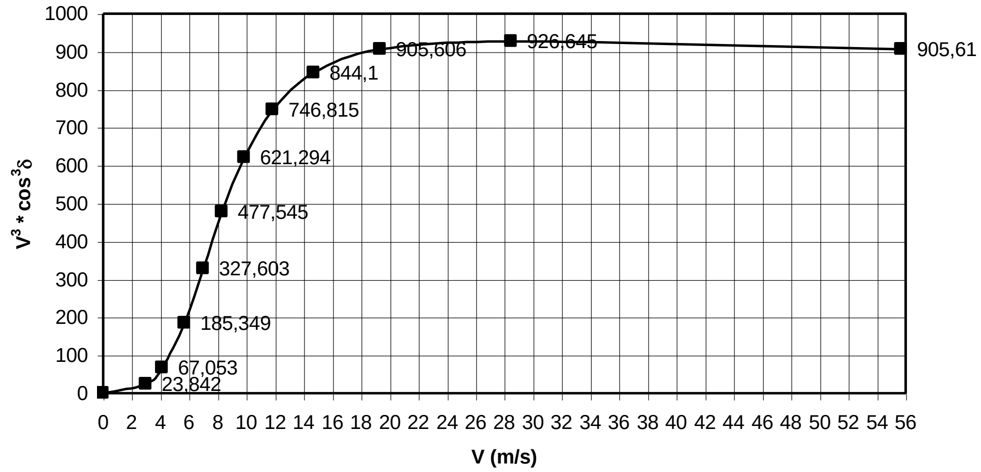

fig. 6 $V^3 * \cos^3\delta$ as a function of V for V_d = 7 m/s

In figure 6 it can be seen that the power is sharply limited and that it rises only a little above a wind speed of about 14 m/s. The power is the mechanical power supplied by the rotor shaft. For the electrical power, the generator efficiency has to be taken into account.

4 Realisation of a certain design wind speed

In chapter 3 it has been shown that a design wind speed V_d = 7 m/s is a good first choice. For this wind speed, δ = 10° and α = 30°. This requires certain values for G and r_G and a certain place of the centre of gravity. Formula 13 can be written as:

$$G * r_G = C_t * \cos^2\delta * ½\rho V^2 * \pi R^2 * e / \sin(\delta + 20°) \quad \text{(Nm)} \quad (18)$$

The eccentricity has to be taken larger than the rotor radius R because the hinge axis is lying in the rotor plane. Assume e = 1.1 R. Substitution of this value in formula 18 gives:

$$G * r_G = 1.1 * C_t * \cos^2\delta * ½\rho V^2 * \pi R^3 / \sin(\delta + 20°) \quad \text{(Nm)} \quad (19)$$

The thrust coefficient C_t for a rotor which is running at the design tip speed ratio is about 0.7. The air density ρ for a temperature of 20° C is about 1.2 kg/m^3. Assume V = V_d = 7 m/s and δ = 10°. Substitution of these values in formula 19 gives:

$$G * r_G = 137.95 R^3 \quad \text{(Nm)} \quad (20)$$

So once the rotor radius is chosen, the required product of G * r_G can be calculated.

The total weight G of all the swinging parts must certainly be larger than the sum weight of the rotor and the generator. The sum weight of these two parts is lying about on the rotor axis which has a distance e from the hinge axis. Now suppose that the two balancing weight are placed on arms with the same length as e. This means that the mass of rotor and generator is balanced if each balance weight has half the weight of the sum weight of rotor and generator and if both balancing arms together have about the same weight as the arm which connects the generator to the hinge hub. So it is advised first to balance the weight of rotor and generator exactly so that the rotor will stay in any position. Formula 20 can now be used to find the extra weight which has to be added at a distance r_G (which can be taken equal to e). The position of this extra weight has to be chosen such that δ = -20° if the extra weight is exactly under the hinge axis. For more details about the geometry it is necessary to make a composite drawing of the pendulum safety system for a certain rotor diameter, a certain rotor and a certain generator.

5 Following variations of the wind direction

The horizontal hinge axis must be kept perpendicular to the wind direction so the head must turn into the wind. This yawing of the head around the tower axis causes a gyroscopic moment perpendicular to the plane of the rotor axis and the tower axis. So this gyroscopic moment has a tendency to topple the rotor along the horizontal hinge axis. The direction of the gyroscopic moment depends on the direction of rotation of the rotor shaft and of the direction of rotation of the head along the tower axis. The rotor turns always in the same direction but the yawing along the tower axis is half the time clock wise and half the time anti-clock wise. So the gyroscopic moment has half the time a tendency to increase δ and half the time a tendency to decrease δ. As the safety system should mainly be influenced by variations of wind speed and preferably not by variations of wind direction, turning of the head into the wind must be done slowly.

A normal vane will turn the head too fast at high wind speeds. A system with side rotors which drive the head in the wind through a reducing gearing gives a very low yawing speed around the tower axis but this system is rather complicated and expensive. I have tested a so called double vane system on one of my earliest windmills which had a rotor diameter of 4 m and a (very noisy) safety system with air brakes on the blade tips.

It was a long pipe parallel to the rotor with a square sheet on each end of the pipe. Each sheet makes an angle of 20° with the rotor axis and the direction of the angles are chosen such that touching lines along the sheets intersect with the rotor axis before the rotor. Each sheet had a width and height of 500 mm and was made of 4 mm steel sheet. The moment of inertia of this vane is very large and fast head movements are therefore damped very well. For a windmill with the pendulum safety system, the optimum position of the pipe is that its axis coincides with the hinge axis. For this position it is not hindering the swinging movement of the head and the balancing arms. Because the hinge axis intersects with the tower axis, the vane exerts no moment on the head bearing housing.

6 Alternatives

The geometry given in figure 1 is chosen such that the hinge axis is lying below the rotor. It is also possible to position the hinge axis such that it is lying above the rotor. This has as advantage that the balancing weights can be much smaller. However, the disadvantage is that a large bow shaped construction is required around the rotor to prevent that the rotor hits the tower. The weight of this construction will probably be more than the reduction of the balancing weights. The large bow shaped construction can be prevented if the hinge axis is situated far behind the tower. But in this case, the weight of the whole construction will give a large bending moment around the tower. This bending moment can be counterbalanced by a weight which is situated far before the tower but it is expected that this whole construction will also be heavier than the original design of figure 2. So this option is also not advised.

The horizontal hinge axis as given in figure 2 is chosen such that it is lying in the rotor plane. This has as advantage that the side force $F_{s\delta}$ is giving no moment around the hinge axis. However, it has as disadvantage that the weight of the generator and the construction which connects the generator to the housing which is rotating around the hinge axis, is giving a right hand moment around the hinge axis. This moment can be counter balanced but the balancing weights have then to be mounted rather far before the rotor plane which doesn't look nice.

An alternative is to lay the hinge axis a bit behind the rotor plane. In this case, the side force on the rotor $F_{s\delta}$ is giving a moment around the hinge axis but the side force is small for rotors with a high design tip speed ratio λ_d and the contribution to the rotor moment can be neglected. In figure 4 of report KD 213 it is shown how much the rotor thrust $F_{t\delta}$, the side force $F_{s\delta}$ and the self orientating moment M_{so} contribute to M_{rotor} if the ratio e / R = 0.2 and if the ratio f / R = 0.2286 (f is the distance in between the rotor plane and the tower axis). The contribution of $F_{s\delta}$ to M_{rotor} can be neglected except for very large yaw angles, even for this rather small ratio e / R = 0.2. The contribution of M_{so} to M_{rotor} can't be neglected for e / R = 0.2.

An other alternative is to chose a smaller eccentricity e, so a smaller ratio e / R than the value e / R = 1.1 which was chosen in chapter 4. This has as advantage that the balancing weights can be much lighter. However, it has as disadvantage that the rotor will hit the tower for low wind speeds. This can be prevented by introducing a stop for a yaw angle $\delta = 0°$. So the δ-V curve of figure 3 will be horizontal for V < 5.7 m/s. Some elasticity of this stop is needed to prevent large shock forces when this stop is hit. Assume e is chosen such that e / R = 0.4. This is a factor two larger than for the VIRYA-4.2 windmill but for e / R = 0.4, both M_{so} and $F_{s\delta}$ can be neglected and this means that the formulas as given in chapter 3 can still be used and that the behavior of the system will still be almost the same as given by figure 4, figure 5 and figure 6.

Another alternative is to use two rotors and two generators on one tower. A long beam is mounted to the head and a hinge mechanism is connected to each end of the beam. The hinge axis can now be chosen such that it is lying above the rotor and the rotors can't touch the tower because of the long beam. It might even be possible to use the beam and rotor assembly as a vane if the rotor planes are making an angle of about 10° with the beam.

7 Determination of the δ-V curve for V_d = 6 m/s

For certain combinations of rotor and generator, a design wind speed of 7 m/s may be too high if the generated power at high wind speeds is very high and if therefore it is not possible to slow down the rotor by making short-circuit in the generator. This problem can be solved by choosing a lower value of V_d. Assume it is chosen that V_d = 6 m/s. Formulas 1 up to 14 of chapter 3 stay the same.

Substitution of $V = V_d$ = 6 m/s and δ = 10° in formula 14 gives:

$C_t * ½\rho * \pi R^2 * e / (G * r_G) = \sin 30° / (36 * \cos^2 10°)$ or

$C_t * ½\rho * \pi R^2 * e / (G * r_G) = 0.014321$ (for V_d = 6 m/s) (21)

(14) + (21) gives:

$\sin(\delta + 20°) / (V^2 * \cos^2\delta) = 0.014321$ (for V_d = 6 m/s) (22)

Formula 22 can be written as:

$0.014321 * V^2 * \cos^2\delta = \sin(\delta + 20°)$ or

$V = \sqrt{\{(\sin(\delta + 20°) / (0.014321 * \cos^2\delta)\}}$ (m/s) (for V_d = 6 m/s) (23)

Next formula 23 is used to calculate V for different values of δ. It has been chosen that δ = -20°, -15°, -10°, -5°, 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80° and 90°. The result is given in table 2.

δ (°)	V (m/s)	cosδ	cos²δ	cos³δ	V * cosδ	V² * cos²δ	V³ * cos³δ
-20	0	0.9397	0.8830	0.8298	0	0	0
-15	2.5540	0.9659	0.9330	0.9012	2.466	6.086	15.014
-10	3.5359	0.9848	0.9698	0.9551	3.482	12.125	42.223
-5	4.2674	0.9962	0.9924	0.9886	4.251	18.072	76.826
0	4.8870	1	1	1	4.887	23.883	116.715
10	6	0.9848	0.9698	0.9551	5.909	34.913	206.302
20	7.1295	0.9397	0.8830	0.8298	6.700	44.883	300.712
30	8.4452	0.8660	0.75	0.6495	7.314	53.491	391.209
40	10.1514	0.7660	0.5868	0.4495	7.776	60.470	470.227
50	12.6020	0.6428	0.4132	0.2656	8.101	65.620	531.553
60	16.5851	0.5	0.25	0.125	8.293	68.766	570.249
70	24.4321	0.3420	0.1170	0.0400	8.356	69.841	583.368
80	47.7550	0.1736	0.0302	0.0052	8.290	68.872	566.317
90	∞	0	0	0	-	-	-

table 2 Calculated relation in between δ and V for V_d = 6 m/s

In table 1 the values for cosδ, $\cos^2\delta$, $\cos^3\delta$, V * cosδ, $V^2 * \cos^2\delta$ and $V^3 * \cos^3\delta$ are also mentioned. V * cosδ is an indication for the increase of the rotational speed (see formula 1). $V^2 * \cos^2\delta$ is an indication for the increase of the thrust and the torque (see formula 2 and 3). The value for δ = 70° is double the value for δ = 10°. $V^3 * \cos^3\delta$ is an indication for the increase of the power (see formula 4).

In table 2 it can be seen that all these four quantities reach a maximum for $\delta = 70°$ which could be expected because for this situation $\alpha = 90°$ and this is the angle for which M_G has a maximum.

The values for δ as a function of V are given as the δ-V curve figure 7.

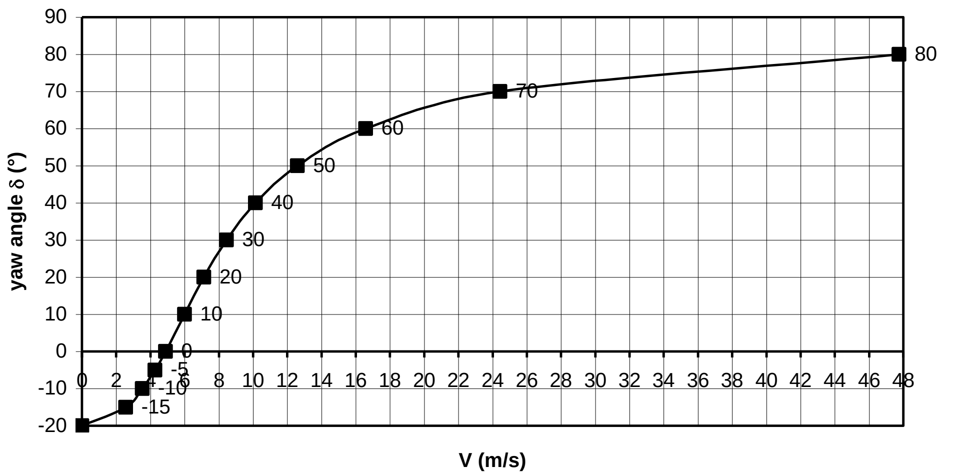

fig. 7 Calculated δ-V curve for the pendulum safety system for V_d = 6 m/s

If figure 7 is compared to the ideal curve and the curve for moderate wind speeds of figure 1, it can be seen that the δ-V curve for the pendulum safety system has about the wanted shape. The most frequent wind speeds for regions with moderate wind speeds are normally lying in between about 3.5 m/s and 6 m/s, The yaw angle δ for these wind speeds is lying in between -10° and 10°. The power loss for yaw angles less than 10° is only small and this demonstrates the value of the pre-angle $\varepsilon = 20°$.

For the chosen value V_d = 6 m/s (at $\alpha = 30°$ and $\delta = 10°$) it is found that the rated wind speed V_{rated} = 24.4321 m/s (at $\alpha = 90°$ and $\delta = 70°$). For this rated wind speed, the maximum rotational speed and the maximum thrust are found and the rotor strength has to be calculated for this wind speed and this yaw angle. In table 2 and figure 7 it can be seen that a very large increase of the wind speed (from 24.4321 m/s up to 47.755 m/s) is needed to increase the yaw angle from 70° to 80°. The helicopter position will never be reached for stationary conditions. However, hard wind gusts at hurricanes or tornados will cause swinging movements resulting in reaching $\delta = 90°$ for a short moment.

The formula for the product of $G * r_G$ for realization of a design wind speed V_d = 7 m/s is given in chapter 4. The same procedure is followed for V_d = 6 m/s. Formula 19 is valid for e = 1.1 R. Substitution of $C_t = 0.7$, $\rho = 1.2$ kg/m^3, $V = V_d$ = 6 m/s and $\delta = 10$ ° in formula 19 gives:

$$G * r_G = 101.35 R^3 \quad \text{(Nm)} \quad (\text{for } V_d = 6 \text{ m/s}) \qquad (24)$$

The calculated values of V * cosδ as a function of V are given in figure 8. This curve is an indication of the variation of the rotational speed.

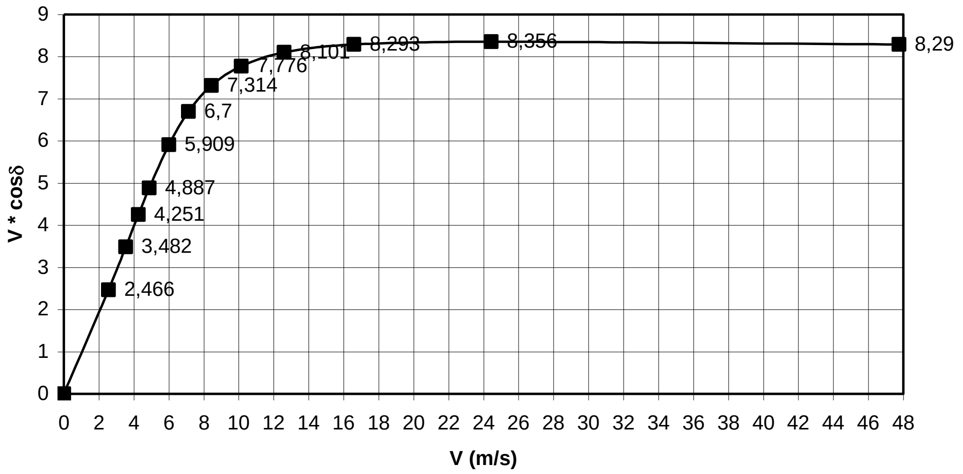

fig. 8 V * cosδ as a function of V for V_d = 6 m/s

In figure 8 it can be seen that the rotational speed is sharply limited and that it rises only a little above a wind speed of about 11 m/s.

The calculated values of $V^2 * \cos^2\delta$ as a function of V are given in figure 9. This curve is an indication of the variation of the thrust and the torque.

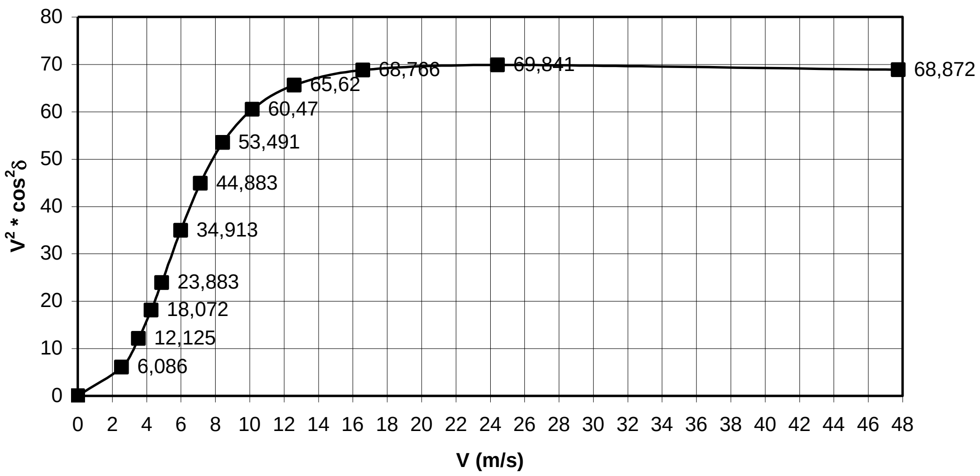

fig. 9 $V^2 * \cos^2\delta$ as a function of V for V_d = 6 m/s

In figure 9 it can be seen that the thrust and the torque are sharply limited and that they rise only a little above a wind speed of about 12 m/s.

The calculated values of $V^3 * \cos^3\delta$ as a function of V are given in figure 10. This curve is an indication of the variation of the power.

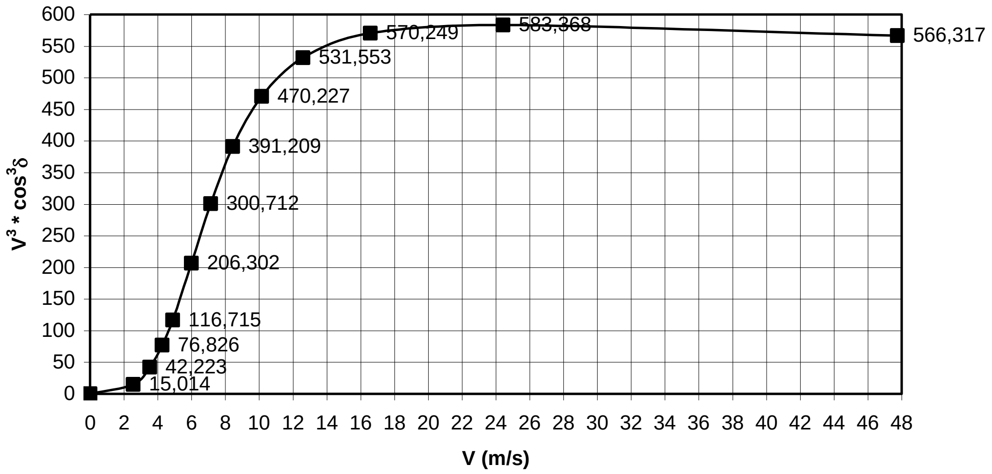

fig. 10 $V^3 * \cos^3\delta$ as a function of V for V_d = 6 m/s

In figure 10 it can be seen that the power is sharply limited and that it rises only a little above a wind speed of about 13 m/s. The power is the mechanical power supplied by the rotor shaft. For the electrical power, the generator efficiency has to be taken into account.

8 References

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