Development of a tubular tower for the VIRYA-3.3S windmill

ing. A. Kragten

June 2014
reviewed December 2014

KD 562

Engineering office Kragten Design
Populierenlaan 51
5492 SG Sint-Oedenrode
The Netherlands
telephone: +31 413 475770
e-mail: info@kdwindturbines.nl
website: www.kdwindturbines.nl

Contains page

1 Introduction

The VIRYA-3.3S windmill has a 34-pole PM-generator which is primary designed to be coupled to the asynchronous motor of a pump. However, it can also be used for battery charging if the generator is provided with a low voltage winding. The VIRYA-3.3S has a 3-bladed steel rotor with a design tip speed ratio $\lambda_d = 4.5$. The rotor is calculated in report KD 576 (ref. 1). The 34-pole generator is described in report KD 560 (ref. 2). The drawings of the VIRYA-3.3S are ready and a folder of the VIRYA-3.3S is available on my page of the website of Bidnetwork. A prototype will be built by the Indian company Tinytech.

The VIRYA-3.3S originally had a tower which is identical to the tower of the former VIRYA-3D and almost identical to the tower of the VIRYA-2.2S. This tower has a lower 6 m long, 4-legs lattice section made of angle iron and strip and a 2 m long upper section made of pipe. The upper section is clamped in the top of the lower section by four clamping blocks and four threaded rods M10. The overlap in between both sections is about 0.5 m and the total tower height therefore is about 7.5 m.

Manufacture of the lower section exactly according to the drawing appears to be impossible in India because the described angle iron 30 * 30 * 4 and the described strip 30 * 4 aren't available. It is also expected that manufacture of this tower is rather expensive because the lower section needs a lot of welding and painting. Another disadvantage is that the lower section has a length of 6 m and the tower is therefore rather difficult to transport over large distances. So it is asked if a free standing tubular tower can be developed made of pipe. Such tower has already been designed for the VIRYA-1.8 and in the first instance it was research if this tower can be scaled such that it can be used for a larger rotor.

The VIRYA-1.8 tower has a 6 m long lower section made of 3" galvanized gas pipe and a 2 m long upper section made of 1 ¼" stainless steel gas pipe. The upper section is connected to the lower section by four clamping blocks which are mounted inside the top of the lower section. The lower section is connected to the two foundation strips by four clamping blocks which are mounted to the outside of the bottom of the lower section. The upper clamping blocks can be mounted inside the lower section because there is a rather large gap in between a 1 ¼" pipe and a 3" pipe. Clamping blocks are used to prevent welds at the point where the bending moment in the pipe is maximal. Welds at this point would have a large stress concentration factor which would reduce the allowable bending stress considerably. The lower clamping blocks are connected to the strips of the foundation such that the tower can be hinged at the tower foot.

A disadvantage of the VIRYA-1.8 tower is that the lower section has a length of 6 m and is therefore difficult to transport over large distances. So it is researched if the tubular VIRYA-3.3S tower can have three 3 m long sections.

2 Description of the tubular tower

The tower will have three 3 m long sections. The overlap in between the sections is about 0.3 m, so the total tower height is about 8.4 m which is 0.9 m higher than the original VIRYA-3.3S tower. In the first instance it is chosen to use 5" pipe for the lower section, 4" pipe for the middle section and 3" pipe for the upper section. The wall thickness is chosen as small as possible to minimize the tower weight. As the gap in between the sections is rather small, it is no longer possible to use clamping blocks for connection of the sections to each other. After researching different options, the following construction is chosen. The construction is described for the joint in between the upper and the middle section but is similar for the connection of the middle and the lower section.

Two 20 mm thick rings are made with an inside diameter equal to the outside diameter of the 3” pipe and an outside diameter equal to the inside diameter of the 4” pipe. The lower ring is welded at the bottom side to the 3” pipe. The upper ring is glued to the 3” pipe by epoxy glue. Each ring is bolted to the inside of the 4” pipe by four bolts M10 * 12 under 90°. The bending moment in the 3” pipe is zero at the lowest ring so it is no problem if the weld causes stress concentration. The bending moment in the 3” pipe is maximal at the upper ring but glue is not causing stress concentration. It even spreads the radial load on the ring very smoothly and it prevents a gap in between ring and pipe. The weight of the head is taken by the weld of the lower ring and by the four lower bolts.

The connection of the 4” pipe to the 5” pipe is similar. For the connection of the 5” pipe to the foundation strips it is possible to use clamping blocks, just like it is done for the VIRYA-1.8 tower. However, clamping blocks will be rather thick because it is necessary that the blocks can be clamped around the pipe with different bolts than the bolts which are used to connect the clamping blocks to the foundation strips. Therefore a similar construction is chosen as for the connection of the pipe segments.

Two square sheets are made with dimensions 20 * 160 * 160 mm. Each sheet is provided with a central hole equal to the outside diameter of the 5” pipe. Two threaded holes M12 mm holes are made at both opposite sides of the sheet at a pitch of 135 mm. The lower sheet is welded at the bottom side to the 5” pipe. The upper sheet is glued to the 5” pipe by epoxy glue.

The foundation is made of two vertical strips size 10 * 160 * 1000 mm. Two 160 mm long distance rods which are cast in the concrete of the foundation keep the strips at a distance of 160 mm from each other during pouring of the concrete. The two square sheets are clamped in between the two foundation strips by eight bolts M12 * 45. Two bolts can be used as a hinge for erection of the tower. One needs an auxiliary tower to do this and a winch. One has to use an auxiliary rope to prevent that the tower falls down in the wrong direction once it has reached the vertical position. The VIRYA-1.8 tower has a stop, bolted in between both foundation strips to prevent falling down in the wrong direction. For the VIRYA-3.3S tower such stop would result in a larger width of the foundation strips which seems to be not necessary. The auxiliary rope can be removed once all eight bolts are tightened.

3 Calculations of the tower strength

For checking of the tower strength it is necessary to know the tower load. The tower top is loaded by a force F_{top} which is caused by the rotor thrust and by the aerodynamic force working on the vane arm and the vane blade. A moment works on the tower top which is caused by not being in balance of the vane weight and the rotor + generator weight but this moment is neglected. The tower is also loaded by the drag force working on each segment. The forces for the upper, the middle and the lower section are called F_u, F_m and F_l.

F_{top} is mainly caused by the rotor thrust F_t. F_t is limited by the safety system because the rotor turns out of the wind at high wind speeds. It is assumed that the rotor turns out of the wind such that F_t is constant for V > 11 m/s. The yaw angle δ at V = 11 m/s is 35° (see KD 576 figure 3). The thrust at a yaw angle δ, $F_{t\delta}$ is given by formula 7.4 of report KD 35 (ref. 3). This formula is copied as formula 1.

$$F_{t\delta} = C_t * \cos^2\delta * \tfrac{1}{2}\rho V^2 * \pi R^2 \quad \text{(N)} \qquad (1)$$

C_t is the thrust coefficient (-). The theoretical value is 8/9 = 0.89 but the real value is lower because of tip losses and because the blade length is shorter than R. Assume C_t = 0.75. Assume δ = 35° for V = 11 m/s. ρ is the air density which is about 1.2 kg/m^3 for air of 20° C at sea level. R is the rotor radius and R = 1.65 m for the VIRYA-3.3S. Substitution of these values in formula 1 gives that $F_{t\delta}$ = 312 N.

F_{top} is larger than $F_{t\delta}$ because there are also aerodynamic forces working on the vane arm and the vane blade. During wind gusts $F_{t\delta}$ may also be larger than the calculated value. Assume F_{top} = 450 N.

The drag forces F_u, F_m and F_l are not reduced by the safety system. It is assumed that each force attaches to the middle of its tower section. These forces are maximal for the highest wind speed which may ever be expected. It is assumed that V_{max} = 35 m/s at the tower top. Because of the wind sheer, it is unrealistic to calculate the whole tower for this wind speed. It is assumed that V = 34 m/s for F_u, that V = 31 m/s for F_m and that V = 26 m/s for F_l. The drag force F is given by:

$$F = C_d * ½\rho V^2 * d * l \qquad (N) \qquad (2)$$

C_d is the drag coefficient (-) which is 1.18 for smooth pipes if the Reynolds value is lower than 10^5 (see KD 223 figure 10, ref. 4). The Reynolds values have been calculated for each of the three sections and for the chosen maximum wind speeds and it was found that Reynolds is about $2.2 * 10^5$. The drag coefficient for this Reynolds value is reduced to about 0.5 (see KD 223 figure 10). d is the pipe diameter in m. l is the visible pipe length in m.

Substitution of C_d = 0.5, ρ = 1.2 kg/m^3, V = 34 m/s, d = 0.0889 m and l = 2.7 m in formula 2 gives that F_u = 83 N.
Substitution of C_d = 0.5, ρ = 1.2 kg/m^3, V = 31 m/s, d = 0.1143 m and l = 2.7 m in formula 2 gives that F_m = 89 N.
Substitution of C_d = 0.5, ρ = 1.2 kg/m^3, V = 26 m/s, d = 0.1397 m and l = 2.7 m in formula 2 gives that F_l = 76 N.

A picture of the tower is given in figure 1. The forces F_{top}, F_u, F_m and F_l are given in this figure. The relevant dimensions are also given in figure 1. The tower has three critical cross sections U, M and L which are lying at the upper rings and at the upper square sheet. The bending moment M is calculated for each critical cross section and the bending stress σ is calculated using the formula.

$$\sigma = M / W \qquad (N/mm^2) \qquad (3)$$

W is the moment of resistance of the concerning pipe. W can be calculated if the outside and the inside pipe diameter is known but W may also be given in the catalogue of the pipe supplier. σ is calculated in N/mm^2 so for M we have to take the moment in Nmm and for W we have to take the moment of resistance in mm^3.

For the pipes it is chosen to use pipes with the smallest available standard thickness. This type of pipe is called kasbuis (green house pipe) in Dutch. This pipe can be supplied black or with a galvanized outside. The main characteristics of the chosen pipes are given in table 1. The nominal pipe diameter in inches is called d_{nom}. The outside pipe diameter is called d_o (mm). The wall thickness is called s (mm). The inside pipe diameter is called d_i (mm). The moment of resistance is called W (mm^3). The moment of inertia is called I (mm^4). m is the pipe mass per meter. m_s is the pipe mass of a 3 m long section (excluding the rings).

d_{nom} (”)	d_o (mm)	s (mm)	d_i (mm)	W (mm^3)	I (mm^4)	m (kg/m)	m_s (kg)
3	88.9	2.5	83.9	14260	633700	5.33	15.99
4	114.3	2.75	108.8	26250	1499900	7.56	22.68
5	139.7	3	133.7	43110	3010900	10.11	30.33

Table 1 Characteristics of the chosen 3”, 4” and 5” pipes

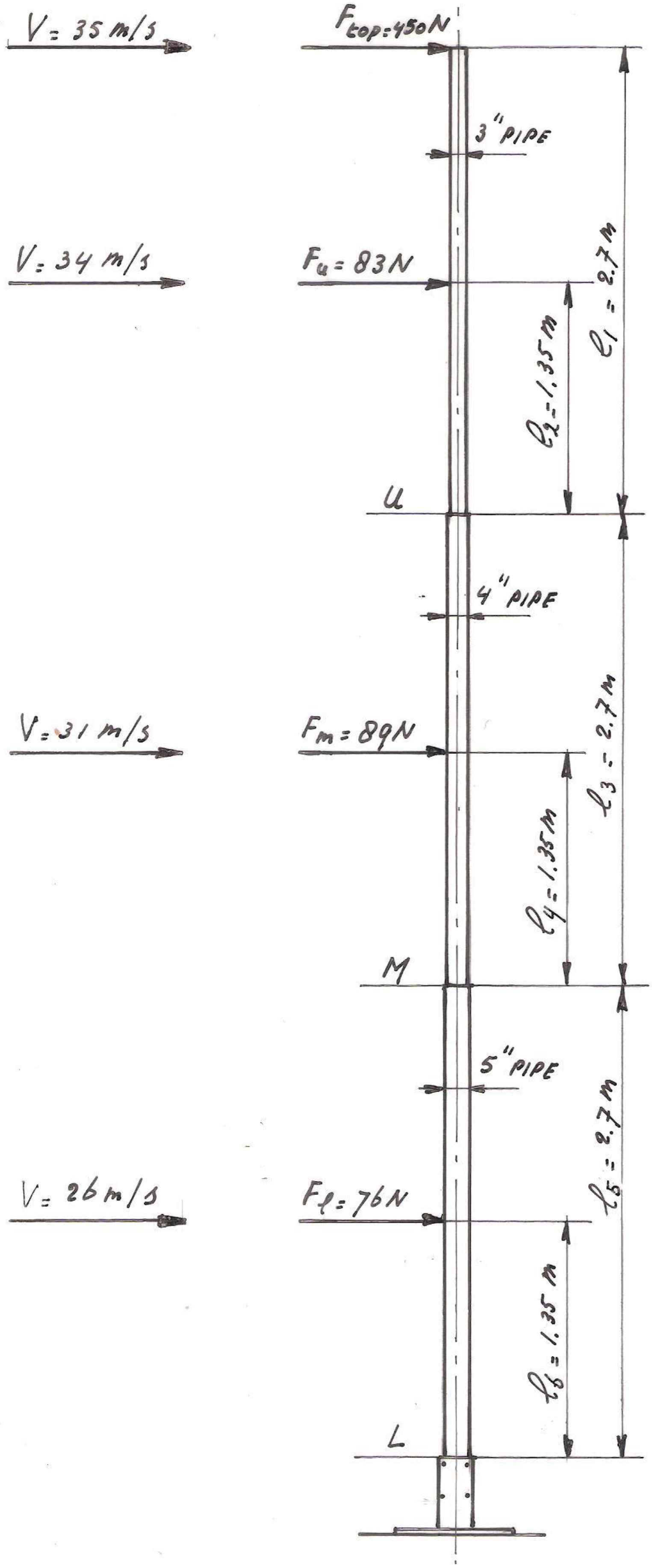

Fig. 1 Forces acting on the alternative tubular tower of the VIRYA-3.3S

The total mass of the three pipes is 15.99 + 22.68 + 30.33 = 69 kg which is rather low for a tubular tower with a height of 8.4 m. The bending stress is now calculated for the cross sections U, M and L. The bending moment M_U is given by:

$M_U = F_{top} * l_1 + F_u * l_2$ (Nmm) (4)

Substitution of F_{top} = 450 N, l_1 = 2700 mm, F_u = 83 N and l_2 = 1350 mm in formula 4 gives that M_U = 1327050 Nmm. Substitution of M_U = 1327050 Nmm and W = 14260 mm^3 in formula 3 gives that σ_U = 93 N/mm^2.

The bending moment M_M is given by:

$M_M = F_{top} * (l_1 + l_3) + F_u * (l_2 + l_3) + F_m * l_4$ (Nmm) (5)

Substitution of F_{top} = 450 N, l_1 = 2700 mm, l_3 = 2700 mm, F_u = 83 N, l_2 = 1350 mm, F_m = 98 N and l_4 = 1350 mm in formula 5 gives that M_M = 2898450 Nmm. Substitution of M_U = 2898450 Nmm and W = 26250 mm^3 in formula 3 gives that σ_M = 110 N/mm^2.

The bending moment M_L is given by:

$M_L = F_{top} * (l_1 + l_3 + l_5) + F_u * (l_2 + l_3 + l_5) + F_m * (l_4 + l_5) + F_l * l_6$ (Nmm) (6)

Substitution of F_{top} = 450 N, l_1 = 2700 mm, l_3 = 2700 mm, l_5 = 2700 mm, F_u = 83 N, l_2 = 1350 mm, F_m = 98 N, l_4 = 1350 mm, F_l = 76 N and l_6 = 1350 mm in formula 5 gives that M_L = 4704750 Nmm. Substitution of M_U = 4704750 Nmm and W = 43110 mm^3 in formula 3 gives that σ_M = 109 N/mm^2.

So the bending stress in cross sections M and L is about the same and about 110 N/mm^2. The bending stress in cross section U is somewhat lower and about 93 N/mm^2. This calculation shows that the chosen pipe diameters and wall thicknesses are almost optimal for the VIRYA-3.3S. The pipes are made of St37 (Fe 360). The allowable pulling stress for this material is about 180 N/mm^2 if the load is not a fatigue load. However, the allowable bending stress is higher than the allowable pulling stress and is about 240 N/mm^2. So the pipes are strong enough and have even a large reserve.

The performance of the tower is not only determined by the required strength but also by the required stiffness. The stiffness in combination with the pipe masses and the total mass of the head, the generator and the rotor determines the natural frequency. The first harmonic of the natural frequency must be about 2 Hz. In this case an unloaded rotor will go through this natural frequency at a wind speed of about 3 m/s. The tower will shake a little at this wind speed because the rotor will always have some mass imbalance or some aerodynamic imbalance but the energy in the oscillation is not high enough at 3 m/s to cause any damage. I can calculate the natural frequency for a tower made out of one pipe but for a tower made out of three sections the calculation is too complicated for me. So a prototype has to be built and the natural frequency has to be measured. This can easily be done by connecting a rope to the tower top and by bring the tower in oscillation. The number of oscillations per minute can be counted and then divided by 60 to find the frequency in Hz.

4 References

1 Kragten A. Calculations executed for the 3-bladed rotor of the VIRYA-3.3S windmill (λ_d = 4.5, steel blades), December 2014, free public report KD 576, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode.

2 Kragten A. Ideas about a direct drive 34-pole permanent magnet generator for the VIRYA-3.3S windmill using the stator stamping of an Indian 6-pole, 3-phase, 2.2 kW asynchronous motor frame size 112 and 51 neodymium magnets size 40 * 10 * 5 mm, May 2014, reviewed December 2014, free public report KD 560, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

3 Kragten A. Method to check the estimated δ-V curve of the hinged side vane safety system and checking of the δ-V curve of the VIRYA-3.3D windmill, (7.14 % cambered steel blades), February 2005, free public report KD 223, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.