Concrete support structures for small wind turbines

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Abstract. Small wind turbines (SWT) generate electricity up to several dozen kilowatts. They can be divided into turbines with a horizontal axis of rotation (Horizontal Axis Wind Turbines) and turbines with a vertical axis (Vertical Axis Wind Turbines). The paper discusses design issues related to various types of wind turbines, and lays down general principles for the selection of support structures for small wind turbines (SWT) with a horizontal axis of rotation. The possibilities of using E-type spun prestressed-concrete poles used in medium voltage overhead power lines as SWT supporting structures are presented and discussed with regard to technical benefits of their application.

1. Introduction

Wind turbines with a horizontal rotation axis (HAWT) are most often equipped with a three-blade wind turbine classified as medium-speed turbine with a specific speed of $1.5 < z_n < 3.5$. The specific speed $z_n$ is the ratio of the linear speed of the propeller blade ends to the wind speed. If it is required for the rotor to have a considerable starting torque, the number of blades ought to be increased.

Traditional rotors can be divided in terms of their position to the wind[1]. In relation to the tower, the rotor is usually placed in front of it (up-wind), and less frequently behind the tower (down-wind) in relation to the blowing wind. The down-wind rotor is not a very popular solution, however, as one needs to take into account the loss of wind pressure on the blades in the leeward area in relation to the windmill structure. Vertical-axis wind turbines are less common. Among them, the turbine patented in 1931 by Darrieus, its variant H-Darrieus with a periodically adjustable engine called ‘gyromill’ and the Savonius turbine deserve special attention. The Darrieus wind turbine has two or three blades fixed to the vertical shaft with a fixed chord and a symmetrical profile. The turbine does not require wind orientation and has virtually zero starting moment; it must be pre-started. The ‘gyromill’ wind turbine has three straight blades parallel to the axis of rotation. The essence of this turbine is the change of the angle of the blades, which are self-adjustable). By changing the angle, the characteristics of the turbine torque are shaped as a function of its relative speed, which makes the turbine torque independent of any changes in wind speed. The Savonius turbine is the simplest solution in terms of technology. One advantage of this turbine is its ability to survive strong winds and use the force of light winds (even from 1.5 m/s). In addition, turbines of this type produce almost no sound (unlike traditional windmills, where the blade tips move at a speed of 250 km/h). PN-EN 61400-2: 2014 [2] provides design principles for SWT with a horizontal axis of rotation of the turbine with a rotor sweep area up to 200 m² (rotor diameter up to 16 m). SWT can produce voltage up to 1000 V AC or up to 1500 V DC. SWT do not require high towers and therefore questions are often asked about the possibility of using E-type spun power poles as support structures [3,4] for wind turbines with a nominal power $P_r < 20$ kW sufficient for complete supply of electricity for a single household, including heating.
Tower foundations for wind farms must safely transfer loads from the structure to the ground, ensure structure stability and protect the structure against excessive deflections and vibrations resulting from any deformations of the support structure. The choice of foundation type is determined on the one hand by soil conditions (layering, load-bearing capacity and deformability of the ground, groundwater level, etc.), and on the other hand by data related to the above-ground structure (type and dimensions of the support structure and the magnitude and nature of the loads transferred).

In the case of foundations for supporting structures of wind turbines, the overturning moment $M_{Ed}$ is the dominant impact. The accompanying horizontal $V_{Ed}$ and vertical $N_{Ed}$ forces are of minor significance. In massive foundations (figure 1), the action of the $M_{Ed}$ moment is opposed by lateral soil resistance and upward forces resulting from soil resistance. The methodology for calculating column and block foundations used as foundation for supporting structures is given in standard [5] and literature [6]. The depth of anchoring (embedding) $l_k$ of the concrete tower structure in the socket foundation (figure 1) depends on the length of reinforcement anchoring $l_{ed}$. It is also required that the depth $l_k \geq 1.2 \cdot d_n$, where $d_n$ is the outer diameter of the pole at its base.

According to standard [5], pole foundations should have a base area $A \leq 0.25 \text{ m}^2$ and a relative width $\beta = b/D \leq 0.5$ (figure 1a). Foundations that do not meet these relationships are treated as blocks (figure 1a, b, c). Light pole foundations laid in holes drilled in the ground are mainly used for putting up nnand SN power poles as well as lighting poles. The most basic variety of massive socket foundations are column (for $b/D \leq 0.5$, figure 1a) or block foundations ($b/D > 0.5$, figure 1b) with a circular or square section. In order to reduce concrete consumption, monolithic or prefabricated pad foundations can be applied ($b/D > 0.5$, figure 1c). In the case of high loads or the presence of a high level of groundwater, slab foundations with a square or circular base ($b/D > 0.5$, figure 1d) are used, in which the height $D$ depends on the diameter of the base of the rotated element ($D \geq 1.2 \cdot D + 0.5 \text{ m}$). Possibly, pad and slab foundations can be placed on piles, which transfer loads to the deeper layers of the bearing soil [7-10]. For pre-stressed concrete spun poles for wind turbines with a power of $P_T = 5-20 \text{ kW}$, the foundations can take the form of monolithic well constructions (figure 2) of the pole or block type. These solutions (figure 2) have undeniable advantages: soil structure adjacent to the foundation side remains intact and the construction site can be very small.

The direct connection of the tower shaft or the spun pole to the well foundation (figure 2a) is troublesome due to the lack of a typical bucket as in figure 1, which is used to position the pole vertically. In the case of a well foundation as in figure 2a, concreting rings must take place in two stages. First, the bottom part of the foundation is concreted to the level of the base of the pole. Then, after the concrete partially sets, the pole is set up and the rings are filled with concrete to a minimum level of 0.15 m above ground level (figure 2a). Assembly of a wind turbine can take place only after the concrete has set (theoretically after 28 days).

The solution given in figure 2b does not have these shortcomings, but requires very precise arrangement of anchor bolts on the pitch diameter identical as in the steel head of a spun pole. This solution enables fast assembly of poles on previously prepared foundations and their rectification with nuts under and above the steel head of the pole. While designing foundations for wind turbine sets,
typical solutions used in chimney constructions and slender silos with quasi-static loads are not recommended. When designing foundations for wind turbine sets, typical solutions used in chimney constructions [11] and slender silos [12] with quasi-static loads are not recommended.

![Figure 2](image)

**Figure 2.** Well type pole and block foundations: a) pole shaft anchored in the foundation block, b) screw fastening of the pole to the foundation

2. Materials and methods

Power poles made of E-type spun concrete are prefabricated semi-prestressed elements with variable ring section in their length. Longitudinal shape is in the form of a truncated cone. The shape of the cross-section results from the accepted technology of producing poles by the method of concrete centrifugation in longitudinally unopened forms [13]. Pre-stressed and partially pre-stressed poles made of spun concrete were introduced in medium- and low-voltage power lines in Poland at the beginning of the 1990s [14].

Technological assumptions for the production of spun poles in the first three factories (1990-1997) were developed on the basis of the experience gained on the so-called laboratory line launched in 1990 at the Wroclaw University of Technology [14]. These factories used the equipment (including centrifuges and moulds) purchased earlier in the 1970s in Czechoslovakia, and applied their own solutions tested on the laboratory line (group tension heads, production of reinforcing baskets, mould lubrication and demoulding). The next five factories producing spun poles according to their own solutions in longitudinally unopened forms were set up after 2000, the last one in 2004. The ninth factory used longitudinally opened forms with identical dimensions of the elements. Polish factories currently have a production capacity of about 150,000 poles per year. In pre-stressed concrete spun poles, C40/50 class spun concrete (less frequently C50/60) is used. The poles are reinforced longitudinally with pre-stressing wires, Ø7.5 mm profiled wire with the symbol Y1670C, and ribbed bars with a characteristic yield strength $f_{yk} = 500$ MPa. The transverse reinforcement of poles is made of Ø3.5 mm smooth wire spiral with a characteristic yield strength $f_{yk} = 500$ MPa. Spun power poles [15] are marked with trade symbols (e.g. E15/25), in which the letter E stands for the power pole, the number before the slash is the length of the pole L [m], and after the slash, the value of the rated peak force $P_k$ [kN] 0.2 m from the top is given. The outer diameter of the E-poles increases from $d_0 = 170; 218; 263$ and $308$ mm at the tip to $d_0 = d_k + L\cdot15$ [mm] at the base with a constant convergence of 15 mm/1 m. Polish factories are currently producing a full range of E-poles for overhead medium- and low-voltage power lines with lengths $L = 9\div18$ m and peak forces $P_k = 2.5\div35$ kN as well as lighting and traction poles. The introduction of E-poles on the market is based on the compliance with the harmonized product standard PN-EN 12843:2008 [16]. Compliance with the material and technological regime during the production of spun poles allows for obtaining prefabricated elements.
with a very good degree of concrete compaction, smooth external surface and high compressive strength of concrete (despite the layering of concrete on the wall thickness of the element cross-section [17]) and the appropriate thickness of the reinforcement cover guaranteeing 50 years durability in the natural environment XC4 and XF2 [14]. Table 1 summarizes the technical parameters for examples of E15 spun poles that could be used as support structures for small wind farms.

### Table 1. Technical parameters of E15 spun poles

| Dimen- sions [mm] | Data type | E15/10 | E15/12 | E15/15 | E15/17.5 | E15/20 | E15/25 | E15/30 | E15/35 |
|-------------------|-----------|--------|--------|--------|----------|--------|--------|--------|--------|
| Top | Diameter d | 218 | 263 | 308 |
| | Wall thickness t_w | 65 | 80 |
| Base | Diameter D | 443 | 488 | 533 |
| | Wall thickness t_w | 110 | 120 | 110 | 120 | 125 |
| Pole weight m [kg] | 2657 | 2809 | 3279 | 3350 | 3545 | 3712 | 4250 | 4406 |
| Peak force P_k [kN] | 10.0 | 12.0 | 15.0 | 17.5 | 20.0 | 25.0 | 30.0 | 35.0 |
| Load capacity M_m [kNm] | 170.91 | 205.70 | 255.84 | 297.62 | 338.62 | 427.04 | 501.89 | 583.20 |

### 3. Results

SWT supporting structures (tower and foundation) should be designed for 30-year durability (sporadically 50-year durability) in natural environmental conditions (exposure classes XC4 and XF2 [18]). For turbine sets with a rotor-swept surface of 2 to 200 m², a supporting structure design should be attached to the construction design of the wind turbine set. For this reason, it is very important to correctly determine the rotor load with wind pressure during the production of electricity by the wind turbine set, and when it stops due to excessively strong wind speed or failure.

In norm [2], four SWT standard classes are introduced (table 2), depending on the average annual wind speed V_ave at the hub height and one special standard for which external conditions are defined individually (e.g. in coastal waters). The SWT classes were introduced in order to take into account (in the simplified method) wind conditions characteristic for most locations of turbine sets.

### Table 2. Design wind speeds [m/s] for calculating SWT loads

| SWT classes | Standard |
|-------------|----------|
| | I | II | III | IV |
| V_ave | 10.0 | 8.5 | 7.5 | 6.0 |
| V_ref = 5 · V_ave | 30.0 | 42.5 | 37.5 | 30.0 |
| V_design = 1.4 · V_ave | 14.0 | 11.9 | 10.5 | 8.4 |
| V_out = 2.5 · V_ave | 25.0 | 21.3 | 18.8 | 15.0 |
| V_e0 = 1.4 · V_ref | 70.0 | 59.5 | 52.5 | 42.0 |
| V_c1 = 0.75 · V_e0 | 52.5 | 44.6 | 39.4 | 31.5 |

For the design of a wind turbine set in electricity-generating conditions, the design wind speed V_design and the stop speed V_out (the highest average wind speed at the height of the rotor hub at which the useful power of the turbine generator is produced) are necessary. The turbine manufacturer should specify the start speed V_ref of the turbine set (the lowest average wind speed at which the useful power of the generator can be produced). In SWT survival (parking) conditions, the maximum wind speeds averaged over 3 seconds V_c1 and V_e0 with a recurrence time of N = 1 year and N = 50 years, or the reference wind speed V_ref are used. Design SWT load cases for a simplified load calculation method are given in Table 2 of standard [2].

The simplified method of determining wind loads on the turbine set components can be used if the horizontal rotor propeller has at least two self-supporting blades, unilaterally fixed in the hub, which in turn is rigidly connected to the generator shaft [2]. For dimensioning the SWT tower with a specific generator with the power P installed at a height of z_hub above ground level, it is necessary to determine the maximum force F_z_shaft from wind pressure on the rotor while electricity is being generated and during standstill F_k1 (survival) at maximum wind V_e0. An example of such calculations for different wind speeds V_ave is shown in Table 3. The rated power of the rotor P_r is determined from the formula:
$P = (C_p \cdot \rho \cdot \pi \cdot R^2 \cdot V_{\text{design}}^3)/2000 = 0.01026 \cdot V_{\text{design}}^3$, assuming the coefficient of wind energy use $C_p = 2/3-C_T = 2/3-0.5 = 1/3$ [2] and $\rho = 1.225 \text{ kg/m}^3$.

### Table 3. Maximum forces from wind pressure on SWT rotor with radius $R = 4.0$ m

| Wind speed at the turbine hub level [m/s] | Force from wind pressure on the rotor | Rated power [2] [kW] | Notes |
|-----------------------------------------|--------------------------------------|----------------------|-------|
| $V_{\text{ave}}$, $V_{\text{ref}}$, $V_{\text{design}}$, $V_{\text{out}}$, $V_{\text{e50}}$ | $F_{\text{shear}}$ [kN] | $F_{\text{in}}$ [kN] | $P_{\text{rated}}$ | $P = \eta \cdot P_{\text{design}}$ |
| 7.5 | 37.5 | 10.5 | 18.75 | 52.5 | 5.412 | 11.132 | 11.88 | 7.72 | III SWT class [2] |
| 8.0 | 40.0 | 11.2 | 20.0 | 56.0 | 6.158 | 12.666 | 14.41 | 9.37 | $V_{\text{out}}$ for manufacturer's turbine |
| 8.18 | 40.9 | 11.45 | 20.45 | 57.26 | 6.438 | 13.242 | 15.40 | 10.01 | $P$ for manufacturer's turbine |

$F_{\text{shear}} = C_v \cdot 0.5 \cdot \rho \cdot V_{\text{ave}}^2 \cdot R^2$ for $C_T = 0.5$. $F_{\text{in}} = C_T \cdot A_{\text{in}} \cdot 0.5 \cdot \rho \cdot V_{\text{in}}^2$, for $C_T = 1.5 \cdot A_{\text{in}} = 4.396 \text{ m}^2$.

$P = P_{\text{design}} = C_v \cdot \rho \cdot R^2 \cdot V_{\text{design}}^3$. For $C_T = 1/3$, $P = P_{\text{design}} = \eta \cdot P_{\text{design}} = 0.65$.

According to wind speed data [19], generally in Poland, the average annual wind speed does not exceed 4.5 m/s. Table 3 shows that to achieve the turbine's rated power $P = 10$ kW, a wind speed $V_{\text{ave}} \approx 18$ m/s (almost SWT class IV) is needed. In Poland, this condition may be met after the SWT is raised to a height of $z_{\text{hub}} \geq 13.5$ m AGL, at which the exposure factor $C_v(z) \geq 1.9$ in category III area or $C_v(z) \geq 2.5$ in category IV area [20].

Table 4 summarizes the loads acting on the E15 spun pole and a 10 kW three-blade wind turbine, rotor radius $R = 4.0$ m, wind start speed $V_{\text{in}} = 2.2$ m/s, stop speed $V_{\text{out}} = 20$ m/s and design speed $V_{\text{design}} = 10$ m/s. The turbine can be qualified to SWT class III [2] (tables 2.5.4). Table 4 shows that the E15/17.5 spun column meets the ultimate bending load condition ($M_{\text{Ed}} \leq M_{\text{Rd}}$ according to standards [2,16]), provided that the wind speed when parking according to the normal procedure will not exceed $V_{\text{e50}} = 40$ m/s (i.e. 144 km/h), which is fully realistic in wind zone 1 of Poland [20]. For the wind speed $V_{\text{e50}} = 52.5$ m/s (189 km/h), which is provided for in standard [2] for class III SWT in conditions of survival during 50 years of operation, the E15 poles have too low bending load capacity.

### Table 4. Loads on a 10 kW SWT tower made of an E15 spun pole

| Type of turbine set operation on the tower $z_{\text{hub}} = 13.5$ m AGL | Moments [kNm] at tower base acc to [2] | Peak force $P_k$ [kN] | Notes (e.g. type of pole) |
|---------------------------------|----------------------------------------|----------------------|-------------------------|
| Wind pressure on rotor $V_{\text{hub}} = V_{\text{out}}$ | $V_{\text{out}} = 18.75$ m/s | 73.06 | 229.104 | $P_k = 13.77$ kN |
| Wind pressure on tower $V(z) = V_{\text{hub}}(z)$ | $V_{\text{out}} = 18.75$ m/s | 3.306 | 272.538 | $P_k = 15.67$ kN |
| Parking acc. to normal procedure $V_{\text{e50}} = 52.5$ m/s | Stationary blades + generator's housing | 150.28 (178.77) | 528.60 (628.80) | $P_k = 31.77$ kN |
| Idle run of rotor $V_{\text{e50}} = 52.5$ m/s | Rotor in motion | 89.60 (90.83) | 346.56 (365.00) | $P_k = 20.83$ kN |
| Parking under disturbed conditions $V_{\text{e50}} = 37.5$ m/s | Stationary blades + generator's housing | 76.68 | 269.73 | $P_k = 16.21$ kN |

1 wind pressure as an exceptional load for $P_{\text{out}} = 1.0$ and $\beta = 1.8$, thus: $M_{\text{Ed}} = 1.8 \cdot 209.6 = 377.3 \text{ kNm} \cdot M_{\text{Rd}} = 427.04 \text{ kNm}$

2 calculation results for $V_{\text{hub}} = V_{\text{out}} = 31.24$ m/s as the maximum wind speed in zones 1 and 3 for A = 1000 m asl[20]
Standard [18] states that the impact of repeatedly variable loads on structural fatigue should be taken into account if they occur at least $n = 106$ times in the expected period of use and constitute at least 60% of the total load (this condition does not occur explicitly). According to formula (48) of standard [2], the number of fatigue load cycles $n$ during 30 years of operation of the turbine set will be: $n = B \cdot n_{\text{des}} \cdot \frac{T_d}{60} = 3 \cdot 150 \cdot 9.4608 \cdot 10^8 = 7.1 \cdot 10^9$, where: $B = 3$ – the number of rotor blades, $n_{\text{des}} = 150 \text{ rpm}$ – design rotor speed, $T_d = 30 \cdot 365 \cdot 24 \cdot 602 = 9.4608 \cdot 10^8 \text{ s}$ – design time of turbine set operation without shutdowns (stops) during 30 years of operation of the turbine set.

Assuming only a 10-year service life of the turbine set and using about 120 days a year with wind enabling electricity generation, $T_d = 10 \cdot 120 \cdot 24 \cdot 60^2 = 103.68 \cdot 10^8 \text{ s}$ is obtained, for which the number of load cycles is $n = 3 \cdot 150 \cdot 103.68 \cdot 10^8 / 60 = 7.766 \cdot 10^9$. Thus, in the case of a wind turbine tower, the number of fatigue load cycles during normal operation (case A according to [2]) will significantly exceed $n = 10^6$ considered as the limit number [18]. The analysis of fatigue strength of concrete and steel carried out in study [4] showed that the towers made of typical power poles E15/17.5 $\div$ E15/35 do not meet the fatigue capacity of concrete during loads close to $V_{\text{out}} = 20 \text{ m/s}$. While generating electricity in the wind speed range $V_{\text{hub}} = V_{\text{in}} + V_{\text{out}}$, no tensile stress may occur in the tower concrete, i.e. the towers should be fully compressed (and not partially compressed, as are E-type power poles).

4. Discussion and conclusions

Wind turbines (turbine sets) with horizontal and vertical axis of rotation differ from each other not only in appearance, but also in the efficiency of converting wind energy into electricity. The differences are so considerable that even in the power scales, the manufacturing of horizontal axis turbines is limited to large power levels (over MWh/year), whereas turbines with the vertical axis of rotation are used in a wide range of applications, from small power plants to energy production for the single family (e.g. about 120 days a year with wind enabling electricity generation). The response of the tower structure and the tower foundation to dynamic loads repeatedly changing). This does not mean, however, that tower material strength requirements of C40/50 concrete in conditions of repeatedly variable loads as well as the ultimate cracking and deflection state. These poles are simply too flaccid as tower constructions for wind turbines with a horizontal axis of rotation with a rotor $R = 4.0 \text{ m}$.

Table 1 lists the designs of some concrete wind turbine towers with peak diameters up to 308 mm reinforced with plain steel are not suitable for direct use as support structures for wind turbines with a power of $P_T = 10 \text{ kW}$ due to the different nature of loads in power poles (almost static loads) and turbine towers (extremely dynamic loads repeatedly changing). This does not mean, however, that tower material strength requirements of C40/50 concrete in conditions of repeatedly variable loads as well as the ultimate cracking and deflection state. These poles are simply too flaccid as tower constructions for wind turbines with a horizontal axis of rotation with a rotor $R = 4.0 \text{ m}$.
(and even to 488 mm as in high-voltage poles [21]), the conditions of concrete fatigue strength and tower deflections can be met. Therefore, pre-stressed concrete towers can be a real alternative to steel towers [22] for small wind turbines.

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