Design principles for Offshore Wind Turbines

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Outline

1. External conditions
2. Hydrodynamic loads
3. Design issues for floating OWTs
4. Design procedures

References:

- DNV 2010. Environmental Conditions and Environmental Loads. DNV-RP-C205 (RECOMMENDED PRACTICE), DET NORSKE VERITAS AS.
- DNV 2011. Design of Offshore Wind Turbine Structures. DNV-OS-J101 (OFFSHORE STANDARD), DET NORSKE VERITAS AS.
- IEC 2009. Wind Turbines - Part 3: Design Requirements for Offshore Wind Turbines. IEC (International Electrotechnical Commission) & BS (British Standards) EN 61400-3.

1. External conditions

External environmental conditions:

Wind conditions (direct load and wave generation).

Marine conditions (waves, sea currents, water level, sea ice, marine growth, seabed movement and scour).

External electrical conditions:

Wind turbine classes (tower, nacelle, rotor, etc.).

Electrical grid connectivity including substations.

External conditions are subdivided into normal and extreme categories:

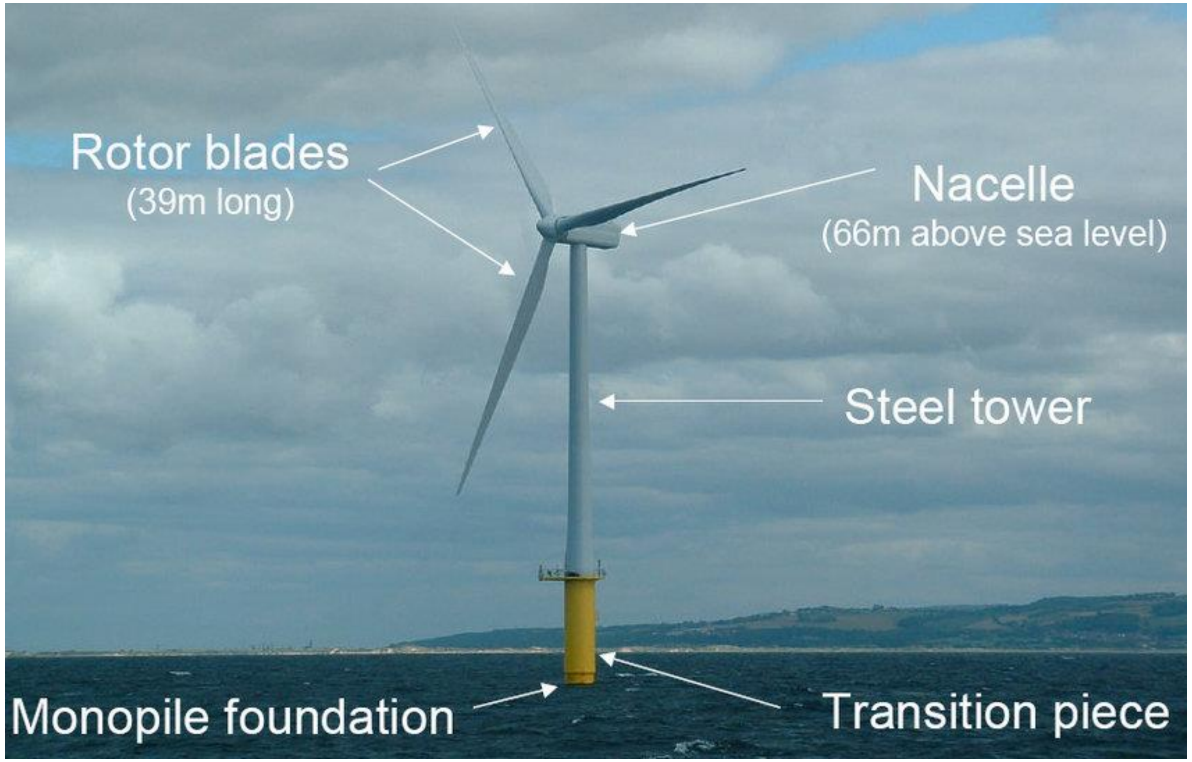
Normal conditions generally concern recurrent structural loading conditions.

Extreme conditions represent rare external design conditions.

The design load cases comprise critical combinations of environmental conditions with wind turbine operational modes and other design situations.

1. External conditions

The design lifetime shall be at least 20 years



1. External conditions

Wind and wave conditions

Normal wind and wave conditions are the ones that will occur more frequently than once per year during normal operation of an OWT, while extreme wind and wave conditions are the ones that have from 1-year to 50-year recurrence period.

Wind conditions and waves are correlated, and this is expressed via the long-term joint probability distribution of the mean wind speed, the significant wave height, and the peak spectral period.

This joint probability distribution is affected by local site conditions such as fetch, bathymetry, etc. The distribution shall be determined from suitable long term measurements supported by the use of numerical hindcasting methods.

1. External conditions

Normal sea state (NSS) – Normal wave height (NWH)

The normal wave height is the significant wave height, H_{NWH} = $H_{s,NSS}$, correlated to the normal mean wind speed.

The corresponding wave period value is selected in the range: $11.1\sqrt{\frac{H_{s,NSS}}{g}} \leq T \leq 14.3\sqrt{\frac{H_{s,NSS}}{g}}$ so that it results in the highest load acting on the OWT.

Severe sea state (SSS) – Severe wave height (SWH)

The severe wave height is the significant wave height, H_{SWH} = $H_{s,SSS}$, correlated to the mean wind speed with a 50-year period of return.

The corresponding wave period value is selected in the range: $11.1\sqrt{\frac{H_{s,SSS}}{g}} \leq T \leq 14.3\sqrt{\frac{H_{s,SSS}}{g}}$ so that it results in the highest load acting on the OWT.

1. External conditions

Extreme sea state (ESS) – Extreme wave height (EWH)

The extreme wave height is the maximum individual wave height, $H_{EWH} = H_{max,ESS}$, with a 50-year period of return. It may be assumed that:

$$H_{\max,ESS} = 1.86 \cdot H_{s,50yr} = 1.86 \cdot H_{s,SSS}$$

The corresponding wave period value is selected in the range: $11.1\sqrt{\frac{H_{EWH}}{g}} \leq T \leq 14.3\sqrt{\frac{H_{EWH}}{g}}$ so that it results in the highest load acting on the OWT.

It is assumed that the extreme wave height occurs simultaneously with the extreme 10-min mean wind speed with a 50-year return period.

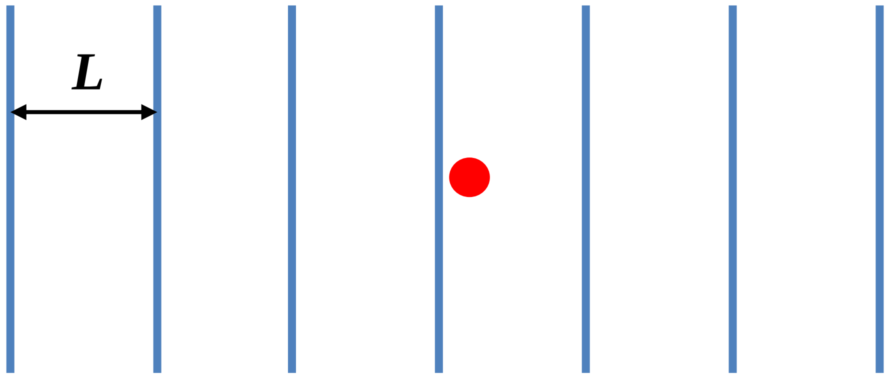
1. External conditions

- Normal and extreme current models
- Normal and extreme water level ranges
- Sea ice
- Marine growth
- Seabed movement and scour
- Temperature
- Lightning
- Icing
- Earthquakes

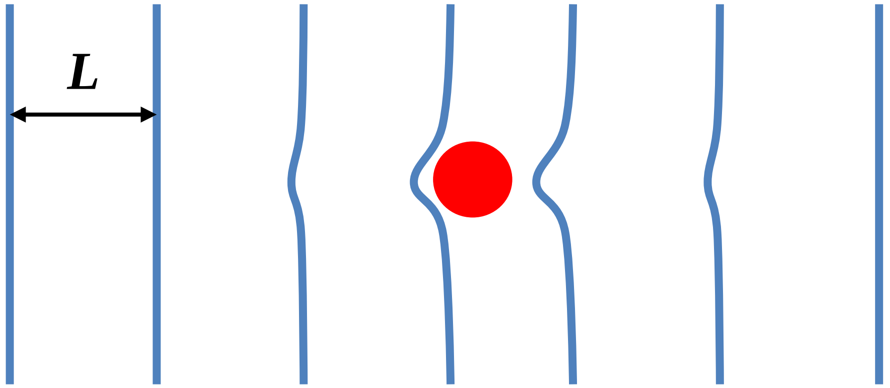
2. Hydrodynamic loads

For waves and currents, depending on the parameters, flow may be approximated as:

1. Potential flow ($H/D < 1$) with negligible wave diffraction ($L/D > 10$) → Froude-Kryloff force



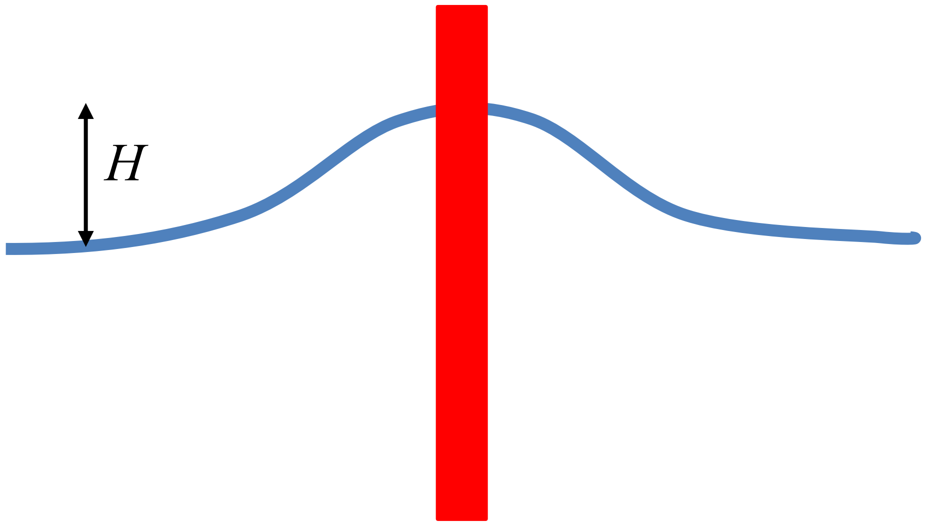
2. Potential flow ($H/D < 1$) with substantial wave diffraction ($L/D < 10$) → Froude-Kryloff force + Diffraction force

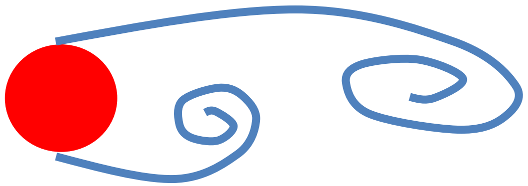


2. Hydrodynamic loads

3. Viscous flow ($H/D > 1$ and/or $U \neq 0$) due to wall friction and flow separation →

Drag force = friction drag and form drag



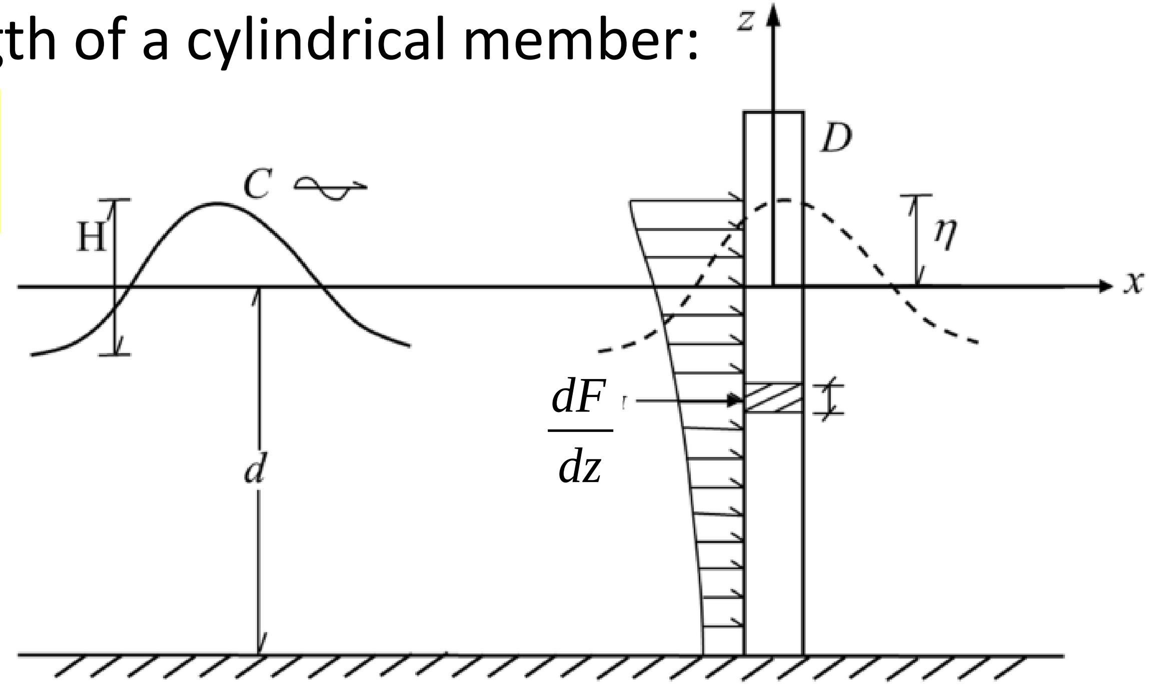


2. Hydrodynamic loads

Morison's equation is a heuristic approach to combine the inertia and drag force contributions to the total force induced by water flow velocity (**due to waves and/or currents**) on cylindrical members.

Force in the normal flow direction per unit length of a cylindrical member:

$$\frac{dF}{dz} = C_M \rho A \frac{du_w}{dt} - C_a \rho A \frac{du_s}{dt} - + C_D \frac{1}{2} \rho D \left| u_w - u_s \right| \left(u_w - u_s \right)$$



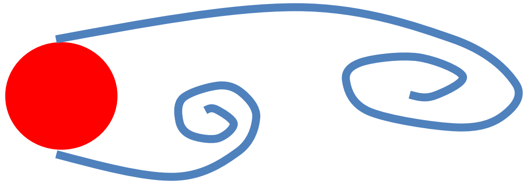
where C_M=1+C_a is the inertia coefficient, C_a is the added-mass coefficient and C_D is the drag coefficient whose values depend on Reynolds and Keulegan-Carpenter numbers:

$$Re = \frac{\rho U D}{\mu} \qquad N_{KC} = \frac{UT}{D}$$

2. Hydrodynamic loads

Vortex induced vibrations (VIV)
Flow separation induces vortex shedding which in turn induces oscillatory lift force, normal to the flow direction, on the cylindrical member.

The principal danger from this situation is the possibility of resonance between a natural frequency f_n of the OWT and the frequency f_s of vortex shedding.



For circular cross-sections, the Strouhal number of vortex shedding is: $St = \frac{f_s D}{U} \approx 0.2$

So the critical flow velocity for OWT resonance, at a particular natural frequency, is in the vicinity of: $U_{cr} = \frac{f_n D}{St} \approx 5 f_n D$

2. Hydrodynamic loads

Breaking wave impact load

It is applied when waves break on members in a plane perpendicular (or almost perpendicular) to the wave direction.

The impact force by wave breaking on a cylindrical member can be considered as an added term in Morison's equation:

$$\frac{dF_{BI}}{dz} = C_{BI} \frac{1}{2} \rho D |c_w| c_w$$

where c_w should be taken as 1.2 times the phase velocity *c* of the examined breaking wave, and C_{BI} is the impact coefficient, whose value is time dependent during the impact, while its maximum value may be considered to be 5.15.

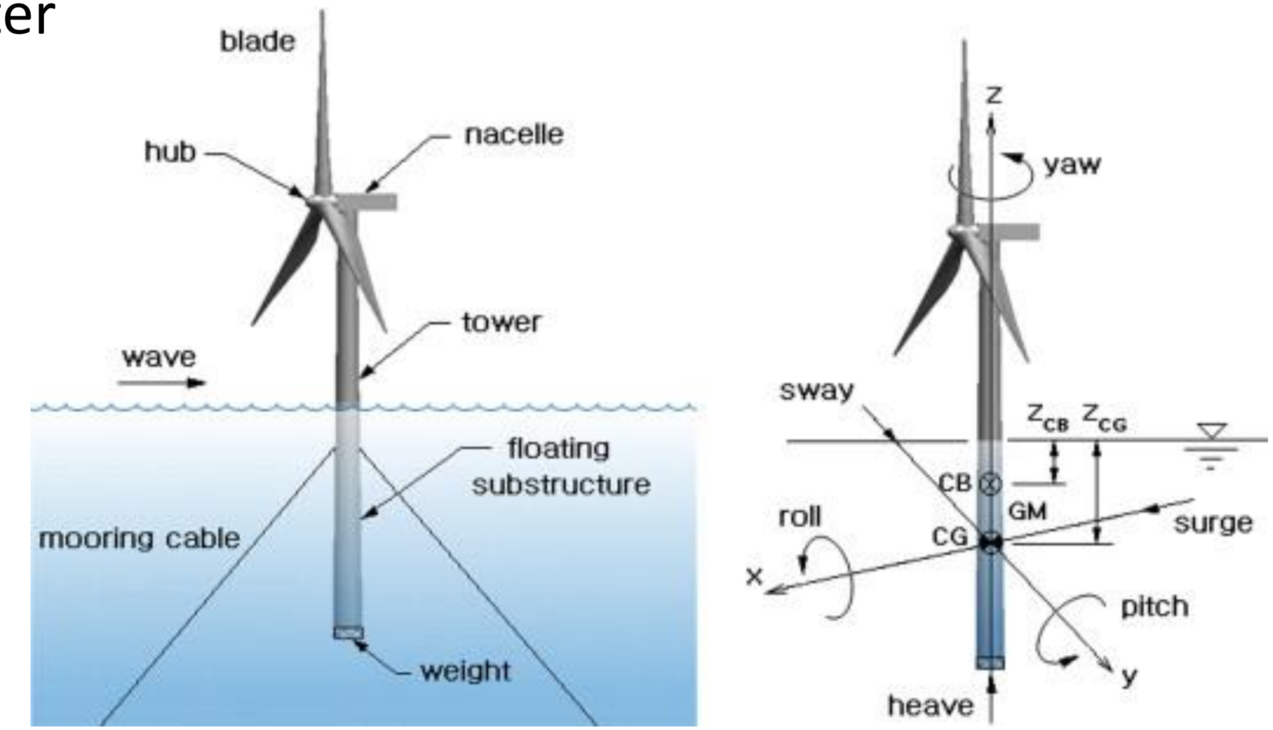
The duration of the impact force on the cylinder may be taken as: $\frac{13D}{64c}$

3. Design issues for floating OWTs

Hydrostatic stability

The center of gravity (**G**) should be below the metacenter (**M**), which is the center of buoyancy when the body is displaced, or tipped, in the water.

In the upright OWT position, the metacenter coincides with the center of buoyancy (**B**).



Metacentric height:

$$GM = GB + BM = GB + \frac{I_{ww}}{\nabla} \geq 0.05 \cdot H_{draft}$$

where I_{ww} is the transverse moment of inertia of the water plane and ∇ is the displacement volume.

Stone ballast in the lower part of the substructure.

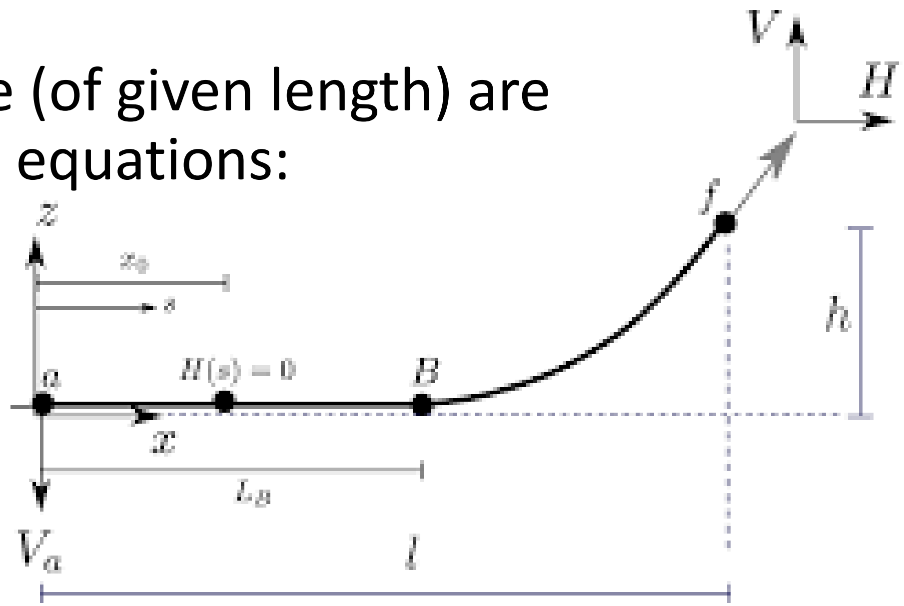
3. Design issues for floating OWTs

Mooring lines

The force components on the OWT by each mooring line (of given length) are computed by the simultaneous solution of the following equations:

$$l = L_B + \frac{H}{w}\ln\left(\frac{V}{H} + \sqrt{1+\left(\frac{V}{H}\right)^2}\right) + \frac{HL}{EA} + \frac{wC_B}{2EA}\left(x_0^2 - L_B^2\right)$$

$$h = \frac{H}{w}\left(\sqrt{1+\left(\frac{V}{H}\right)^2} - 1\right) + \frac{V^2}{2EAw}$$



where $x_0 = L_B - H/(wC_B) \geq 0$, *w* is the cable buoyant weight per unit length, *E* is the cable Young's module, *L* is the unstreched cable length, *A* is the cable cross-sectional area, and C_B is the cable-bed friction coefficient.

The cable tension is: $T(s) = \begin{cases} \max\left[wC_B(s-x_0), 0\right] & \text{for} \quad 0 \leq s \leq L_B \\ \sqrt{H^2 + \left(w(s-L_B)\right)^2} & \text{for} \quad L_B < s \leq L \end{cases}$

4. Design procedures

A number of design load cases have to be examined which result by the combinatory consideration of:

- The condition of the OWT (power production, parked, fault occurrence, start up, shut down, transport, assembly, erection and maintenance).
- The wind condition (normal, extreme, gust, turbulence)
- The waves condition (normal, severe, extreme)
- The current condition (normal, extreme)
- Other conditions like ice, temperature, etc.

4. Design procedures

Furthermore, each design load case is characterized as **"U"**, which corresponds to ultimate loads, with reference to material strength, blade tip deflection and structural stability, or **"F"**, which corresponds to fatigue loads for the assessment of fatigue strength.

The "U" design load cases are further classified as normal (**N**), abnormal (**A**), or transport and erection (**T**).
Normal design load cases are expected to occur frequently within the lifetime of an OWT. These cases include OWT minor faults or abnormalities.
Abnormal design load cases are less likely to occur. They correspond to design situations with severe faults that result in activation of system protection functions.

4. Design procedures

Table 1 – Design load cases

Design situation	DLC	Wind condition	Waves	Wind and wave directionality	Sea currents	Water level	Other conditions	Type of analysis	Partial safety factor
1) Power production	1.1	NTM $V_{in} < V_{hub} < V_{out}$ RNA	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL	For extrapolation of extreme loads on the RNA	U	N (1,25)
	1.2	NTM $V_{in} < V_{hub} < V_{out}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, MUL	No currents	NWLR or ≥ MSL		F	*
	1.3	ETM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL		U	N
	1.4	ECD $V_{hub} = V_r - 2$ m/s, V_r, $V_r + 2$ m/s	NSS (or NWH) $H_s = E[H_s \| V_{hub}]$	MIS, wind direction change	NCM	MSL		U	N
	1.5	EWS $V_{in} < V_{hub} < V_{out}$	NSS (or NWH) $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL		U	N
	1.6a	NTM $V_{in} < V_{hub} < V_{out}$	SSS $H_s = H_{s,SSS}$	COD, UNI	NCM	NWLR		U	N
	1.6b	NTM $V_{in} < V_{hub} < V_{out}$	SWH $H = H_{SWH}$	COD, UNI	NCM	NWLR		U	N

4. Design procedures

Table 1 – Design load cases *(continued)*

Design situation	DLC	Wind condition	Waves	Wind and wave directionality	Sea currents	Water level	Other conditions	Type of analysis	Partial safety factor
2) Power production plus occurrence of fault	2.1	NTM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL	Control system fault or loss of electrical network	U	N
	2.2	NTM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL	Protection system or preceding internal electrical fault	U	A
	2.3	EOG $V_{hub} = V_r \pm 2$ m/s and V_{out}	NSS (or NWH) $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	No currents	NWLR or ≥ MSL	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP $V_{in} < V_{hub} < V_{out}$	NSS (or NWH) $H_s = E[H_s \| V_{hub}]$	COD, UNI	No currents	NWLR or ≥ MSL		F	*
	3.2	EOG $V_{hub} = V_{in}, V_r \pm 2$ m/s and V_{out}	NSS (or NWH) $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL		U	N
	3.3	EDC_1 $V_{hub} = V_{in}, V_r \pm 2$ m/s and V_{out}	NSS (or NWH) $H_s = E[H_s \| V_{hub}]$	MIS, wind direction change	NCM	MSL		U	N

4. Design procedures

Table 1 – Design load cases *(continued)*

Design situation	DLC	Wind condition	Waves	Wind and wave directionality	Sea currents	Water level	Other conditions	Type of analysis	Partial safety factor
4) Normal shut down	4.1	NWP $V_{in} < V_{hub} < V_{out}$	NSS (or NWH) $H_s = E[H_s \| V_{hub}]$	COD, UNI	No currents	NWLR or ≥ MSL		F	*
	4.2	EOG $V_{hub} = V_r \pm 2$m/s and V_{out}	NSS (or NWH) $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL		U	N
5) Emergency shut down	5.1	NTM $V_{hub} = V_r \pm 2$m/s and V_{out}	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL		U	N
6) Parked (standing still or idling)	6.1a	EWM Turbulent wind model $V_{hub} = k_1 V_{ref}$	ESS $H_s = k_2 H_{s50}$	MIS, MUL	ECM	EWLR		U	N
	6.1b	EWM Steady wind model $V(z_{hub}) = V_{e50}$	RWH $H = H_{red50}$	MIS, MUL	ECM	EWLR		U	N
	6.1c	RWM Steady wind model $V(z_{hub}) = V_{red50}$	EWH $H = H_{50}$	MIS, MUL	ECM	EWLR		U	N
	6.2a	EWM Turbulent wind model $V_{hub} = k_1 V_{ref}$	ESS $H_s = k_2 H_{s50}$	MIS, MUL	ECM	EWLR	Loss of electrical network	U	A
	6.2b	EWM Steady wind model $V(z_{hub}) = V_{e50}$	RWH $H = H_{red50}$	MIS, MUL	ECM	EWLR	Loss of electrical network	U	A
	6.3a	EWM Turbulent wind model $V_{hub} = k_1 V_1$	ESS $H_s = k_2 H_{s1}$	MIS, MUL	ECM	NWLR	Extreme yaw misalignment	U	N
	6.3b	EWM Steady wind model $V(z_{hub}) = V_{e1}$	RWH $H = H_{red1}$	MIS, MUL	ECM	NWLR	Extreme yaw misalignment	U	N
	6.4	NTM $V_{hub} < 0{,}7\ V_{ref}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, MUL	No currents	NWLR or ≥ MSL		F	*

4. Design procedures

Table 1 – Design load cases *(continued)*

Design situation	DLC	Wind condition	Waves	Wind and wave directionality	Sea currents	Water level	Other conditions	Type of analysis	Partial safety factor
7) Parked and fault conditions	7.1a	EWM Turbulent wind model $V_{hub} = k_1 V_1$	ESS $H_s = k_2 H_{s1}$	MIS, MUL	ECM	NWLR		U	A
	7.1b	EWM Steady wind model $V(z_{hub}) = V_{e1}$	RWH $H = H_{red1}$	MIS, MUL	ECM	NWLR		U	A
	7.1c	RWM Steady wind model $V(z_{hub}) = V_{red1}$	EWH $H = H_1$	MIS, MUL	ECM	NWLR		U	A
	7.2	NTM $V_{hub} < 0,7\ V_1$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, MUL	No currents	NWLR or ≥ MSL		F	*
8) Transport, assembly, maintenance and repair	8.1	To be stated by the manufacturer						U	T
	8.2a	EWM Turbulent wind model $V_{hub} = k_1 V_1$	ESS $H_s = k_2 H_{s1}$	COD, UNI	ECM	NWLR		U	A
	8.2b	EWM Steady wind model $V_{hub} = V_{e1}$	RWH $H = H_{red1}$	COD, UNI	ECM	NWLR		U	A
	8.2c	RWM Steady wind model $V(z_{hub}) = V_{red1}$	EWH $H = H_1$	COD, UNI	ECM	NWLR		U	A
	8.3	NTM $V_{hub} < 0,7\ V_{ref}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, MUL	No currents	NWLR or ≥ MSL	No grid during installation period	F	*

4. Design procedures

Partial safety factors

For the design of the support structure, the partial safety factor format is used to account for uncertainties and variability in loads and materials, uncertainties in the analysis methods and the importance of structural components with respect to the consequences of failure.

The type of design situation, N, A, or T, determines the partial safety factor γ_f to be applied to the ultimate loads.

The design criteria are in the form: $S_i\left(F_{d,j}\right) \leq R_i\left(M_{d,k}\right)$

where S_i , i=1,2,..., are the design load effects, which depend on the design loads $F_{d,j}$, j=1,2,..., and R_i are the corresponding design resistances, which depend on the structure and materials design property values $M_{d,k}$, k=1,2,....

4. Design procedures

Partial safety factors

Using partial safety factors, the design criteria are in the form:

$$S_i\left(\gamma_{f,j}F_{c,j}\right)=\frac{1}{\gamma_{n,i}}R_i\left(M_{c,k}\right)$$

where $F_{jc,}$, j=1,2,…, is the characteristic value of each load, and $M_{c,k}$, k=1,2,…, is the characteristic value of each structure and material property.

4. Design procedures

The load partial safety factor values for the design of the support structure, according to IEC 61400-3, are:

Unfavorable loads Type of design situation			Favorable loads (pretension and gravity loads)
Normal (N)	Accidental (A)	Transport (T)	All design situations
$\gamma_f = 1.35$	$\gamma_f = 1.10$	$\gamma_f = 1.50$	$\gamma_f = 0.90$

The resistance partial safety factor values for the design of the support structure, according to IEC 61400-3, are:

Ultimate strength (U)	Fatigue failure (F)
All design situations	All design situations
$\gamma_n = 1.00$	$\gamma_n = 1.15$