



BSI Standards Publication

Marine energy — Wave, tidal and other water current converters

Part 2: Design requirements for marine energy systems

National foreword

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A list of organizations represented on this committee can be obtained on request to its secretary.

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ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**MARINE ENERGY – WAVE, TIDAL AND
OTHER WATER CURRENT CONVERTERS –****Part 2: Design requirements for marine energy systems**

FOREWORD

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Technical Specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 62600-2, which is a Technical Specification, has been prepared by IEC technical committee 114: Marine energy – Wave, tidal and other water current converters.

The text of this Technical Specification is based on the following documents:

Enquiry draft	Report on voting
114/168/DTS	114/176A/RVC

Full information on the voting for the approval of this Technical Specification can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62600 series, published under the general title *Marine energy – Wave, tidal and other water current converters*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

- transformed into an International Standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This part of IEC 62600 outlines minimum design requirements for marine energy converters and is not intended for use as a complete design specification or instruction manual.

Several different parties may be responsible for undertaking the various elements of the design, manufacture, assembly, installation, erection, commissioning, operation and maintenance of a marine energy system and for ensuring that the requirements of this document are met. The division of responsibility between these parties is a contractual matter and is outside the scope of this document.

Any of the requirements of this document may be altered if it can be suitably demonstrated that the safety of the system is not compromised. Compliance with this document does not relieve any person, organization, or corporation from the responsibility of observing other applicable regulations.

MARINE ENERGY – WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS –

Part 2: Design requirements for marine energy systems

1 Scope

1.1 General

This part of IEC 62600 provides the essential design requirements to ensure the engineering integrity of wave, tidal and other water current energy converters, referred to as marine energy converters (MECs), for a specified design life. Its purpose is to provide an appropriate level of protection against damage from all hazards that may lead to failure of the primary structure, defined as the collective system comprising the structural elements, foundation, mooring and anchors, piles, and device buoyancy designed to resist global loads.

This document includes requirements for subsystems of MECs such as control and protection mechanisms, internal electrical systems, mechanical systems and mooring systems as they pertain to the structural viability of the device under site-specific external environmental conditions. This document applies to wave, tidal and other water current converters and to structures that are either floating or fixed to the seafloor or shore. This document applies to structures that are unmanned during operational periods.

This document addresses site-specific conditions, safety factors for critical structures and structural interfaces, external load cases (including extreme load magnitude, duration, and frequency), failure probability and failure consequences for critical structures and structural interfaces (overall risk assessment), and failsafe design practices (demonstration of adequate redundancy). The effect of subsystem failure on the primary structure is also addressed.

This document does not address the effects of MECs on the physical or biological environment (unless noted by exception). This document is used in conjunction with the appropriate IEC and ISO standards, as well as regional regulations that have jurisdiction over the installation site.

1.2 Applications

This document is applicable to MEC systems designed to operate from ocean, tidal and river current energy sources, but not systems associated with hydroelectric impoundments or barrages. This document is also applicable to wave energy converters. It is not applicable to ocean thermal energy conversion (OTEC) systems or salinity gradient systems.

Although important to the overall objectives of the IEC 62600 series, this document does not address all aspects of the engineering process that are taken into account during the full system design of MEC systems. Specifically, this document does not address energy production, performance efficiency, environmental impacts, electric generation and transmission, ergonomics, or power quality.

This document, to the extent possible, adapts the principles of existing applicable standards already in use throughout the marine industry (structure, moorings, anchors, corrosion protection, etc.) and by reference, defers to the appropriate international documents. This document adheres to a Load Resistance Factor Design (LRFD) approach and the principles of limit state design as described in ISO 2394.

MECs designed to convert hydrokinetic energy from significant hydrodynamic forces into other forms of usable energy, such as electrical, hydraulic, or pneumatic may be different from

other types of marine structures. Many MECs are designed to operate in resonance or conditions close to resonance. Furthermore, MECs are hybrids between machines and marine structures. The control forces imposed by the power takeoff (PTO) and possible forces from faults in the operation of the PTO distinguish MECs from other marine structures.

The goal of this document is to adequately address relevant design considerations for MECs that have progressed to an advanced prototype design stage or beyond. This refers to technology concepts that have been proven either through analysis, open water test data, scale model testing in tanks or dry land test facilities, and that are ready for commercialization. It is anticipated that this document will be used in certification schemes for design conformity.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60812, Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA)

IEC 61400-1, *Wind turbines – Part 1: Design requirements*

IEC 61643-11, *Low voltage surge protective devices – Part 11: Surge protective devices connected to low-voltage power systems – Requirements and test methods*

IEC 62305-3, *Protection against lightning – Part 3: Physical damage to structures and life hazard*

IEC TS 62600-1, *Marine energy – Wave, tidal and other water current converters – Part 1: Terminology*

IEC TS 62600-10, *Marine energy – Wave, tidal and other water current converters – Part 10: Assessment of mooring system for marine energy converters (MECs)*

ISO 527-1, *Plastics – Determination of tensile properties – Part 1: General principles*

ISO 2394, *General principles on reliability for structures*

ISO 12473, *General principles of cathodic protection in sea water*

ISO 13003, *Fibre-reinforced plastics – Determination of fatigue properties under cyclic loading conditions*

ISO 14125, *Fibre-reinforced plastic composites – Determination of flexural properties*

ISO 14126, *Fibre-reinforced plastic composites – Determination of compressive properties in the in-plane direction*

ISO 14129, *Fibre-reinforced plastic composites – Determination of the in-plane shear stress/shear strain response, including the in-plane shear modulus and strength, by the $\pm 45^\circ$ tension test method*

ISO 14130, *Fibre-reinforced plastic composites – Determination of apparent interlaminar shear strength by short-beam method*

ISO 15024, *Fibre-reinforced plastic composites – Determination of mode I interlaminar fracture toughness, G_{IC} , for unidirectionally reinforced materials*

ISO 19900, *Petroleum and natural gas industries – General requirements for offshore structures*

ISO 19901-4, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 4: Geotechnical and foundation design considerations*

ISO 19902:2007, *Petroleum and natural gas industries – Fixed steel offshore structures*

ISO 19903, *Petroleum and natural gas industries – Fixed concrete offshore structures*

EN 12495, *Cathodic protection for fixed steel offshore structures*

EN 13173, *Cathodic protection for steel offshore floating structures*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 62600-1 as well as the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1

normal wave height

NWH

significant wave height corresponding to a concurrent 10 min mean wind speed

3.2

primary structure

<marine energy converter> collective system comprising the structural elements, foundation, mooring and anchors, piles, and device buoyancy designed to resist global loads

4 Symbols and abbreviated terms

For the purposes of this document, the symbols and abbreviated terms given in IEC TS 62600-1 as well as the following apply.

d	water depth
f	wave spectrum frequency
f_P	wave spectrum peak frequency
f_{ck}	characteristic concrete compressive strength
f_{ckj}	characteristic cylinder strength
f_e	elastic buckling stress
f_y	specified minimum yield stress
F_d	load design value
F_k	load characteristic value
g	gravitational acceleration

h	ice thickness with a 50-year recurrence period
H_1	extreme wave height with a recurrence period of 1 year
H_5	extreme wave height with a recurrence period of 5 years
H_{50}	extreme wave height with a recurrence period of 50 years
H_B	breaking wave height
H_{EWH}	extreme wave height
H_{NWH}	normal wave height
H_{rated}	device rated wave height
H_S	significant wave height
$H_{S,NSS}$	significant wave height of the normal sea state
H_{s1}	extreme stochastic wave height with a recurrence period of 1 year
H_{s5}	extreme stochastic wave height with a recurrence period of 5 years
H_{s50}	extreme stochastic wave height with a recurrence period of 50 years
$H_{s\ out}$	extreme wave height exiting a device
$H_{s\ in}$	extreme wave height into a device
H_{sT}	limiting value of H_s for transport, erection and/or maintenance
R	internal forces
R_d	design resistance
s	slope of beach floor
S	pseudo response spectrum
SWL	still water level
T	wave period
T_P	peak wave period
U_{bw}	breaking wave current velocity
U_{in}	current velocity into a device
U_{rated}	device rated current velocity
U_{out}	current velocity exiting a device
U_{ss}	sub-surface current velocity
U_T	limiting value of current velocity for transport, erection and/or maintenance
U_w	wind-generated current velocity
V	10 min mean wind speed
V_{1-hour}	1 h mean value of wind speed at 10 m height above SWL
V_5	extreme wind speed with a recurrence period of 5 years
Φ	resistance factor
σ_c	ice crushing strength
σ_U	standard deviation of the current velocity
$\sigma_{U,c}$	characteristic standard deviation of mean current velocity at a specified probability distribution
γ	damping ratio
γ_F	partial load safety factor
γ_{FM}	partial load effect and resistance factor
γ_M	material factor
γ_{Rd}	resistance model factor

γ_S	system effect factor
γ_{Sd}	load model factor
ω	angular frequency
λ	slenderness parameter; wave length

5 General considerations

5.1 General

There are a diversity of concepts and different approaches for MECs and there are broad and varied considerations for ensuring their structural integrity during lifecycle phases.

A common characteristic of all MEC structures that distinguishes them from other marine structures is the requirement to determine the loading and response of the structures due to their interaction with PTO and control systems. This affects strength, fatigue, and the capacity to survive operating and extreme meteorological and ocean conditions. In addition, failure of PTO, grid loss, and other conditions that may not be considered accidental shall be considered.

As part of the design process, the risks to structural integrity shall be assessed by means of a Failure, Modes and Effects Analysis (FMEA), a Failure, Modes, Effects and Criticality Analysis (FMECA), or similar method as per IEC 60812. This risk assessment shall be used to determine the possible structural failure modes associated with the fabrication, transportation, installation, service and removal of the MEC. It should consider the location of installation, the device characteristics, installation methodology, maintenance requirements, and activities of third parties in the area, including accidental scenarios.

5.2 Regulations

The requirements of regional regulations may be different from those given in this document. The designer shall ensure that the requirements of safety, reliability and durability of this document and regional regulations are met.

5.3 Suitability and/or relevance of standards

The use of a standard from other mature industries where nothing explicitly written for MECs is available carries a risk that important considerations for the marine energy application are given insufficient emphasis or ignored completely. This applies to standards written for offshore wind, oil and gas, and shipping.

It is expected that standards from other industries will be required to fill gaps in the design process. In many cases those standards are not identified by this document. Formal risk assessment techniques shall be used whenever a 'non-marine-renewable-energy' standard or guideline is used unless it can be demonstrated that the standard or guideline has been successfully adapted in previous designs with a similar application.

5.4 Quality assurance and quality control

The level of quality assurance and quality control shall be related to the consequences of the component, sub-system, system or assembly failing. Certification of quality systems of designers, manufacturers and operators by an accredited certifying body is desirable. Effective quality control through verification of design, testing, inspection and monitoring are essential for the success of the implementation of the technology. It is recommended that the quality system comply with the requirements of an internationally recognized quality management system.

5.5 Safety levels

In addition to the multitude of MEC concepts, there are several aspects to consider when defining the targets for safety and design life. Safety levels shall consider different expectation levels from different stakeholders and a balance among survivability, reputation, maintenance, repairs and production costs.

A safety level shall be clearly established covering all phases of MEC installation, operation, maintenance and decommissioning.

Safety levels shall be derived considering the following aspects and stakeholders:

- risk to life during installation, operation and removal of the MEC during in-service life;
- environmental impact, including for example: fluid releases, anti-fouling coatings, bilge water, and location of site relative to sensitive environments (protected species or sensitive sites and visual impacts);
- inspection and maintenance cost, risks during removal of equipment for inspection and maintenance;
- expected safety level by authorities where the MEC is designed to operate;
- financial risk (including loss of power generation); and
- public reputation and societal considerations.

When selecting the safety level, the consequences identified by a FMECA shall be referenced (see 5.1).

Three safety levels with reference to consequences for MECs have been identified and are defined in Table 1 along with target probabilities of failure. Reference should be made to Clause 7 for the use of these safety levels as part of the design process.

Table 1 – Safety levels

Safety level	Definition	Probability of failure
SL1	Operating conditions where failure implies high risk of human injury, significant environmental pollution or major economic or political consequences	$< 10^{-5}$ per year
SL2	For temporary or operating conditions where failure implies: some risk of human injury, some environmental pollution or significant economic or political consequences This level normally aims for a risk of less than 10^{-4} per year of a major single accident. It corresponds to a major incident happening on average less than once every 10,000 installation- years. This level equates to the experience level from major representative industries and activities.	$< 10^{-4}$ per year
SL3	Failure implies low risk of human injury and minor environmental and economic consequences	$< 10^{-3}$ per year

Guidance is given in this document to achieve a safety level of 2 based on reference to offshore wind and other offshore standards. Other safety levels may be appropriate based on project particulars. Partial load safety factors specified in Clause 7 of this document are based on target safety level 2. Partial load safety factors for any alternative target safety level can be adjusted accordingly, provided that the probability of failure of the target safety level is achieved.

Safety levels shall be considered while defining redundancy or safety features for the equipment and systems. Higher levels of safety might be required for critical sub-systems and components depending on their consequences of failure.

A higher safety level may be required due to the difficulty in access for maintenance and costs related to intervention offshore and the potential penalty of downtime to provide energy to the grid. The assessment of reliability, availability and survivability strategy for a particular device will directly influence the selection of an appropriate safety level.

Lower safety levels may be considered where there is a lower consequence of failure, which may be applicable to smaller unit sizes or to river current energy conversion systems.

5.6 Design principles – structure and foundations

Due consideration shall be given to aspects related to the relevant limit state: ultimate (ULS), serviceability (SLS), fatigue (FLS) and accidental (ALS). These limit states are normally associated with the limit state design methodology often referred to as Load and Resistance Factor Design (LRFD) or Partial Safety Factor Design (PSFD). Guidance is given in this specification based on LRFD methodology.

Allowable Stress Design (ASD) methods consider the same limit states through use of a single safety factor rather than separate load and resistance factors. This approach may be adopted provided the target safety levels in Table 1 are achieved.

An alternative design methodology, involving direct estimation of reliability of a MEC for a given limit state, may also be adopted to fulfill the safety levels as per Table 1. This approach requires:

- definition of different limit states for a design;
- definition of random variables entering in each limit state;
- consideration of probability distribution for each variable; and
- accepted method for estimating annual probability of failure in each limit state.

A particular design approach shall be used throughout the entire design process of a MEC to ensure a coherent execution that is acceptable to the client, regulators and certification authority.

5.7 Load definition and load combinations

The FMEA/FMECA shall be used to identify limit states where the structure would no longer meet the prescribed safety level requirements. Clauses 6 to 9 further detail methodologies to ensure that adequate consideration shall be given to the following:

- overall device stability against translation or overturning forces;
- integrity of any sub-components, where relevant;
- performance of ground anchorage, including consideration of ground fatigue;
- structural capacity and fatigue performance of structural components; and
- operational limits on mechanical equipment, seals and bearings.

Based on identified limit states, all load cases where these limit states could be exceeded shall be identified to enable design assessment (refer to Clause 7). For all identified load cases, consideration shall be given to device fault and failure conditions that could affect the device loading. It is important that the level of uncertainty surrounding the behavior of the MEC at an early stage of development is considered when defining the basic load cases.

For all load cases identified, sufficient analysis based on the underlying physical principles shall be undertaken to establish that the probability of exceeding any of the identified limit states falls within the limits set out in Table 1.

5.8 Other considerations

5.8.1 Stability and watertight integrity

The designer shall consider scenarios that could cause flooded or partly flooded compartments or inadvertent shift of permanent ballast. Permanent ballast shall be adequately restrained to avoid excessive movement and shifting due to device movements. The designer shall consider how to restore adequate stability after flooding by connecting or alternatively starting onboard bilge and/or ballast pumps. Provision of emergency supply to pumps, or provisions for piping for external connection of such pumps shall be considered. Free surface conditions for all floodable compartments shall be considered.

Subclause 7.3.7.11 deals with stability and watertight integrity.

5.8.2 Electrical, mechanical, instrumentation and control systems

Reference should be made to Clause 10 for detailed guidance on electrical and mechanical systems and how they can impact structural integrity.

5.8.3 Reliability issues

A MEC consists of structural, mechanical, electrical and control systems that are interdependent. Thus, it is essential to check not only the reliability of each of the systems separately but their impact on the device as a whole. The planned inspection and maintenance of the device shall be considered during the design stage as discussed in Clause 12. Guidance on considering reliability for various components and systems is provided in Annex B.

5.8.4 Corrosion protection

Due consideration shall be given to the adequate durability and performance of the structure and components in corrosive environments. See Clause 8 and Annex C for additional information.

5.8.5 Design for operation, inspection, maintenance and decommissioning

The manner in which the MEC is operated and maintained will have a significant impact on the structural integrity and functionality throughout the service life of the device. In order for any maintenance methodology to be effective, it shall be considered in a holistic manner throughout the design, construction and operation process. In particular, the planned inspection and maintenance shall be considered during the design stages to ensure that it is practical, economic and safe. The designer shall also consider removal and decommissioning during the design phase. See Clause 13 for life cycle considerations.

5.9 Operational and structural resonance

The designer shall take into account the harmonic response of both structural and mechanical elements. Structural damping can be expected to be quite low. Hydrodynamic damping can be quite significant and shall be estimated.

There are two types of MECs: ones that exploit a resonant response, in order to maximize the power captured, and those that do not. Operational resonance refers to devices that exploit a resonant response in order to maximize the power captured. For these MECs, the designer shall pay close attention to the fatigue stresses and the fatigue life. The dynamic behavior of the device may also require special considerations for stability beyond the normal margins provided by the stability curves and requirements for ships or floating offshore installations.

For devices that do not exploit a resonant response, environmental loads may induce structural resonance. The designer shall either ensure the natural frequencies of the structural and mechanical elements are sufficiently separated from the exciting frequencies.

ensure that there is sufficient damping in the design so fatigue stresses induced are not significant. Structural resonance can also occur in modes not associated with energy conversion. It should be noted that avoiding natural frequencies will not completely eliminate fatigue stresses. All MEC designs shall have adequate strength and safety factors to accommodate fatigue stresses.

Guidance on the approach to consider operational and structural resonance and the assessment of natural and exciting frequencies for MECs is provided in Annex D.

5.10 Basis of design

The basis of design describes the technical approach and design parameters planned for the project. The basis of design summarizes all baseline data, loadings, material characteristics, design methodology, and applicable design standards that are to be considered during the design process.

The basis of design shall be applicable to all stages of development from the prototype design stage of an MEC (after the initial concept has been proven to work) up to the final detailed design. The key objective of the basis of design is to act as an overarching document that promotes consistency during all design work. Further guidance on the typical contents of a basis of design is provided in Annex E.

6 External conditions

6.1 General

The external conditions described in Clause 6 shall be considered in the modeling, analysis and prediction of environmental conditions for calculating environmental loads on MECs. The most important environmental phenomena for MECs are waves and currents, but consideration shall also be given to wind, ice, earthquake, soil conditions, temperature, fouling and other external conditions.

The marine conditions for load and safety considerations are divided into the normal marine conditions, which will occur more frequently than once per year during normal operation of the MEC, and the extreme marine conditions, which are defined as having a 1-year and 50-year recurrence period. The normal and extreme conditions to be considered in design are prescribed in Clause 7.

6.2 Waves

6.2.1 Normal sea state (NSS)

The Normal Sea State (NSS) is characterized by a significant wave height, a peak period and a wave direction. The designer shall follow ISO 19902 when developing fatigue and ultimate load calculations based on the NSS. Where available, regional or site specific data shall be used to specify spectral shape and directional distributions

6.2.2 Normal wave height (NWH)

The Normal Wave Height (NWH), H_{NWH} shall be assumed equal to the expected value of the significant wave height based on the concurrent 10 min mean wind speed, $H_{S,NSS}$ or derived from analysis of appropriate measurements and/or hindcast data for the site of deployment of the MEC. Consideration shall be given to the range of wave periods T appropriate to the normal wave height. Design calculations shall be based on values of the wave period within this range that result in the highest loads on the MEC.

The wave periods T in combination with the normal wave heights, H_{NWH} may be assumed to be within the range given by IEC 61400-3:

$$11,1\sqrt{H_{S,NSS}(V)/g} \leq T \leq 14,3\sqrt{H_{S,NSS}(V)/g} \quad (1)$$

where:

$H_{S,NSS}$ is the significant wave height of the normal sea state in metres;

V is the 10 min mean wind speed in metres per second;

T is the wave period in seconds.

Short-term stationary irregular sea states may be described by a wave spectrum that represents the power spectral density function of the vertical sea surface displacement. Different combinations of wave periods, wave heights and directions at the same probability level (e.g., 10^{-2} or 10^{-4}) shall be considered to arrive at the most unfavorable values for the different action effects.

The most frequently used spectra for wind-generated seas are Pierson-Moskowitz (PM) spectrum for a fully developed sea, and the JONSWAP spectrum for a developing sea. Standard wave spectrum formulations are given in Annex F. The Ochi-Hubble spectrum based on superposition of two modified Pierson-Moskowitz spectra or the Torsethaugen double peak spectral model based on sea state and swell may also be appropriate. Information on swell spectra can be found in ISO 19901-1.

6.2.3 Extreme sea state (ESS)

The designer shall consider the extreme stochastic sea state model for the extreme significant wave height, H_{s50} , with a recurrence period of 50 years; the extreme significant wave height, H_{s5} , with a recurrence period of 5 years; and the extreme significant wave height, H_{s1} , with a recurrence period of 1 year. The values of H_{s50} , H_{s5} and H_{s1} shall be determined from analysis of appropriate measurements and/or hindcast data for the site of MEC deployment. The extreme significant wave height, H_{s50} estimated from hindcast data may underestimate the recurrence conditions. The designer shall take into account the range of peak spectral period, T_p appropriate to H_{s50} , H_{s5} and H_{s1} respectively. Design calculations shall be based on values of peak spectral period that result in the highest loads acting on the MEC.

In the absence of information defining the long-term joint probability distribution of extreme wind and waves, it shall be assumed that the extreme 10-min mean wind speed with 50-year recurrence period occurs during the extreme 3 h sea state with 50-year recurrence period. The same assumption shall apply with regard to the combination of the extreme 10 min wind speed and the extreme 3 h sea state, each with a 1-year recurrence period.

6.2.4 Extreme wave height (EWH)

The extreme wave height is the largest significant wave height for a given recurrence value. The extreme deterministic design wave shall be considered for the extreme wave height H_{50} with a recurrence period of 50 years; extreme wave height H_5 with a recurrence period of 5 years; and the extreme wave height H_1 with a recurrence period of 1 year. The values of H_{50} , H_5 , H_1 and the associated wave periods may be determined from analysis of appropriate measurements at the MEC deployment site. Alternatively, the designer may assume the following based on the Rayleigh distribution of wave heights:

$$H_{50} = 1,86 H_{s50} \quad (2)$$

$$H_5 = 1,86 H_{s5} \quad (3)$$

and

$$H_1 = 1,86 H_{s1} \quad (4)$$

where the significant wave heights H_{s50} , H_{s5} and H_{s1} are values for a 3 h reference period.

A recurrence period of 50 years corresponds to SL2. This shall be adjusted for sites where extreme events with higher recurrence periods than 50 years are relevant (e.g. Gulf of Mexico or North Atlantic).

The range of wave periods T appropriate to the severe wave height shall be considered in the design calculations. The computations shall be based on values of the wave period within this range that result in the highest loads on the MEC.

In deep waters, the wave periods T to be used with H_{EWH} may be assumed to be within the range given by Formula (1).

NOTE Water is considered 'deep' for a wave, if its depth is greater than one-half of the wavelength of the wave. Otherwise, it is considered 'shallow.'

The extreme wave heights H_{50} , H_5 , H_1 and the associated wave periods for shallow water sites shall be determined from analysis of appropriate site-specific measurements. In the absence of measurements, H_{50} , H_5 and H_1 shall be assumed equal to the breaking wave height if the breaking wave height is less than the values of H_{50} , H_5 and H_1 determined from the Rayleigh distribution given by Formulae (1) and (3).

6.2.5 Breaking waves

A breaking wave is a wave whose amplitude reaches a critical level that causes large amounts of wave energy to be transformed into turbulent kinetic energy when the crest of the wave overturns. The effect of breaking waves shall be assessed, if necessary, for a given site during the design of the MEC. Depending on the wave steepness and the slope of the seabed, breaking waves are classified as spilling, plunging or surging.

Annex G provides guidance for determination of the nature and dimensions of breaking waves based on site conditions and presents an empirical model of the distribution of wave heights for shallow water.

6.2.6 Wave run-up

The designer shall consider hydrodynamic loads arising from the maximum vertical extent of wave travel on a beach or structure above the still water level.

6.3 Sea currents

6.3.1 General

The most common categories of ocean currents are: wind generated currents, tidal currents, circulatory currents, loop and eddy currents, soliton currents, and longshore currents. The total current velocity is the vector sum of all components at a given position in the water column. The designer shall determine whether sea currents may be neglected for calculation of fatigue loads on the components of the supporting structure considering the site characteristics and MEC's geometry.

6.3.2 Sub-surface currents

The sub-surface current velocity $U_{ss}(z)$ profile may be characterized by a simple power law over the water depth d , as a function of height z above SWL:

$$U_{ss}(z) = U_{ss}(0) \{(z+d)/d\}^{1/7} \quad (5)$$

The 1-year, 5-year and 50-year recurrence values of the sea surface velocity $U_{ss}(0)$ may be determined from analysis of measurements of tidal, storm surge, wind generated and wave

induced surf. If the current velocity is of significant importance to the design, current velocity measurements shall be carried out at the MEC deployment site.

Currents through the depth shall be combined vectorially with the design wave conditions.

6.3.3 Wind-generated near-surface currents

The wind-generated current may be characterized as a linear distribution of velocity $U_w(z)$ reducing from the surface velocity $U_w(z)$ to zero at a depth of 20 metres (m) below the static water level SWL:

$$U_w(z) = U_w(0) \{(1+z)/20\} \quad (6)$$

The wind generated current velocity at the sea floor will be non-zero at sites where the water depth is less than 20 m.

The wind generated sea surface current velocity may be assumed to be aligned with the wind direction and may be determined from

$$U_w(0) = 0,01 V_{1\text{-hour}}(z = 10 \text{ m}) \quad (7)$$

where $V_{1\text{-hour}}(z = 10 \text{ m})$ is defined as the 1 h mean value of wind speed at 10 m height above SWL.

The 1-year, 5-year and 50-year recurrence values of $V_{1\text{-hour}}(z = 10 \text{ m})$ may be determined from analysis of site measurements.

6.3.4 Tidal currents

Tidal currents are often magnified by topographical features, such as headlands, inlets and straights, or by the shape of the seabed when water is forced through narrow channels. Strong tidal currents may exist in inlets and straits in coastal regions (IEC TS 62600-201).

Marine tidal current turbulence generated by sea bed material, ripples, bed forms, changes in bathymetry, waves and swell, ambient environment, and vortices shed from the blades and support structure shall be considered in determining frictional drag, flow separation, transition from laminar to turbulent flow, thickness of boundary layers, extent of secondary flows, and the spreading of jets and wakes

6.3.5 Breaking wave-induced surf currents

The surf currents generated by the shear forces of breaking waves along the coast shall be considered when the MEC is to be sited near a breaking wave zone.

Numerical methods (e.g. a Boussinesq model considering fully coupled wave and current motions) can be used for the estimation of the breaking wave induced surf currents. The near-shore surf currents that have a direction parallel to the shoreline (longshore currents) may be estimated based on the current velocity U_{bw} at the location of breaking waves as:

$$U_{bw} = 2s\sqrt{gH_B} \quad (8)$$

where:

H_B is the breaking wave height;

g is the gravity acceleration;

s is the beach floor slope.

The breaking wave height may be estimated based on the site characteristics presented in Annex G.

6.3.6 Normal current model (NCM)

The normal current model includes the appropriate site-specific combination of wind-generated currents and breaking wave surf induced currents, if any, associated with normal wave conditions.

For ultimate load cases involving normal and severe wave conditions the normal current model shall be used with the velocity of the wind generated currents estimated from the relevant mean wind speed (refer to Clause 7).

6.3.7 Extreme current model (ECM)

The extreme current model is defined as the appropriate site-specific combination of sub-surface currents; wind generated currents and breaking wave surf induced currents, if any, associated with recurrence periods of 1, 5 and 50 years, respectively.

For ultimate load cases involving extreme wave conditions, the extreme current model shall be assumed together with sea currents using the same recurrence period as the waves.

6.3.8 Normal turbulence model (NTM)

The level of turbulence in a tidal flow depends on the roughness of the bed, the shape and length of the channel and the flow mean velocity. Turbulence is generally described by the spectrum of velocity fluctuations in the mean flow direction.

The NTM represents turbulent current velocity in terms of a characteristic standard deviation of mean current velocity, $\sigma_{U,c}$. The characteristic standard deviation $\sigma_{U,c}$ is defined as the 90 % quantile in the probability distribution of the standard deviation σ_U of the current velocity conditioned on the 10 min mean current velocity at a specific point in the water column. Guidance on calculating characteristic standard deviation $\sigma_{U,c}$ based on wind turbulence is provided in IEC 61400-1. When modelling the NTM, a frequency spectrum shall be used with suitable length scales. This frequency spectrum will be a function of standard deviation of mean current. The NTM shall also take account of spatial coherence. It has been shown in a number of references that measured tidal turbulence seems to fit wind turbulence models.

NOTE See example in the NREL TurbSim user guide (TurbSim User's Guide Version 1.06.00) that has the relevant formulae for a tidal NTM. This model is similar to the turbulence model used (in TurbSim) for non-complex wind sites. Also Milne et al. (2013) reported that the Von Karman spectrum model, a wind turbulence spectrum model, seemed to have a reasonable fit to measurements of tidal turbulence if suitable length scales were used.

6.3.9 Extreme turbulence model (ETM)

The extreme turbulence model describes dynamic loads produced by tidal or estuarial flows in extreme conditions. The Extreme Turbulence Model (ETM) represents turbulent current velocity in terms of a characteristic standard deviation of current velocity, $\sigma_{U,c}$. The characteristic standard deviation $\sigma_{U,c}$ is defined as the 98 % quantile in the probability distribution of the standard deviation σ_U of the current velocity conditioned on the 10 min mean current velocity at a specific point in the water column. For guidance on the frequency spectrum, spatial coherence, etc. see the guidance given for the NTM.

Guidance on the turbulence models can be taken from IEC 61400-1 but the models shall be calibrated with the (partial) factors of safety to ensure the governing safety level is achieved. In both cases the standard deviation is defined in terms of a reference turbulence intensity (and velocity at the turbine hub and other factors). But, for tidal streams turbulence intensity seems to vary with mean tidal speed (Milne et al. 2013, Osalusi, 2010), with turbulence intensity increasing as mean tidal speed decreases. The NTM and ETM shall therefore be related to a specific point in the tidal cycle, i.e. there shall be NTM and ETM for each point at

the tidal cycle where the loading is calculated. In addition the turbulence shall be measured in all three orthogonal directions and then the standard deviation derived for each direction.

Tidal site measurements for turbulence shall take account of the influence of waves on fluctuating tidal speed. When deriving the loading from the tidal current, the influence of waves and turbulence shall be dealt with separately as the influence of the wave loading will have more variability than the turbulence.

6.4 Wind conditions

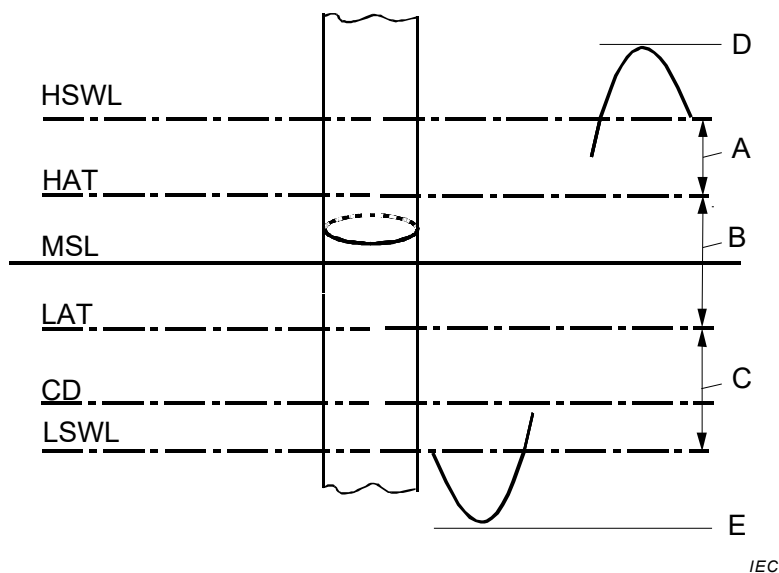
The MEC shall be designed to safely withstand the wind conditions adopted as the basis for design. The normal wind conditions and the design wind conditions shall be taken in accordance with IEC 61400-1. The wind conditions may be ignored if freeboard is insignificant.

The wind regime for load and safety considerations is divided into the normal wind conditions that occur more frequently than once per year during normal operation of the MEC and the extreme marine conditions, which are defined as having 1-year, 5-year, and 50-year recurrence periods.

6.5 Water level

6.5.1 General

The variation in water level at the site shall be taken into account in the calculation of the hydrodynamic loading of MECs. The designer may assume a constant water level equal to the mean sea level (MSL) for ultimate load cases involving normal wave conditions (NSS and NWH). Different water levels are illustrated in Figure 1.



HSWL	highest still water level
HAT	highest astronomical tide
MSL	mean sea level
LAT	lowest astronomical tide
CD	chart datum (often equal to LAT)
LSWL	lowest still water level
A	positive storm surge
B	tidal range
C	negative storm surge
D	maximum crest elevation
E	minimum trough elevation

Figure 1 – Definition of water levels (see IEC 61400-3)

6.5.2 Normal water level range (NWLR)

The normal water level shall be assumed equal to the variation in water level with a recurrence period of 1 year. The normal water level range may be assumed to be equal to the variation between highest astronomical tide (HAT) and lowest astronomical tide (LAT) in the absence of site-specific data to characterize the long-term probability distribution of water levels.

The NWLR shall be assumed for those fatigue and ultimate load cases involving the normal sea state model (NSS) based on the joint probability distribution of sea state conditions, wind speed and current speed (H_s , T_p , U_{ss}).

6.5.3 Extreme water level range (EWLR)

The extreme water level range shall be used for ultimate load computations on the MEC due to the wave conditions with a recurrence period of 50 years. Determination of loads shall be based on the water levels that result in the highest loads acting on the MEC. The relevant governing design water levels shall be determined for computing the hydrodynamic loading, ice loading, and buoyancy of the support structure.

The design calculations shall include the following water levels if the long-term joint probability distribution of water level is not available:

- highest still water level with a recurrence period of 50 years, based on an appropriate combination of highest astronomical tide and positive storm surge;
- lowest still water level with a recurrence period of 50 years, based on an appropriate combination of lowest astronomical tide and negative storm surge; and
- water level associated with the highest breaking wave load.

6.6 Sea and river ice

Loading on the component/support structure of a MEC due to sea or river ice can be critical in some areas. Ice may form in areas where subfreezing temperatures can prevail a major portion of the year. Ice may exist in these areas as first-year ice, multi-year floes, first-year and multi-year pressure ridges, and/or ice islands. Ice features will influence the design and construction of MECs. Global ice forces vary depending on factors such as location, size and configuration of the MEC, mode of ice failure, temperature, salinity, speed of load application, and ice composition.

Ice forces may cause static loading from a fast ice cover, or dynamic loading caused by wind and current induced motion of ice floes. Moving ice floes impacting the MEC over an extended period of time may result in significant fatigue loading. River MECs need to consider the spring freshet 'wall of ice'. A site-specific assessment of the occurrence and properties of the ice shall be undertaken prior to the design of the support structure. The following parameters shall be determined from the assessment:

- ice thickness, h , with a 50-year recurrence period;
- ice crushing strength, σ_c ;
- risk of current or wind induced ice floe;
- risk of forces induced by fluctuating water level; and
- frequency of ice concentration.

NOTE Ice capable of disrupting the harvest of tidal power currently occurs in the Bay of Fundy, Nova Scotia. Recommendation has been made for deployment of tidal current harvesting devices in the headwaters of the Bay of Fundy to be designed for 30 % cover by 15 cm thick ocean ice in 100 m floes.

6.7 Earthquakes

Seismic forces shall be considered for sites that are determined to be seismically active. The designer shall define the pseudo response spectra for the design of the MEC primary and support structures. For a given damping ratio γ and angular frequency ω , the pseudo response spectrum S gives the maximum value of the response over the duration of the response. The designer shall consider non-linear effects that may require site-specific time history analysis for specified ground motions.

6.8 Marine growth

Marine growth influences the dynamic and hydrodynamic characteristics of structural members through the added mass of the growth, increased outer dimensions and increased roughness of the surface. The thickness of marine growth is site-specific and depends on location, member orientation, water depth and structure age (or time since removal of growth). Site-specific data shall be used to establish the extent of marine growth, likely thickness and depth dependence of the growth for a given location.

A strategy for inspection and possible removal of marine growth shall be planned as part of the support structure design. Inspection frequency, inspection method and growth removal criteria shall be based on the impact of marine growth on the structural reliability and performance of the MEC and the extent of marine growth for the site-specific conditions.

6.9 Seabed movement and scour

The component or support structure of the MEC shall be designed taking into account the influence of seabed movement and scour.

The analysis of seabed movement and scour, and the design of appropriate protection shall conform to the requirements of ISO 19901-4.

6.10 Ship collisions

The effect from maritime traffic and service vessel collisions shall be considered.

6.11 Other environmental conditions

The designer shall take into account environmental conditions such as: air temperature, humidity, air density, solar radiation, rain, hail, snow and ice, chemically active substances, mechanically active substances, salinity causing corrosion, lightning, water density and viscosity, water temperature and any other environmental condition that may impact the MEC. The probability of simultaneous occurrence of climatic conditions shall be taken into account.

7 Loads and load effects

7.1 General

The integrity of the load-carrying components of a MEC structure shall be verified to an acceptable safety level as defined in Clause 5. The ultimate and fatigue strength of structural members shall be verified by calculations and/or tests.

Scale model tank testing and field test data may be used as a support for calculations to verify the structural design.

7.2 Loads

The loads described in Table 2, which are relevant for the specific MEC site and geometry, shall be considered in all design calculations.

An analysis of the dynamic response of the MEC shall be performed.

Table 2 – Types of loads that shall be considered

Load	Description and design approach
Gravitational and inertial loads	Static and dynamic loads resulting from gravity, vibration, rotation and seismic activity.
Actuation loads	Result from the operation and control of the MEC. The interaction of the MEC control system with the low-frequency motions of the structure shall be considered in the control system design and load analysis. The designer shall pay close attention to the assessment of fatigue stresses and the fatigue life where resonance and dynamic amplification of motions happen.
Hydrostatic loads	Result of still water pressure acting on the immersed surfaces of a body.
Hydrodynamic loads	Result of stationary and dynamic loads that are caused by water flow and its interaction with the immersed body. Hydrodynamic loads depend on the water kinematics, water density, water depth, the shape of the immersed structure, and hydro-elastic effects. It covers wave loads, current loads, etc. as described in 7.3.2. and Table 2.
Wave loads	Result of interaction of the wave with the structure. A relevant wave theory shall be used to calculate wave kinematics parameters such as water particle velocities and accelerations at MEC components. For submerged components of the MEC, periodic pressure variations from passing waves shall be considered. In the analysis of wave-induced loads, the influence of marine growth and of appurtenances, if not explicitly modeled, shall be considered.
Breaking wave loads	Result of breaking wave impact loads that can lead to dynamic magnification, depending on the duration of the impact relative to the natural period of the structure. In the case where a MEC is installed close to the shoreline, fatigue loading due to breaking waves shall be considered. Since the analysis of breaking wave loads contains many uncertainties, model tests are recommended for the evaluation of the loads. Annex G provides guidance relating to shallow water hydrodynamics and the influence of site characteristics on the nature and dimensions of breaking waves.
Wave slamming loads	Result of passing wave interaction with MEC components. Where structural components of the MEC (e.g. platforms), cannot resist the wave impact, the latter shall be avoided providing sufficient distance between the probable highest wave elevations with a 50-year recurrence period and the lower edge of the MEC component.
Greenwater loads	Result of overtopping of a body of seawater during severe wave conditions. Structural members exposed to greenwater shall be designed to withstand appropriate design head pressures.
Current loads, including river currents	Result of water flowing around a structure producing variable pressures and flow paths. Turbulence may be within the resonant frequencies of structural components of the MEC and impose significant loading on the structure. Due to the vertical velocity profile of the current cyclic bending moments can arise and shall be considered in the design of the MEC where relevant. Cavitation can impose additional loads on the structure and shall be considered. Periodic loading due to passing waves on current may act on the MEC and shall be considered where relevant. The influence of marine growth and of appurtenances on current loads shall be considered. Current loads on mooring lines and other components connected to the structure shall be accounted for in the analysis using appropriate drag coefficients.
Vortex shedding	Dynamic loads determined by the geometry of the structure and the velocity of the currents and waves.
Aerodynamic loads	Quasi-static and dynamic loads that are caused by the airflow and its interaction with the MEC's components above the water surface. Determined by average wind speed, the turbulence intensity, the density of the air and the aerodynamic shape of the MEC's components above the water surface and their interactive effects, including the aero-elastic effects.
Vessel impact	Determined by vessel size, mass, speed, and incident angle. The indirect interaction are typically dominated by the vessel wake, vessel induced velocity and propeller/rudder effects.

Load	Description and design approach
Debris impact loads	Includes fouling from floating debris, such as fishing nets and plastic waste that may include large entrained masses, such as floating logs, chemical debris and fuel slicks.
Array effects	Includes loads from mechanical, mooring or other interconnections between neighboring units, hydrodynamic sheltering and other interaction effects between devices or other structures in proximity.
Seismic loads	Includes direct loads generated by seabed movements and fluid loads caused by the seismically induced fluid motions such as tsunamis.
Topside icing	Includes stability and structural issues caused by icing of the structure above the waterline.
Ice loads	Results from a fast sea or river ice cover and/or dynamic loading caused by wind and current induced motion of ice floes and cause significant fatigue loading.
Construction loads	Includes loads during fabrication, assembly, transportation and installation of the MEC.

7.3 Design situations and load cases

7.3.1 General

For design purposes, the life of a MEC can be represented by a set of design situations covering the various conditions that the MEC may experience. In this subclause the derivation of design load cases is described.

The load case shall be determined from the combination of specific installation, maintenance, and operational modes or design situations with the external conditions. All relevant load cases with the corresponding probability of occurrence shall be considered in conjunction with the behaviour of the control and safety systems.

The design load cases used to determine the structural integrity of the MEC shall be calculated from the following combinations:

- normal design situations and normal external conditions;
- fault design situations when the MEC is operating with a single major system failure and appropriate external conditions;
- normal design situations and extreme external conditions; and
- design situations for transportation, installation, maintenance and decommissioning and the appropriate external conditions.

If any correlation exists between an extreme external condition and a fault situation, a realistic combination of the two shall be considered as a design load case.

7.3.2 Interaction with waves, currents, wind, water level and ice

MECs shall be analysed considering the interaction with waves, currents, wind, water level and ice. Theoretical formulations developed for ships, offshore structures and coastal engineering problems can be used for analysing MECs as per guidance provided in 5.3.

The combination of extreme external conditions shall be performed in a way that results in the global extreme environmental action on the structure with the combined specified recurrence period of 50 years.

If there is no project site information available about the combination of the extreme external conditions, the recurrence periods as stated in Table 3 can be used to derive environmental combinations for a 50-year recurrence period. The adverse directional alignment of wind, waves and currents shall be considered. A worst case directional alignment need not necessarily be the co-alignment of environmental loads and the interaction of wind, current and waves may be relevant.

Table 3 – ULS combinations of uncorrelated extreme events

Environmental combinations	External event and recurrence period (years) to define characteristic value of corresponding load effect					
	Waves	Current	Water level	Wind	Ice	Comment
1	5	5	50	50	–	
2	50	5	50	5	–	
3	5	50 (wind) 18 (tidal)	50	5	–	
4	–	5	MSL	5	50	
5	50	5	50	50	–	For windswell

7.3.3 Design categories

Normal, extreme, abnormal and transport and erection design categories are defined in Table 4.

Table 4 – Design categories

Design category	Design situation
Normal	Normal operation Normal operation plus fault Parked/idling Parked/idling plus fault
Extreme	Parked/idling Parked/idling plus fault Survival Survival plus fault
Abnormal	Earthquake/tsunami Parked/idling plus major fault Survival plus major fault Rare ULS fault conditions Accidental events
Transport and erection	Installation Maintenance Decommissioning

7.3.4 Limit states

7.3.4.1 General

The structural performance of a whole structure or part of it shall be described with reference to a specified set of limit states beyond which the structure no longer satisfies the design requirements. The following limit states shall be considered.

7.3.4.2 Ultimate limit state (ULS)

Ultimate limit state (ULS) places a structure at the cusp of failure, and typically corresponds to the maximum load-bearing capacity. The following failure modes shall be considered when determining the ULS:

- loss of static equilibrium of the structure, or of a part of the structure, considered as a rigid body (e.g. overturning or capsizing);
- failure of critical components of the structure caused by exceeding the ultimate strength (in some cases caused by repetitive actions) or the ultimate deformation of the components;
- transformation of the structural geometry (collapse or excessive deformation);
- loss of structural stability (buckling, etc.);
- loss of station keeping (free drifting); and
- sinking.

7.3.4.3 Fatigue limit state (FLS)

The fatigue limit state, which generally corresponds to the effect of cyclic loading, includes the following states:

- cumulative damage due to repeated loads; and
- reduction of structural integrity beyond safety factor allowance.

7.3.4.4 Serviceability limit state (SLS)

Depending on the design and function, the serviceability limit state is determined by various limiting values that are oriented towards the normally envisaged use. Limits to be observed include:

- deformations or movements that affect the function of structural or non-structural components;
- excessive vibrations producing discomfort for maintenance personnel or affecting non-structural components or equipment (especially if resonance occurs);
- local damage (including cracking) that reduces the durability of a structure or affects the use of structural or non-structural components;
- corrosion that reduces the durability of the structure and affects the properties and geometrical parameters of structural and non-structural components; and
- motions that exceed the limitations of equipment.

7.3.4.5 Accidental limit state (ALS)

The ALS check ensures that local damage or flooding does not lead to complete loss of integrity or performance of the structure.

The intention of this limit state is to ensure that the structure can tolerate specified accidental and abnormal events and maintain structural integrity for a sufficient period to enable evacuation to take place, where necessary.

7.3.5 Partial safety factors

The target safety level for a MEC shall be assumed to be SL2 according to Clause 5 and the probability of failure shall be less than 10^{-4} .

A partial load safety factor γ_f shall take into account the probability of the load occurring and that certain limiting values will not be exceeded with a given probability. γ_f reflects the uncertainty of the loads and their probability of occurrence (e.g. normal and extreme loads), possible deviation of the loads from the characteristic values, plus the accuracy of the load model (e.g. gravitational or hydrodynamic forces). Partial load safety factors are defined for the ULS limit state for design categories in combination with the load sources in Table 5.