SEPS SP-1002

Subsea power transformers

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FOREWORD

The intent of this document is the development of a standard that will be accepted globally. Presently discussions are underway with IEC and IEEE about the possibility of their development of this document into a joint IEC/IEEE standard.

This, document, SEPS-SP -1002, has been compiled and approved by the following members of the SEPS JIP on behalf of their respective companies.

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1 SCOPE

This International Standard is applicable to three-phase and single-phase liquid immersed subsea power transformers (including auto transformers) with at least one winding with rated voltages in the range $3.6 \le U_m \le 145$ kV and with rated power in the range 50 kVA to 100 MVA. The intention is to specify additional requirements that are not covered by IEC 60076 and ANSI/IEEE C57.12 series.

Subsea transformers designed and tested in accordance with this specification shall fulfil both IEC 60076 and ANSI/IEEE C57.12 series with respect to performance and testing. In order to achieve this, the following philosophy has been used:

- Rated power shall be established (verified by testing) both in accordance with IEC and IEEE definitions. Only one figure (based on IEC or IEEE) shall however be on the rating plate, this shall be specified by purchaser in the contract.
- The most stringent design and test requirements are specified in this document, ensuring that both IEC and IEEE requirements are met.

For subsea transformers where no winding has a rated voltage above or equal to 3.6 kV, this standard may still be applicable, either as a whole or in part.

The mechanical design principles are also applicable for liquid-immersed reactors.

Where necessary, the terms Transformer Assembly and Transformer Module are used in this document. Where the terms “subsea transformer” or “transformer” are used, this shall mean Transformer Assembly.

2 NORMATIVE REFERENCES

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60076-1: *Power Transformers. Part 1: General*

IEC 60076-2: *Power Transformers. Part 2: Temperature rise for liquid immersed transformers*

IEC 60076-3: *Power Transformers. Part 3: Insulation levels, dielectric tests and external clearances in air*

IEC 60076-5: *Power Transformers. Part 5: Ability to withstand short circuit.*

IEC 60247: *Insulating liquids – Measurement of relative permittivity, dielectric dissipation factor (tan δ) and DC resistivity*

IEC 60296: *Fluids for electrotechnical applications. Unused mineral insulating oils for transformers and switchgear*

IEC 60422: *Mineral insulating oils in electrical equipment - Supervision and maintenance guidance*

IEC 61800-4: *Adjustable speed electrical power drive systems - Part 4: General requirements - Rating specifications for a.c. power drive systems above 1 000 V a.c. and not exceeding 35 kV*

IEC 61378-1: *Converter transformers-Part 1: Transformers for industrial applications*

ANSI/IEEE PC57.32/DM16.3: *Standard for requirements, terminology and test procedures for Neutral grounding devices*

ANSI/IEEE C57.12.00: *General requirements for liquid-immersed distribution, power and regulating transformers*

ANSI/IEEE C57.12.90: *IEEE standard test code for liquid-immersed distribution, power and regulating transformers*

ANSI/IEEE C57.110-2008: *IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents*

ANSI/IEEE C57.152: *IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors*

API 17F: *Standard for Subsea Production Control Systems*

ASTM D1141 - 98 (2008): *Standard Practice for the Preparation of Substitute Ocean Water*

DNV 2.7.3: *Standard for certification. Portable offshore units.*

EN ISO 288 (series): *Specification and approval of welding procedures for metallic materials*

EN ISO 287-1: *Approval testing of welders. Fusion welding. Part 1: Steels*

EN ISO 15614-1*: Specification and qualification of welding procedures for metallic materials - Welding procedure test - Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloy*

EN ISO 5817: *Arc-welded joints in steel - Guidance on quality levels for imperfections*

EN 1011: *Welding — Recommendations for welding of metallic materials.*

EN 10204: *Metallic products — Types of inspection documents*

EN ISO 21457: *Petroleum, petrochemical and natural gas industries -- Materials selection and corrosion control for oil and gas production systems*

SEPS-SP-1001: *Subsea Equipment - Power connectors, penetrators and jumper assemblies with rated voltage from 3 kV (Umax = 3,6 kV) to 30 kV (Umax = 36 kV)*

ISO 12103-1: *A4: Coarse Test Dust*

NEMA Standards Publication ICS 61800-4-2004: *Adjustable Speed Electrical Power Drive Systems, Part 4: General Requirements—Rating Specifications for a.c. Power Drive Systems above 1000 V a.c. and Not Exceeding 35 kV*

NORSOK M-001: *Materials selection*

NORSOK M-601: *Welding and inspection of piping.*

NORSOK M-650: *Qualification of manufacturers of special materials*

NORSOK M-710: *Qualification of non-metallic materials and manufacturers – Polymers*

3 TERMS, DEFINITIONS AND ABBREVIATED TERMS

For the purposes of this document, the terms and definitions given in IEC 60076-1 and the following apply.

3.1 Terms and definitions

3.1.1

Auxiliary chamber
Chamber where components other than active parts can be installed (NGR, accessories, instrumentation, controls).

3.1.2

Boost factor
Term used to express the magnetic flux margin of a transformer core;

$$BF = \left(\frac{(U/f)_{design}}{(U_r/f_r)} - 1\right) * 100(\%)$$

3.1.3

Cable termination
Device fitted to the end of a cable to ensure electrical connection with other parts of the system and to maintain the insulation up to the point of connection

3.1.4

Cathodic protection
Reduction or prevention of corrosion by making a metal the cathode in a conducting medium by means of a direct current (impressed or galvanic).

3.1.5

Connection chamber
Intermediate chamber between chamber for active parts and external connections.

3.1.6

Connector assembly
Any assembly of wet and/or dry mate connectors, penetrators, cable terminations, cable pigtails or jumper cables between subsea components – or any combination of these

3.1.7

Connector
Fully insulated termination permitting the connection and the disconnection of a cable to other equipment

3.1.8

Differential Pressure
The difference between the two absolute values of pressure that are acting on either side of a wall or partition.

3.1.9

Dry mateable connector
Connector designed to be submerged in sea water, but connected/disconnected in a dry (topside/onshore) environment only

3.1.10

Extended routine test
A test to which each individual transformer is subjected. The test shall be performed with all connector assemblies (that form an integral part of the subsea transformer) installed.

3.1.11

Penetrator
A device that enables one or several conductors to pass through a partition such as a wall or a tank, and insulates the conductors from it. The means of attachment, flange or fixing device, to the partition forms part of the penetrator. Penetrators include bulkhead mounted connector assembly components.

3.1.12

Pressure compensator
Device fitted to a tank that ensures that the internal medium pressure is identical or close to the ambient water pressure.

3.1.13

Rated Absolute Pressure
Maximum absolute pressure that a subsea transformer has been designed to operate at under the specified conditions of use.

3.1.14

Rated Differential Pressure
The maximum differential pressure that a transformer assembly has been designed to operate at under the specified conditions of use. The rated differential pressure for a transformer assembly shall be taken as the maximum pressure difference between the tank inboard side and the outboard side.

3.1.15

Routine test
Definition used in IEC 60076-1 applies.

3.1.16

Transformer Assembly
Assembly consisting of transformer active parts, instrumentation, tank, volume (pressure) compensators and connector assemblies.

3.1.17

Transformer Module
Complete module including (but not limited to): Transformer Assembly, handling/protection structure, shock absorbers/dampers, ROV panels etc.

3.1.18

Type test
Definition used in IEC 60076-1 applies. For instance, increased water depth or different type of penetrators (new interfaces) implies that new type tests shall be performed. Extent of type tests on previously type tested designs is subject to agreement between manufacturer and purchaser.

3.1.19

Wet mateable connector
Connector designed to be submerged in sea water, and can also be connected/disconnected in a submerged condition

3.2 Abbreviated terms

3.2.1

AV
Applied Voltage Test

3.2.2

AV-R
Applied Voltage Test – Reduced level

3.2.3

BF
Boost Factor

3.2.4

CP
Cathodic Protection

3.2.5
CR
Contact Resistance

3.2.6
FEA
Finite Element Analysis

3.2.7
IR
Insulation Resistance

3.2.8
IVPD
Induced Voltage test with Partial Discharge

3.2.9
IVW
Induced Voltage Withstand test

3.2.10
LI
Lightning Impulse

3.2.11
MT
Magnetic Particle Testing

3.2.12
NGR
Neutral Grounding Resistor

3.2.13
PD
Partial Discharge

3.2.14
PI
Polarization Index

3.2.15
PMI
Positive Material Identification

3.2.16

PT
Penetrant testing

3.2.17

RAP
Rated Absolute Pressure

3.2.18

RDP
Rated Differential Pressure

3.2.19

RT
Radiographic testing

3.2.20

ROV
Remotely Operated Vehicle

3.2.21

SFRA
Sweep Frequency Response Analysis

3.2.22

U_m
Highest voltage for equipment

3.2.23

U_r
Rated voltage of a winding

3.2.24

UT
Ultrasonic testing

3.2.25

WPS
Welding Procedure Specification

4 SERVICE, TRANSPORTATION AND STORAGE CONDITIONS

4.1 Normal service conditions

The following service conditions apply

a) Operational water depth:

As specified in the data sheet.

b) Rated frequency:

As specified in the data sheet.

c) Ambient water temperature range: Unless specified differently in the data sheet, the following ambient water operational temperature range shall apply:

-5 to+10 °C

d) Ambient air storage, handling and transportation temperature range: Unless specified differently in the data sheet, the following temperature range shall apply:

-25 to +60 °C

e) Sea water current velocity:

0 m/s

4.2 Transportation, handling and installation requirements

The requirements listed below apply to the transformer module. Unless otherwise agreed between purchaser and manufacturer, the requirements shall also apply to the transformer assembly.

a) Basis of design

DNV standard 2.7-3 shall be the basis for mechanical design of the subsea transformer assembly. Unless otherwise stated in the data sheet, operational class shall be R45-Subsea. Design factor shall be minimum 2.5.

b) Maximum landing speed

0.5 m/s

c) Maximum impact acceleration during landing

1 g

d) Maximum tilting during handling and installation

22 °

e) Minimum inclination during operation

3 °

f) Shock recorders

Acceleration/shock recorders shall be installed for supervision during transport and installation up to the moment of submerging of the subsea transformer.

4.3 Storage

Unless specified differently in the data sheet, the subsea transformer shall be designed for minimum two year storage onshore and for minimum one year storage subsea, in addition to the specified design service lifetime. The manufacturer shall present procedure for operations, handling and preservations required for the storage period.

5 DESIGN ANALYSES

The subsea transformer including accessories (connector assemblies, connection chambers, compensators, ground resistors, instruments etc.) shall be subject to a design analysis covering as a minimum:

- Electrostatic, magnetic, thermal and mechanical finite element analysis, covering type tests and intended operational conditions. The analysis shall verify that the worst case design loads do not exceed electrical, magnetic, thermal or mechanical limitations for any material. The analysis shall include:
    - All modelling assumptions for the FEA and the design
    - Worst case design loads (test, storage, handling, installation/retrieval and operation) including fault scenarios
    - Thermal analysis. The complete transformer shall be analysed and effect of the pressure, any marine growth, calcium deposits etc. shall be taken into account. An ambient water current velocity of 0 m/s shall be used in the thermal analysis. The analysis shall be performed both at the rated power, and at the actual load power (if different) and cover as a minimum:
        - Load-losses due to rms and harmonic currents. The calculation principle of additional losses is presented in the standard IEC 61378-1 (IEEE C57.110).
        - Maximum continuous temperatures of insulating materials and winding temperature rises.
        - Maximum continuous hot spot temperature.
        - Maximum temperatures at the surface of the transformer tank.
        - The thermal analysis shall cover the complete operating range as specified in section 4.1 both with respect to temperature and water depth (pressure).
        - Start-up conditions (with cold oil) shall be addressed separately.
    - Possible nonlinear material properties.
    - The parameters used in the thermal analysis shall be based on measured data for example for viscosity, thermal resistance etc.
    - Mechanical and thermal effects of calcium deposits, marine growth and debris
    - Impact of seismic activity shall be included as specified by the purchaser.

- Design analysis shall include calculations to verify suitability of the pressure compensating system. The analysis shall include test, storage, transportation, installation, retrieval and operational conditions. Any hysteresis shall be included.
- Ability to withstand short circuits. The calculations shall be performed in accordance with IEC 60076-5.
- The material selection, material properties and limitations used in the analysis shall be identified and documented based on qualified, recognized and repeatable fabrication processes. This is also applicable for bonding between materials.
- Description of welding, sealing and corrosion protection, including surface treatment solutions.

6 DESIGN REQUIREMENTS

6.1 Design life time

Unless specified differently in the data sheet, the subsea transformer shall have a design life time of 30 years.

6.2 Rated power

Although rated power of a transformer is defined differently in existing IEC and IEEE standards for topside transformers, a subsea transformer shall be tested only once but shall comply with the power rating of both standards. To accomplish this requirement, the transformer shall be tested at a fundamental frequency to determine the power rating of the secondary windings (in accordance with IEEE requirements) - while simultaneously obtaining the power rating of the primary windings (in accordance with IEC requirements).

While rated power shall be established both for IEC and IEEE definitions, only one nameplate shall be provided. This shall be specified by purchaser in the data sheet (annex B).

The subsea transformer shall be capable of carrying, in continuous service, the rated power under conditions listed in section 4.1 and without exceeding the temperature limits specified in section 6.10.

The temperature rise and the cooling requirements of the transformer in operation shall be determined after allowance is made for any increased losses due to harmonics, ref. IEC 61378-1 and IEEE C57.110.

6.3 Highest voltage for equipment

The values of U_m for the subsea transformer shall be chosen from the standard values of the highest voltage for equipment, as defined in IEC 60076-3 (IEEE C57.12.00)

6.4 Winding insulation

Winding insulation shall be uniform.

6.5 Neutral terminal

Neutral point(s) shall have uniform insulation.

The rated current of the neutral point shall be equal to the rated current of the corresponding transformer windings terminals.

6.6 Tappings

Tappings may be required for tuning of the turns ratio prior to final assembly, as specified in the data sheet. If tappings are installed they shall be realized by means of bolted connections and shall not be changed after sealing of the transformer tank.

6.7 Neutral grounding resistors

If a Neutral Ground Resistors shall be installed, this shall be specified in the data sheet. The NGR shall have the following characteristics.

- The rated voltage shall be equal or higher than the line to neutral voltage of the transformer
- The NGR shall be rated for continuous duty

6.8 Penetrators and connectors

Penetrators and connectors used on the power terminals (including the neutral point connection, as applicable) shall comply with SEPS–SP–1001. Penetrators and connectors for instrumentation and control purposes shall comply with API 17F.

6.9 Transfer of over-voltages and transients

Unless agreed differently between purchaser and manufacturer, there shall be an electrostatic shield between high voltage and low voltage windings to prevent voltage transients being transferred due to capacitive coupling. The electrostatic shield shall be earthed.

6.10 Cooling and Temperature Limits Guaranteed at the Rated Conditions

The following sub-clauses describe additional requirements compared to those stated in IEC 60076-2 and IEC 61378-1.

For converter transformer or in cases where additional losses are present due to harmonic currents, the requirements in IEC 61378-1 (IEEE C57.110) apply.

The temperature limits given in Table 6-1 are valid for transformers with solid insulation designated as class 105 °C according to IEC 60085 and immersed in mineral liquid or synthetic liquid with a fire point not above 300 °C. The limits are valid for both Kraft and thermally upgraded paper.

The temperature limits are applicable to continuous rated power at service conditions as specified in section 4.1.

Table 6-1 – Temperature limits – paper type insulation

Requirements for	Temperature limit [°C]
Top insulating liquid	80
Average winding	85
Hot spot winding	98

If high-temperature materials are used in the insulations, other values may be used. IEC 60076-14 and IEEE C57.12.00 shall then be applied.

The temperature limits refer to steady state conditions under continuous rated power with a sea water temperature not exceeding 5 K above the maximum operating temperature specified in section 4.1 (yearly average).

No numerical limits are specified for the maximum temperatures of magnetic core, bare electrical connections, electrical or magnetic shields and structural parts in the tank. However, it is a requirement that they shall not reach a temperature which will cause damages to adjacent parts or undue ageing of the insulating liquid, or lead to a rapid corrosion increase.

6.11 Magnetic Interference Protection

If the material of the tank is non-magnetic, an extra magnetic internal shielding shall be required. This will prevent EMC issues with adjacent equipment and potential heating issues in external materials.

6.12 Transformer magnetic core

Unless specified otherwise in the data sheet, the transformer core shall be dimensioned for continuous operation at 110 % of rated voltage referred to the principal tapping and rated power. To minimize possible saturation effects of the core steel during operation above rated voltage, the flux density of the core steel without harmonic de-rating shall not exceed 1.8 T (at 110 % of rated voltage). When harmonics are present, the maximum flux density of 1.8 T shall be decreased by the required harmonic de-rating requirement.

All metal parts of the core, frame, tank etc. shall be bonded to earth.

The core sheets of the magnetic circuit of transformers shall be bonded to the core clamping structure.

6.13 Tolerances

The more stringent tolerances as defined in IEC 60076-1 and IEEE C57.12.00 shall apply. Unless specified in the data sheet, the following tolerances apply:

Voltage ratio

Voltage ratio at no load on principal tapping for a specified first pair of windings:

- ± 0.5 % of the specified ratio.

Impedance

Measured short-circuit impedance:

- ± 5 % of the specified value.

Losses

- Total losses (P_0+P_k): +5 %
- Component losses (P_0 and P_k): +10 %, provided that the tolerance for total losses is not exceeded.

No-load current

Measured no-load current:

- + 20 % of the specified value.

6.14 Service and maintenance

The exterior of the subsea transformer shall be suitable for water jetting with ROV.

6.15 Mechanical stresses

Vibrations, tensions and compressions shall not impair the later function or quality of the subsea transformer, during storage, transportation and installation, and also throughout designed service lifetime.

6.16 Tank design

Design of the tank shall include worst case conditions during assembly, oil-filling, transportation/installation and operation. The following factors shall as a minimum be catered for in the design:

- Oil filling. The tank shall be vacuum proof, which is necessary for the liquid filling and degassing processes.
- Internal fault.
- Structural strength during lifting and handling.

A safety factor of minimum 1.5 shall be used both for pressure retaining capability (differential pressure) and structural strength.

6.17 Pressure compensators

Operation area (volume) of the pressure compensator shall cover both storage, transportation installation and operation phase needs in different temperatures, loads and pressures. The structural strength shall be at least 1.5 times the differential design pressure. Withstand for vacuum filling process shall also be covered.

Pressure compensation systems have the following operational requirements:

- Ensure that the pressure of the transformer tank is close to the water pressure on the outside of the tank.
- Supply fluid into the transformer tank during installation when the fluid temperature falls.
- Accumulate fluid from the transformer tank during operation when the fluid temperature rises.

Compensators shall allow minimum 3 bar/minute rate of change.

For pressure compensators that are not available for inspection and cleaning, mud filtering shall be applied at the water inlet.

6.18 Seals

The transformer tank structures with accessories shall meet the following requirements:

a) The subsea transformer including all accessories shall incorporate minimum two water sealing barriers between seawater and electrical conductors/live parts. Each barrier shall be testable during type testing; at least one barrier shall be testable during routine testing.

b) Each sealing barrier shall be separately designed and qualified for continuous exposure to sea water (at required absolute design pressure). Failure of one of the sealing barriers shall not jeopardize the function or integrity of the remaining sealing barrier. The subsea transformer shall be fully functional and operate within its specified electrical requirements with only one seal in operation.

c) A welded metallic static housing is accepted as a sufficient water sealing barrier between external water and live conductors, provided all welds have been subject to full QC inspection, as outlined in section.10.8.3. This is not applicable to dynamic metal housings/seals, such as compensators, where two water sealing barriers are required.

d) Seals shall be qualified for continuous subsea operation for all operating conditions.

e) Materials used shall be compatible with all applicable interfacing materials and liquids, also if one sealing barrier should fail.

The use of test ports / filling ports for testing of seals should be minimized. Where test penetrations are introduced, careful consideration shall be made in order not to introduce new potential leakage paths and reduce the main seals integrity level. Seal test ports shall be plugged and sealed after use.

7 MATERIAL REQUIREMENTS

7.1 General material requirements

a) The subsea transformer including accessories shall comprise materials and components which are qualified and suitable for relevant equipment, applications and environments for the life time of the product. The subsea transformer including accessories shall be compatible with relevant fluids/materials as per operational requirements, throughout design service life

b) A materials selection report shall be prepared and presented to the purchaser, before construction of the subsea transformers.

c) Manufacturers of 22 Cr, 25 Cr duplex and 6 Mo steel alloys shall be pre-qualified according to Norsok M-650.

7.2 Material certification

a) All transformers shall have traceable manufacturing records to allow identification and subsequent rectification of defects after delivery. Manufacturing records and test results shall be traceable to each assembly by a unique identifier (e.g product serial number).

b) For seawater wetted materials and materials used in load bearing constructions (structural, differential pressure, fasteners, etc.), individual traceability and marking shall be provided. For all other components, batch traceability is permitted. For batch traceability, it is not necessary to individually mark each component but a record shall be provided showing where each batch of components has been used against the unique identifier (serial number) for the final assembly.

c) Certificates of conformity for metallic components shall be supplied with the product according to Type 3.1 of EN 10204. Records shall be retained by the manufacturer for 10 years

d) The composition of all corrosion resistant alloys and titanium alloys components including fasteners shall be verified by positive material identification (PMI) according to the manufacturer's procedure. The PMI shall be performed as late as possible in the assembly process and the result documented.

e) All testing and traceability documentation shall be available for review upon request.

f) Additional certification requirements beyond the above requirements are subject to agreement between purchaser and manufacturer.

7.3 Tank material

The material should be selected according to ISO 21457. Subsea transformer tank and components shall be electrically connected with the corrosion protection system or have a separate dedicated corrosion protection system. After assembly, the electrical continuity shall be measured and documented. Unless agreed differently by purchaser and manufacturer, the following requirements apply:

- The tank shall be cathodically protected and coated.
- Materials for sealing faces for non-pressure compensated enclosures shall be a seawater resistant alloy with PREN > 40.
- Materials for sealing faces for pressure compensated enclosures shall be made of 316 SS or a more corrosion resistant alloy.
- Sealing faces shall be cathodically protected

- Sealing faces in alloys with PREN < 40 and other surfaces that rely on cathodic protection shall be properly preserved to avoid pitting corrosion during fabrication, transportation and storage.

7.4 Dielectric Liquid

The following aspects shall as a minimum be addressed when selecting the dielectric fluid:

- Compatibility with the transformer internal materials. The materials used shall not compromise the thermal and electrical properties of the liquid.
- Cooling properties; the cooling characteristics at the service conditions specified in section 4.1 shall be addressed. The effects of both pressure and temperature shall be evaluated in the thermal analysis.
- Liquid density relative to water, such that potential migration and/or ingress of water do not gather in critical areas within the subsea transformer.
- Liquid properties in the transformer factory shall be monitored by the standardized tests in accordance with the applicable IEC/IEEE standards for the selected fluid. The following characteristics shall in particular be addressed: dielectric strength, water susceptibility/saturation, cleanliness, drying, dissolved gas etc.
- If an inhibited mineral oil is used, this shall:
    - Comply with IEC 60296, edition 4, basic requirements for inhibited oils in table 2 *and* the special requirements in section 7.1 *or* ASTM D 3487, type II
    - Test as non-corrosive in accordance with both IEC 62535 *and* ASTM D 1275 method B

8 INSTRUMENTATION AND MONITORING

8.1 General requirements

If instrumentation and monitoring is required by purchaser then this should preferably be raised at an early stage and specified in the data sheet.

Any penetrations into the transformer tank increase the risk of leakages, thus minimum number of penetrations is recommended. All assembled equipment shall be qualified and proven for the specified operational conditions.

Failure of any part in the instrumentation/monitoring system shall not lead to a reduction in the transformer functionality.

Some possible monitoring functions are discussed in the following sections.

8.2 Pressure compensator position

It shall be possible to visually inspect the external pressure compensator position by means of ROV. If visual inspection cannot be achieved, and if agreed between purchaser and manufacturer, a position sensor can be used instead.

8.3 Liquid Temperature

Transformers liquid temperature can be monitored through liquid pocket with embedded temperature element, e.g. PT100. The effect of the sensor housing, mounting flange etc. on the temperature measurement (when submerged) must be known and the instrument calibrated for this condition.

NOTE: Monitoring by ROV camera and removing marine fouling when necessary by jetting the external surfaces will also provide good trace on external cooling operation without instrumentation.

8.4 Winding Temperature

For temperature rise type tests, fiber optic temperature sensors can be installed inside the windings. Unused fiber optic penetrations shall be sealed off by welding after the test.

8.5 Water Penetration Monitoring

A sensor which is able to monitor water leakage (or humidity) into the tank may be installed. Device installation requires a penetration for the output signals and for possible power input.

8.6 Pressure monitoring

A sensor which is able to monitor pressure may be installed. Pressure build up can be a result of pressure compensators reaching their capacity limit or mechanical jamming, or due to transformer internal electrical faults. Sudden differential pressure is an indication of internal fault.

8.7 Transformer Insulation Monitoring

Insulation monitoring system can be installed for continuous monitoring of system insulation condition.

8.8 Voltage and Current Measurements

Internal voltage and current transformers may be specified for measurement and protection purposes.

9 RATING PLATE

The rating plate shall be in accordance with IEC 60076-1 (IEEE C57.12.00) and IEC 61800-4 (NEMA ICS 61800-4) for converter transformers with the following additional data:

- Type of transformer – Subsea Transformer
- Governing standard (IEC 60076 or IEEE C57.12.00)

- Maximum system- short-circuit power or current used to determine the transformer withstand capability if not infinite.
- A short notation of insulation levels (withstand voltages) as described in IEC 60076-3.(IEEE C57.12.00)
- Vacuum withstand capability of the tank and pressure compensators.
- Minimum ambient water temperature
- Maximum ambient water temperature
- Boost factor, as applicable
- Maximum lifting and submersion speed
- Maximum temperature rise (top oil)
- Total mass, including oil.
- Mass and type of insulating liquid(s), with reference to relevant IEC or IEEE standard

10 TESTING

10.1 General Requirements

The general test requirements in IEC 60076-1, IEEE C57.12.00 and IEC 61378-1 apply with additional requirements as stated herein. Where possible, the relevant IEC and/or IEEE standard is referenced; where specific test requirements apply, they are listed in this standard.

If type tests of identical units already exist, the manufacturer shall provide test protocols to the purchaser.

As a part of the type testing, dismantling and examination should be performed when deemed necessary.

Sensors, as required, shall be included in the test setup, to monitor the applicable parameters, e.g. pressures, temperatures and electrical performance. Sensors should also enable measurements of differential pressures between pressure compensated areas and pressure compensator.

All measuring systems used in the tests shall have certified, traceable accuracy and be subjected to periodic calibration, according to the rules of 7.6 of ISO 9001.

Dielectric tests shall be repeated for a transformer that has been refurbished or repaired, unless agreed otherwise between manufacturer and purchaser.

10.2 Artificial Seawater Requirements

For tests performed in artificial sea water, the following requirements shall be met:

- Artificial sea water shall be according to ASTM D1141-98.

- Salinity shall be approx. 35000 ppm (sea salt plus mains water) containing approximately 1.5 % by weight sand and silt.
- The particle size distribution shall be according to ISO 12103-A4, Coarse test dust.
- The composition and temperature of the sea water shall be established, recorded and verified prior to testing, and circulation shall be provided and maintained during testing.

10.3 Test voltage levels

Test voltage levels shall be in accordance with Table 10-1 – Test voltage levelsTable 10-1.

Table 10-1 – Test voltage levels

Highest voltage for equipment winding U_m [kV]	Full wave lightning impulse (LI) [kV]	Applied voltage (AV) [kV]	Applied voltage reduced level (AV-R) for extended routine tests [kV]
3.6	40	10	4.5
7.2	60	20	9
12	95	28	15
17.5	95	38	22
24	145	50	30
36	170	70	45
52	250	95	65
72.5	325	140	90
100	450	185	
123	550	230	160
145	650	275	190

10.4 Type tests

10.4.1 Type tests for new transformer designs

Component type testing.

a) Material and component testing (10.8.2)
b) Fabrication and welding (10.8.3)
c) Helium leakage control test (10.8.5)
d) Leak testing with pressure for liquid immersed transformers (10.8.6)
e) Pressure deflection tests for liquid immersed transformers (10.8.7)
f) Vacuum tightness test (10.8.8)
g) Vacuum deflection test (10.8.9)
h) Long term pressure cycling of pressure compensators (10.8.10)
i) Oil sample tests (10.8.4)

j) Tests of Neutral Grounding Resistor (10.8.20)

Active parts type tests (without connector assemblies):

k) Measurement of winding resistance (IEC 60076-1/IEEE C57.12.90)

l) Measurement of voltage ratio and check of phase displacement (IEC 60076-1/IEEE C57.12.90)

m) Measurement of short-circuit impedance and load loss (IEC 60076-1/IEEE C57.12.90)

n) Measurement of no-load loss and current at 90 %, 100 % and 110 % of rated voltage (IEC 60076-1/IEEE C57.12.90)

o) Measurement of DC insulation resistance between each winding to earth and between windings (10.8.12)

p) Measurement of Polarization Index (10.8.13)

q) Measurement of boost factor (10.8.14)

r) Dielectric routine tests (10.8.15)

s) Check of the Ratio and Polarity of Built in Current Transformers (IEC 60076-1/IEEE C57.12.90)

t) Determination of capacitances of windings-to-earth, and between windings (IEC 60076-1/IEEE C57.12.90)

Assembled subsea transformer type tests (including connector assemblies):

u) Extended routine tests (10.8.16)

v) Temperature rise test in air (10.8.18)

w) Temperature rise test in water (10.8.17)

x) Winding hot spot temperature rise measurements (IEC 60076-1)

y) Extended routine tests (10.8.16)

z) Oil sample tests (10.8.4) [Note 1]

aa) Determination of weight of transformer by measurement

Note 1: When to perform the oil sample tests after testing, is subject to agreement between purchaser and manufacturer

10.5 Routine tests for all transformers

Component routine tests:

a) Fabrication and welding (10.8.3)

b) Helium leakage control test (10.8.5)

c) Leak testing with pressure for liquid immersed transformers (10.8.6)

d) Pressure deflection tests for liquid immersed transformers (10.8.7)

e) Vacuum tightness test (10.8.8)

f) Vacuum deflection test (10.8.9)

g) Oil sample tests (10.8.4)

Active parts routine tests (without connector assemblies):

h) Measurement of winding resistance (IEC 60076-1/IEEE C57.12.90)

i) Measurement of voltage ratio and check of phase displacement (IEC 60076-1/ IEEE C57.12.90)

j) Measurement of short-circuit impedance and load loss (IEC 60076-1/IEEE C57.12.90)

k) Measurement of no-load loss and current at 90 %, 100 % and 110 % of rated voltage (IEC 60076-1/IEEE C57.12.90)

l) Measurement of DC insulation resistance between each winding to earth and between windings (10.8.12)

m) Measurement of Polarization Index (10.8.13)

n) Measurement of boost factor (10.8.14)

o) Tests of Neutral Grounding Resistor (10.8.20)

p) Dielectric routine tests (10.8.15)

q) Check of the Ratio and Polarity of Built in Current Transformers (IEC 60076-1/ IEEE C57.12.90)

r) Functional test of monitoring devices

Assembled subsea transformer routine tests (including connector assemblies):

s) Extended routine tests (10.8.16)

t) Temperature rise test in air (10.8.18)

u) Winding hot spot temperature rise measurements (IEC 60076-1)

v) Extended routine tests (10.8.16)

w) Oil sample tests (10.8.4) [Note 1]

x) Functional test of monitoring devices

y) Determination of weight of transformer by measurement

Note 1: When to perform the final oil analyses in the test sequence is subject to agreement between purchaser and manufacturer.

10.6 Additional type and routine tests for transformers with U_m > 72.5 kV

a) Determination of capacitances of windings-to-earth, and between windings (IEC 60076-1/ IEEE C57.12.90)

b) Measurement of dissipation factor (tan δ) of the insulation system capacitances.

10.7 Special tests

Special tests or other tests than listed below shall be specified by purchaser in the data sheet. If the test methods are not prescribed in IEC 60076-1 / IEEE C57.12.90 then such test methods are subject to agreement.

a) Dielectric special tests (IEC 60076-3)
b) Short-circuit withstand test (IEC 60076-1/IEEE C57.12.90)
c) Determination of capacitances of windings-to-earth, and between windings (IEC 60076-1/ IEEE C57.12.90)
d) Measurement of dissipation factor (tan δ) of the insulation system capacitances
e) Measurement of zero sequence impedance(s) on three phase transformers (IEC 60076-1)
f) Check of external coating (ISO 2178 and ISO 2409 or as specified)
g) Mechanical test or assessment of tank for suitability for transport (to customer specification)
h) SFRA (sweep frequency response analysis) test (IEC 60076-18/ IEEE C57.149)
i) Determination of magnetization characteristic and core saturation inductance. Magnetization characteristics and core saturation inductance may be important parameters in some network analyses (e.g. energization studies). Magnetization characteristic may be calculated from an extended measurement of no-load loss and current specified in 10.5 k). The following data are necessary:

   i. Measurement of no-load loss and current at least at 80%, 90%, 100%, 110% and 115% of rated voltage (IEC 60076-1/IEEE C57.12.90). The following data shall be recorded:

      - True-rms and average-responding rms-calibrated voltage readings
      - True-rms and peak value of current
      - No-load losses (waveform corrected)
      - Digital recording of voltage and current waveforms

      The terminal magnetization characteristic flux-linkage/current-peak (λ-i) shall be obtained from the recorded average-responding rms-calibrated voltage readings $\left(\lambda = \frac{\sqrt{2}}{\omega} \cdot V_{AVG}\right)$ and recorded peak value of current.

   ii. Saturated inductance shall be calculated by manufacturer. When a manufacturer has no established method for calculation of the saturated inductance, following[1,2] or equivalent equations may be used: $L_{sat-HV} = \mu_0 \cdot N_{HV}^2 \cdot \frac{A_{HV}}{h_{HV}/K_R}$ with K_R the Rogowski factor (<1.0) based on manufacturer know-how and A_{HV} the area inside the mean turn of the excited winding.

   Additional recommended data:

   iii. Type and catalogue data (B-H curves) of magnetic material, rated flux density in T, number of turns and geometric dimensions of core limbs (lengths and cross section area) and windings (height and inner/outer diameters).

[1] S.V. Kulkarni, S.A. Khaparde, *Transformer Engineering : Design, Technology, and Diagnostics*, 2nd Ed, CRC 2012
[2] J. A. Martinez-Velasco, *Power System Transients: Parameter Determination*, CRC 2009.

10.8 Test procedures

10.8.1 General

This section describes the procedures for tests that are not described in details in the IEC / IEEE standards.

10.8.2 Material and component testing

10.8.2.1 General requirements

Type testing of new materials, new combination of materials or bonding between materials shall be performed. New is defined as a new material grade or materials not used in similar equipment, application and/or environment. The type test programme and acceptance criteria shall be agreed between manufacturer and purchaser. This testing also covers polymeric materials. A change in polymer material or in seal design shall require a new type test.

NORSOK M-001 should be used as a reference standard for materials selection and testing.

10.8.2.2 Polymeric materials test requirements

The following requirements are applicable to polymeric materials:

- Compatibility shall be documented according to those requirements and the test methodology given in NORSOK M-710, Qualification of non-metallic sealing materials and manufacturers.
- Testing of polymeric materials shall also include seal ability testing in relevant fluids or gas. Testing of this kind should be done in the actual seal/gland geometry and size, to ensure that sealing is adequate for the required functionality.
- For insulation materials, electrical properties shall be verified also after ageing tests. (Breakdown strength, volume resistivity, tan δ etc.)
- New non-metallic sealing and barrier materials, new combination of materials or bonding between materials shall be tested and qualified to prove the ability to withstand the thermal, electrical and mechanical stresses it may be exposed to. The test programme should typically include, but not be limited to, the following:
    - Compatibility tests
    - Sealing test
    - Long term diffusion characteristics, to demonstrate acceptable diffusion rates (e.g. compensator bladder materials)
    - Disc bursting tests (for insert moulding materials, e.g. epoxy)
    - Mandrel test for boot seals. The mandrel test shall be performed at the same test conditions as the general ageing test (temperature, fluid, duration etc.)
    - Bonding tests
- For non-metallic materials, the compatibility test programme and acceptance criteria shall, in general, be based on NORSOK M-710 (Annex A and C). All acceptance criteria shall be defined prior to the commencement of testing, be based on operational

knowledge of the equipment, and shall be agreed between all parties prior to testing taking place.

Testing performed to other standards than mentioned above may be acceptable, based on comparative qualification between the applicable standards. Due to material selection it may be appropriate to perform testing to other standards.

10.8.2.3 Component hyperbaric testing

The objective of the tests is to ensure that the internal components of the subsea transformer assembly and its internal accessories (e.g. oil, windings and insulation materials, support materials, CTs, VTs, NGRs etc) are able to withstand the hydrostatic pressure, and a number of installation/retrieval cycles without degradation or damage – and that acceptable characteristics are maintained at pressure. Actual components or scaled test structures may be used in the test.

The outline test specification and sequence are as follows:

a) Establish electrical/magnetic/mechanical characteristics (dielectric, dimensions, IR etc.) before pressure cycling
b) Pressure cycling x 20 (from atmospheric pressure to 1.1 x RAP)
c) Establish electrical/magnetic and mechanical characteristics at pressure, 1.1 x RAP.
d) Electrical/magnetic/mechanical characteristics after pressure cycling, including visual inspection, dissection etc.

Pressurization and depressurization rate should be minimum 3 bar/min and maximum 6 bar/min. Hold time after each pressurization or depressurization shall be minimum 30 minutes. Other testing parameters may also be used, if agreed between the manufacturer and purchaser.

The properties to be measured before, at and after pressure cycling depend on the function of the component and material characteristics. Detail test procedure shall be agreed between manufacturer and purchaser.

<u>Acceptance criteria</u>: The properties of the components shall remain within specification and the functionality maintained. Any degradation or damages shall be noted, and explanation given as to why performance and life time is not affected. Detail criteria to be agreed between manufacturer and purchaser.

10.8.3 Fabrication and welding

Fabrication shall follow the following requirements:

- Fabrication and welding shall be in accordance with the recommendations given in relevant parts of EN 1011.
- Welding Procedure Specifications (WPS) shall be established and qualified for all welding. The WPS shall contain the information specified in EN ISO 15614.

- Welding procedures for duplex stainless steels and SS 6Mo shall be qualified in accordance with EN ISO 15614 with the additional requirements of NORSOK M-601, Sections 4 and 5, and requirements to oxidation levels in paragraph 6.6.
- Charpy impact testing shall be included in procedure qualification for welding of impact tested materials. The impact testing shall be carried out at -20°C (lower temperatures are acceptable). Requirements shall be according to selected material specification but the minimum average value shall not be lower than 27 J with a minimum single energy value of 20 J for full size test specimens.
- All welds shall be continuous. Fillet welds shall be double side welded to avoid corrosion. Single side fillet welds may be acceptable (e.g. for covers), provided agreement between purchaser and manufacturer.

Inspection and NDT shall be according to the design code. The extent of testing shall be as follows:

- 100% visual inspection of all welds.
- 10% RT of butt welds.
- 100% MT/PT of corner joints and butt welds in tank plates.
- 100% MT/PT of nozzle and reinforcing pad welds.
- 100% UT (full penetration welds).
- 10% MT/PT of plate/stiffeners connections.

The transformer tank shall be subject to a pressure test after fabrication, prior to further assembly work; 0.5 bar overpressure by pressurized air - hold for 12 hours.

10.8.4 Oil sample tests

An oil sample shall be obtained (IEC 60475) before and after transformer dielectric tests. Oil sample testing is performed for “before and after” comparison and also for benchmarking for future maintenance comparisons. When to perform the “after” samples in the test sequence may depend on transformer design and shall be agreed between purchaser and manufacturer.

IEC 60422 shall be used as guidance for most of the tests. The following indicates the required transformer oil tests:

- Water (moisture) – IEC 60814 (ASTM D1533)
- Neutralization Number (Acidity) – IEC 62021-1 and IEC 62021-2 (ASTM D974)
- Interfacial Tension – EN 14210 (ASTM D971)
- Specific Gravity – ASTM D1298
- Visual – ASTM D1524
- Dielectric Breakdown Voltage – IEC 60156 (ASTM D1816)
- PCB – IEC 61619 (ASTM D4059)
- Dissolved Gas Analysis (DGA) – ASTM D3612 (Complete Method)

- Corrosive Sulphur – IEC 60296 Annex A, IEC 62535, IEC 62697-1 (ASTM D1275-B)
- Oil DC resistivity at 20 °C and 90 °C - IEC 60247
  Note: Acceptance criteria for oil DC resistivity at 20 °C and 90 °C shall be set at:
  - Minimum 80 GΩ m after filling prior to energization at component type tests and routine tests
  - Minimum 60 GΩ m after type tests and routine tests for assembled subsea transformers (including connector assemblies). If it is planned to carry out Site Integration Test (SIT) and if an oil sample test has been specified, this criterion shall also be used.

10.8.5 Helium leakage control test

10.8.5.1 General

The objective of the helium leakage control test is to verify that the external equipment connected to the tank, welded seams and all sealing barriers are correctly fitted during assembly and do not leak. Also the required two independent sealing barriers shall be tested during assembly, where a helium leakage control test shall be carried out to verify the intended sealing functions.

The test procedure shall be supported with drawings where each sealing barrier is defined.

Maximum pressure in the vacuum side chamber during the test is 1 mbar (=100 Pa).

The vacuum technique as outlined in section 10.8.5.2 shall be used for tightness control tests.

If the outer tank of the double shell double barrier structure can withstand 1.0 bar over and under-pressure but the inner tank alone is not capable, a special reduced pressure difference method called "*Differential pressure method*" in section 10.8.5.3 shall be used. In this case, the inner tank is tested inside the structure.

Note: Correct use of Helium vacuum techniques will reveal a single seal leakage almost immediately, after a short period of Helium purging (typically << 1 min). If Helium is exposed for longer periods (typically > 5 min.) diffusion through soft materials (seals, membranes, non-metallic parts) may take place - which would then complicate the interpretation of test results. The test procedure should cater for diffusion effects, and the test equipment supply/return lines should be short – contributing to a successful test performance. When testing across a double/multi seal barrier or double/multi string welded seam, a leak indication will be delayed - and it could be very difficult to discriminate a leak from diffusion. E.g. Helium leak test for double metal wall bellow of the pressure compensator has to endure in the level of one hour to make sure that the possible two serial small leaks can be detected.

10.8.5.2 Vacuum technique

Helium shall be applied so that it swamps one, higher pressure side of the sealing barrier/wall of the tank (or /pressure compensator) to be tested. Helium leakages shall be sensed on the other lower pressure side of the sealing barrier /wall of the tank (or /pressure compensator) with Helium leak detector including typically a mass spectrometer - having an accuracy minimum detectable leak rate better than $1 \cdot 10^{-9}$ mbar·l/s Temperature and pressure shall be continuously recorded.

An outline procedure/sequence should be as follows:

- Connect the test equipment on one side of the sealing barrier/wall of the tank (or pressure compensator) to be tested, and let the test equipment run until the background helium level indication is stable - and low enough to allow reading in the acceptance criteria range.
- Purge helium systematically at the other side of the sealing barrier/wall of the tank (or pressure compensator) to be tested, where it shall be assured that helium fully surrounds each seal or wall.
- The mass spectrometer helium leak rate before and after each purging shall be recorded.

The outer tank of a double shell structure (as well as the tank of a single shell structure) shall be tested in a tight test room or plastic canopy or by building extra cabinet around the tank. This surrounding is filled by Helium at the normal air pressure and vacuum inside the tank is preserved by vacuum pumps running for the test period for minimum 30 min. Leak detector as well as vacuum in the tank are monitored during the test. The inner wall will be tested by filling the inner tank by helium respectively.

Acceptance criteria: The leak rate reading shall not increase with more than $5\ 10^{-8}$ mbar l/s during the test.

10.8.5.3 Differential pressure technique

By means of the differential pressure method the test can be made for double shell double barrier structure with a weakened inner tank by utilizing the vacuum proof outer tank and only pressure difference between the outer tank and the inner tank which is not fully vacuum-proof.

Inner tank can be tested by sucking vacuum to both of the tanks simultaneously and then increasing the over-pressure in the inner vessel to the acceptable level (for instance, 20-30 kPa) by inserting Helium gas into it. Then keeping the pressure difference for minimum 30 min, the leak shall be measured in the outer tank.

The acceptance criteria shall be based on a documented analysis for each case/design solution that is tested. The leakage rate reading shall not increase with more than above $1 \cdot 10^{-5}$ mbar·l/s during the test.

10.8.6 Leak Testing with Pressure for liquid immersed transformers

The test is applicable to the transformer tank(s) and is described in IEC 60076-1 (IEEE C57.12.90). The following additional requirements apply:

The pressure test shall be made on the outer tanks.

For testing of the inner tank in a double shell transformer design, a test pressure of at least 1.5 x RDP (when the compensator(s) is/are maximum expanded) shall be applied.

An overpressure test after sealing shall be performed. For practical reasons, this design pressure shall not exceed twice the maximum operational differential (if not defined, 1 bar + ambient shall be used) overpressure for pressure compensated areas of large volumes.

Acceptance criteria: No leakage shall occur during and after the test is completed.

10.8.7 Pressure deflection test

The test is applicable to the transformer tank(s) and shall be performed in accordance with IEC 60076-1 (IEEE C57.12.00?).

10.8.8 Vacuum tightness test

The test is applicable to the transformer tank(s) and shall be performed in accordance with IEC 60076-1 (IEEE C57.12.00?).

Acceptance criteria: The increase in pressure shall be less than 1 mbar per hour measured over a period of at least 60 minutes

10.8.9 Vacuum deflection test

The test is applicable to the transformer tank(s) and shall be performed in accordance with IEC 60076-1 (IEEE C57.12.00).

10.8.10 Long term pressure cycling of pressure compensators

The objective of the tests is to ensure that the pressure compensator is able to withstand long term service at operational conditions, without leakage, degradation or damage. The following sequence of tests shall be used:

a) Helium leakage test before (10.8.5)
b) Liquid quality parameters: sampling and analyses (10.8.4)
c) Definition of volume - pressure –curve
d) Cyclic endurance tests, ref Table 10-2
e) Liquid quality parameters: sampling and analyses (10.8.4)
f) Helium leakage test after (10.8.5)

The pressure compensator structure shall separately undergo an endurance test, where the number of cycles shall represent the total prospective number of cycles during the design life of the subsea transformer. The cases as specified in Table 10-2 shall as a minimum be represented in the test cycle profile and performed in the given sequence. V_{min} and V_{max} represent the lower and upper volumetric limits for each cycle, where -100 % and +100 % are the maximum compression and maximum expansion respectively.

Test conditions shall be as representative as possible for the actual operating conditions. For very large pressure compensators, representative scale models may be used for pressure cycle testing.

Table 10-2 – Pressure cycles

Case	No cycles	Pressure	V_{min} (%)	V_{max} (%)	Comment
1	120	Atm.	-100	-30	Onshore storage, low temperature
2	125	Atm.	-30	+30	Onshore storage, middle temperature
3	120	Atm	+30	+100	Onshore storage, high temperature
4	10	RAP	-60	+40	
5	2000	RAP	-30	+20	
6	10	RAP	-60	+40	
7	1000	RAP	-60	-10	
8	10	RAP	-60	+40	
9	1000	RAP	-30	+20	
10	10	RAP	-60	+40	
11	1000	RAP	-10	+40	
12	10	RAP	-60	+40	
13	1000	RAP	-30	+20	
14	10	RAP	-60	+40	
15	1000	RAP	-60	-10	
16	10	RAP	-60	+40	
17	1000	RAP	-30	+20	
18	10	RAP	-60	+40	
19	1000	RAP	-10	+40	
20	10	RAP	-60	+40	
21	2000	RAP	-30	+20	
22	10	RAP	-60	+40	

Cases 1-3 shall be performed at the corresponding ambient temperatures (minimum, nominal, maximum).

The speed of the operation cycle is dependent on the characteristics of the compensator and testing facilities and shall be agreed between manufacturer and purchaser.

Acceptance criteria:

- Successful helium leakage tests
- Water-in-oil content and electrical characteristics of the liquid samples shall comply with the requirements listed in section 10.8.4.
- No mechanical breaks and leaks
- No jamming of the moving parts
- Correct operation of the flexible structure parts.

10.8.11 Measurement of winding resistance

The test described in IEC 60076-1 (IEEE C57.12.90) applies.

Acceptance criteria: The measured winding resistance shall be within ±3 % of the calculated winding resistance

10.8.12 Measurement of DC insulation resistance between each winding to earth and between windings

The test described in IEEE C57.12.90 and IEEE C57.152 applies with the following additional requirements:

- The test shall be performed in dry conditions only.
- The test voltage shall be increased in steps of 500 V until the maximum test voltage, 5000 V. Insulation resistance shall be measured at each point and a graph prepared.
- The insulation resistance measurements shall be performed with 5000 VDC
- The insulation resistance shall be recorded after 1 and 10 minutes

Acceptance criteria: IR ≥ 500 MΩ after 10 min

10.8.13 Measurement of Polarization Index

The test procedure for the measuring the polarization index is the same as described in section 10.8.12. This test shall be combined with the DC insulation resistance measurement test.

The PI shall be calculated as the ratio of the 10 minute insulation resistance value (IR) to the 1 minute insulation resistance value, as follows:

$$\text{PI} = \frac{IR_{10}}{IR_1}$$

Acceptance criteria: Polarization index ≥ 1.5 as per IEEE C57.152

10.8.14 Measurement of boost factor

This test is performed to verify transformer boost factor and that core saturation does not occur during testing and operation. The test may be performed with reduced test voltage and test frequency, if testing with rated values is not possible. The test voltage shall then be calculated as follows:

Test voltage = $(1+\frac{BF\%}{100})*U_r*\frac{f_{test}}{f_r}$ where

BF = Boost factor
U_r = Rated voltage of a winding developed at no-load
f_{test} = Test frequency
f_r = Rated frequency

The test should be performed on the LV winding and the test setup can be the same as for the "measurement of the no-load loss and current tests" as per IEC 60076-1.

Measurements shall at least be performed at:

BF = 0 %
BF = Minimum % as per data sheet

No load current and losses shall be recorded as given in IEC 60076-1/IEEE.C57.12.90 (Measurement of no-load loss and current).

A graph showing the boost factor as a function of the no load current (I_0) shall be provided.

Accept criteria: The transformer core shall not saturate during the testing

10.8.15 Dielectric routine tests

The tests described in IEC 60076-3 (IEEE C57.12.90) apply with the following additional requirements:

- Partial Discharge (PD) tests shall be performed before and after the lightning impulse tests.
- The IVPD test substitutes the IVW test (induced voltage test) with an enhancement test voltage level of $\frac{2U_r}{\sqrt{3}}$, refer to IEC 60076-3 section 7.3.1.3.

  In some special cases the value of Ur may be considerable lower than Um. This usually occurs when the highest voltage equipment Um is one voltage class higher than the maximum rated voltage of the winding Ur. In these cases the enhancement and PD measurement test voltage levels (phase to earth) shall be $\sqrt{3}\frac{U_m}{\sqrt{3}}$ and $\frac{\sqrt{3}}{2}U_m$ respectively.
- Voltage test levels for LI and AV tests are specified in 10.3

	$U_m \leq 72.5$ kV	72.5 kV $\leq U_m \leq$ 145 kV
Full wave lightning impulse test for the line terminals (LI)	Routine	Routine
Chopped wave lightning impulse test for the line terminals (LIC)	Special	Special
Lightning impulse test for the neutral terminals (LIN)	Routine	Routine
Switching impulse test for the line terminals (SI)	N/A	Special
Applied voltage test (AV)	Routine	Routine
Induced voltage test with PD measurements (IVPD)	Routine	Routine
Line terminal AC withstand voltage test (LTAC)	N/A	Special
Auxiliary wiring insulation test (AuxW)	Routine	Routine

The dielectric tests should be performed in the following order:

a) Partial discharge (PD) test (10.8.19)

b) Full wave lightning impulse test for line terminals (LI) (IEC 60076-3)

c) Lightning impulse test for the neutral terminals (LIN) (IEC 60076-3)

d) Partial discharge (PD) test (10.8.19)

e) Applied voltage test (AV) (IEC 60076-3)

f) Induced voltage withstand test with PD measurements (IVPD) (IEC 60076-3)

g) Auxiliary wiring insulation test (AuxW) (IEC 60076-3)

If dielectric tests must be repeated for a transformer that has been in service, then the dielectric tests shall be repeated at the test levels of 100 % of the original value.

10.8.16 Extended routine tests

The extended routine tests shall be performed after assembly of all permanent penetrators, connectors and cables, forming an integral part of the subsea transformer. Unless otherwise agreed between manufacturer and purchaser, the following tests shall be performed:

a) Measurement of winding resistance (IEC 60076-1)
b) Measurement of DC insulation resistance between each winding to earth and between windings (IEC 60076-1)
c) Applied voltage test (AV-R) – reduced level (IEC 60076-3, for test levels refer to section 10.3 in this document)
d) IVPD test (IEC 60076-3)
e) Measurement of frequency response (IEC 60076-1) – for ASD applications only.

10.8.17 Temperature rise test in water

10.8.17.1 Temperature Limits

The temperature limits given in 6.10 apply.

The test pool, where the subsea transformer is submerged during the test, shall be dimensioned so that the temperature of the cooling outside water does not rise significantly and cause disturbing flows or other phenomena. The water temperature shall be stable (max 1 °C change/hr) and maximum 20 °C.

Temperature rise tests shall include in-oil dissolved gas analysis (see Annex D in IEC 60076-2).

If the temperature rise test of full scale transformer cannot be performed in relevant operating sea water temperature, relevant model tests shall be performed in order to estimate reliable power rating and temperature figures for the relevant operating temperatures.

10.8.17.2 Temperature Rise Test Procedure- in water

The tests shall be carried out with short-circuit load method described in the standard IEC 60076-2 (IEEE C57.12.90).

For converter transformer or in cases where additional losses are present due to harmonic currents, the requirements in IEC 61378-1 (IEEE C57.110-2008) applies.

Losses due to current in Neutral Grounding Resistor, if assembled, shall be considered.

The transformer shall be completely submerged in water for at least 12 hours before the temperature rise tests commences. A reference measurement (R_1 and Θ_1) of all winding resistances shall then be performed in steady state conditions including measurement of the corresponding ambient oil and winding hot spot temperatures. These values will be used for determine the average winding temperature.

Resistance measurement (after the 1 hour rated current injection period) shall be performed for minimum two hours. Results shall be logged every 30 seconds for the first 5 minutes, thereafter every minute for the remaining period.

Any additional resistances due to transformer accessories shall be taken into account when the average winding temperature is determined by resistance variations. On windings with low resistance (compared to the additional accessory resistances), the determination of the average winding temperature by resistance variation may be difficult and subjected to large uncertainty. In this case, the winding resistance may be measured by means of indirect measurements of voltage and current at the winding terminals. This will require two parallel measuring cables to be connected to the terminals, ref Figure 10-1. If this is not possible, the winding temperature rise requirements are limited to the hot spot winding temperature rise which shall be determined by direct measurements.

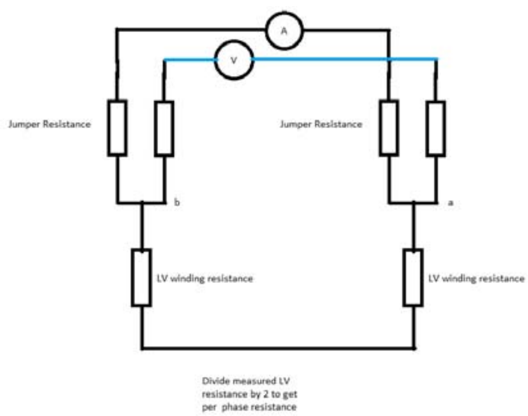

Figure 10-1 – Indirect measurement of winding resistance

Liquid temperatures (including top oil and average winding oil temperatures) and the hot spot winding temperature shall be determined by direct measurements. The surface temperature shall also be directly measured, at various positions of the tank (top, middle and bottom as a minimum)

NOTE: When the average surface temperature and the temperature of the surrounding water are measured, several sensors shall be used (more than in the open air), because the water behavior (layering) may differ from the behavior of the air. If the critical positions of the sensors are not known, it is recommended to first run a short heating period in open air in order to determine the hottest surface spots (places for the sensors) by means of thermal camera.

10.8.18 Temperature rise test in air

10.8.18.1 General

The requirements stated in IEC 60076-2 (IEEE C57.12.90) apply.

For converter transformer or in cases where additional losses are present due to harmonic currents, the requirements in IEC 61378-1 (IEEE C57.110) applies.

The temperature limits given in 6.10 apply.

10.8.18.2 Temperature rise test procedure – in air

The test shall be performed in air.

Two alternative methods may be used when determining the required current to be injected during the temperature rise test in air:

1. A loss figure that gives a hot spot winding temperature close to (but below) 98 ^{o}C. This figure is applicable for transformers with conventional insulations systems (solid insulation designated as class 105 °C according to IEC 60085). For transformers with high-temperature insulation materials, other figures may be used.
2. A loss figure that corresponds to at least 80 % of the total loss value. The temperature values for top-liquid, average liquid and for the windings shall then be determined using corrections factors as given in IEC 60076-2.

Since the ambient cooling medium is air, Liquid temperatures and the hot spot winding temperature shall be determined by direct measurements. Signal penetrations for temperature measurements during this test that shall not be used in service, shall be sealed off by welding after the test.

10.8.19 Partial discharge tests

This test procedure is based on the requirements from IEC 60076-3 and IEC 60076-13. The test setup shall be the same as in the IVPD tests. The test shall be performed in accordance with IEC 60076-13, but with applied voltage test levels (phase to earth) as shown in Figure 10-2 and Figure 10-3 below.

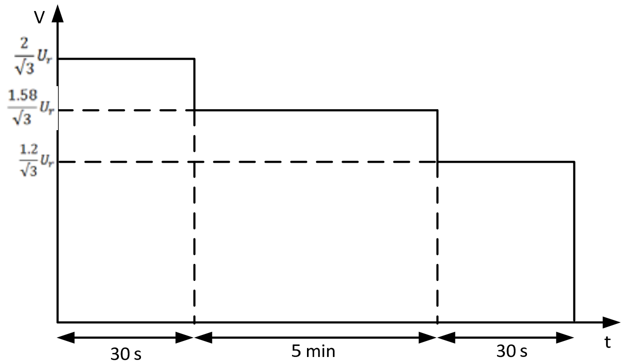

Figure 10-2 – Partial discharge measurement cycle

Acceptance criteria:

PD level < 250 pC @ $1.58\frac{U_r}{\sqrt{3}}$

PD level < 100 pC @ $1.2\frac{U_r}{\sqrt{3}}$

Figure 10-3 shows the required test voltages in special cases where the test voltages are based on U_m, refer to section 10.8.15.

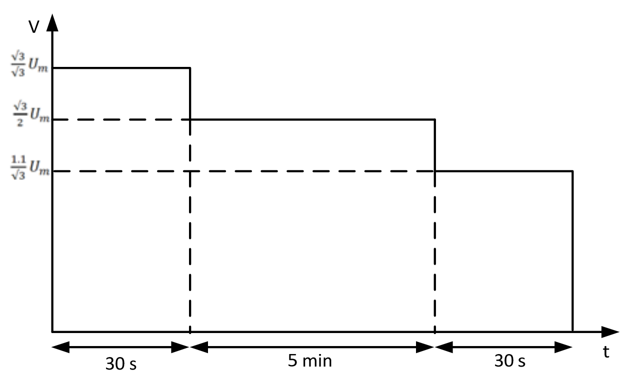

Figure 10-3 – Partial discharge measurement cycle (special case)

Acceptance criteria:

PD level < 250 pC @ $\sqrt{3}\frac{U_m}{2}$

PD level < 100 pC @ $1.1\frac{U_m}{\sqrt{3}}$

10.8.20 Tests of Neutral Grounding Resistors

Tests of NGRs shall be performed in accordance with IEEE PC57.32/DM16.3. Test levels shall be agreed between manufacturer and purchaser, and stated in the data sheet. The temperature rise test shall be performed at conditions representative for the actual installation. The following tests shall be performed:

Table 10-3 – NGR tests

	Routine test	Type test	Special test
Resistance measurement	X		
Impedance measurement	X		
Temperature rise test		X	
Applied voltage test	X		
Lightning impulse test			X

ANNEX – IEC vs IEEE

IEC		IEEE	
IEC 60044-1	Instrument transformers Part 1: Current transformers	IEEE C57.13	Requirements for Instrument Transformers
IEC 60076-1	Power transformers, Part 1: General	IEEE C57.12.00 IEEE C57.12.90	General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers
IEC 60076-2	Power transformers, Part 2: Temperature rise	IEEE C57.12.00	General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers
IEC 60076-3	Power transformers, Part 3: Insulation levels, dielectric tests and external clearances in air	IEEE C57.12.00	General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers
IEC 60076-4	Guide to the lightning impulse and switching impulse testing – Power transformers and reactors		
IEC 60076-5	Power transformers, Part 5: Ability to withstand short circuit	IEEE C57.12.00	General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers
IEC 60076-7	Power transformers, Part 7: Loading guide for oil-immersed power transformers	IEEE C57.12.00	General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers
IEC 60076-8	Application guide for power transformers		
IEC 60076-13	Self-protected liquid-filled transformers		
IEC 60085	Electrical insulation - Thermal evaluation and designation		
IEC 60137	Insulated bushings for alternating voltages above 1000 V	IEEE C57.19.00	General Requirements and Test Procedure for Power Apparatus Bushings
IEC 60270	High voltage test techniques – Partial discharge measurements		
IEC 60296	Fluids for electrotechnical applications – unused mineral insulating oils for transformers and switchgear	IEEE C57.106	Guide for Acceptance and Maintenance of Insulating Oil in Equipment
IEC 60422	Supervision and maintenance guide for mineral insulating oils in electrical equipment		
IEC 60616	Terminal and tapping markings for power transformers		
IEC 61099	Insulating liquids - Specifications for unused synthetic organic esters for electrical purposes	IEEE HOLD	HOLD
IEC 61378-1	Converter Transformers, Part 1: Transformers for industrial applications	IEEE C57.18.10	Practices and Requirements for Semiconductor Power Rectifier Transformers
IEC 61800-4	Adjustable speed electrical power drive systems, Part 4: General requirements Rating specifications for a.c. power drive systems above 1000 V a.c. and not exceeding 35 kV	NEMA ISCS 61800-4	Adjustable Speed Electrical Power Drive Systems, Part 4: General Requirements – Rating Specifications for AC Power Drive Systems Above 1000 V AC and Not Exceeding 35 kV