DERlab

NETWORK OF DER LABORATORIES AND PRE-STANDARDISATION

JPA 2.1 PRE-STANDARDISATION ACTIVITIES FOR DER

ELECTROMAGNETIC COMPATIBILITY FOR DISTRIBUTED ENERGY RESOURCES

GUIDE DOCUMENT

Working Paper

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DERlab Working Group "EMC for DER"

1. SCOPE

The objective is the assessment of the EMC requirements and certification procedures for DER (Distributed Energy Resources) equipment, established by different national and international standards and regulations.

Depending on the situation, the term "DER equipment" may include the entire installation or the individual modules (generating unit, interface module, control and protection devices, etc.).

This assessment does not cover safety issues and interconnection requirements (this means that this analysis does not deal with earthing/grounding methods, protection issues, disconnect switching, and so on).

2. CERTIFICATION PROCEDURES IN THE EUROPEAN UNION ACCORDING TO THE NEW EMC DIRECTIVE

The new EMC Directive [1], like the old version [2], harmonises the protection against electromagnetic disturbances in order to guarantee the free movement of electrical and electronic equipment in the European Union. The relevant dates for the implementation of the new EMC Directive are:

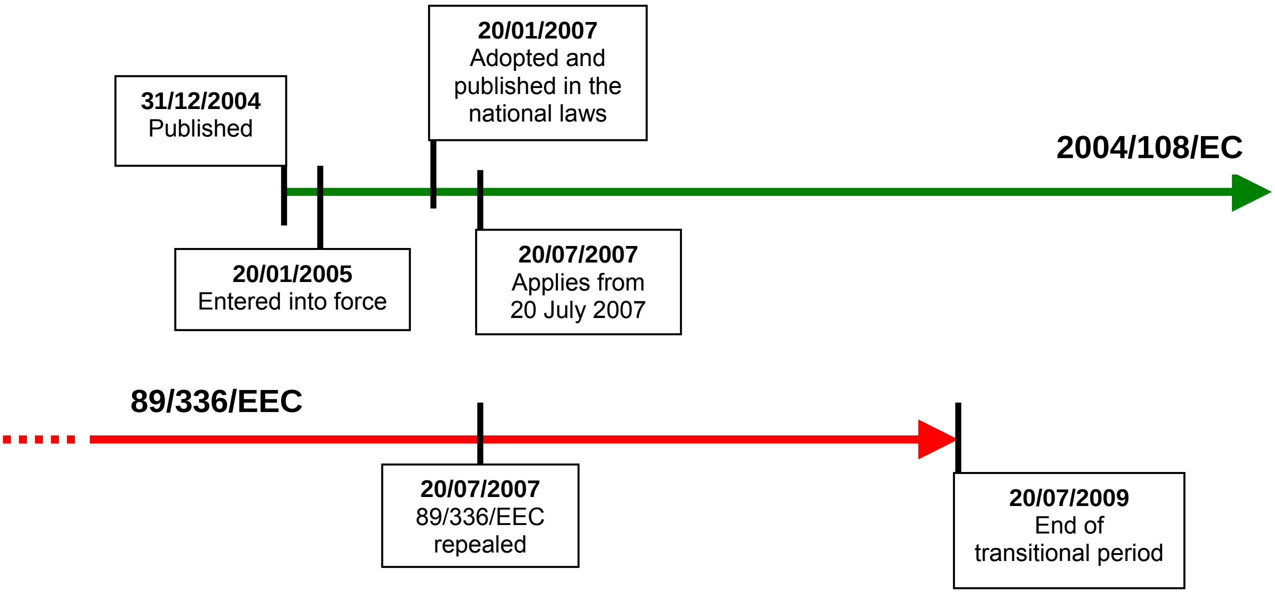

Figure 1 – Relevant dates for the implementation of the new EMC Directive

The equipment covered by this law is divided into two categories: apparatus and fixed installations. DER equipment can be covered by both categories:

a) Apparatus (for example, an inverter):

- Finished appliance or combination
- Commercially available
- As a single functional unit
- For the end-user
- May move freely within the EU

b) Fixed installation (for example, a wind turbine or a PV installation):

- Particular combination of apparatus and/or other devices

- Assembled, installed and intended to be permanently used at a predefined location
- Includes also large machines and networks

Requirements for "DER apparatus"

DER equipment as an apparatus must meet the protection requirements:

- Emissions: *the electromagnetic disturbance generated does not exceed the level above which radio and telecommunications equipment or other equipment cannot operate as intended*
- Immunity: *it has a level of immunity to the electromagnetic disturbance to be expected in its intended use which allows it to operate without unacceptable degradation of its intended use.*

The manufacturer shall perform an EMC assessment based on the relevant phenomena, in all normal intended operating conditions and in all the possible configurations identified of its intended use. The application of all the relevant harmonized standards is equivalent to this assessment.

After this, the manufacturer shall draw up technical documentation providing evidence of compliance with the essential requirements of the Directive. It must cover the design and manufacture of the DER apparatus:

- General description of the DER apparatus.
- Evidence of compliance with the harmonized standards, if applied in full or in part
- Description and explanation of the steps taken to comply with the essential requirements (including a description of the EMC assessment, design calculations, test reports, etc.)
- If a Notified body has been involved (not mandatory), its statement confirming the compliance with the aspects assessed.

Finally, the manufacturer signs a Declaration of Conformity (DoC) to attest the compliance of the DER apparatus with all relevant essential requirements of the EMC Directive, and proceeds with the "CE" marking. The technical documentation and the DoC shall be hold for 10 years at the disposal of authorities.

Requirements for "DER fixed installations"

DER equipment as a fixed installation must meet the protection requirements:

- Emissions
- Immunity

as well as some specific requirements for fixed installations, which must be installed and operated:

- Applying good engineering practices
- Respecting information on the intended use of components
- With a view to meet the protection requirements
- Documenting the good engineering practices (documentation must be held for disposal as long as the installation is in operation).

However, DER equipment as a fixed installation do not need:

- EMC assessment
- "CE" marking (regarding the EMC Directive)
- Declaration of Conformity

But, Authority:

- May request evidence of compliance
- Initiate an assessment
- Where there are indications of non-compliance (neighbour complains!)

2.2.1. Apparatus incorporated into a fixed installation

a) For the apparatus intended for incorporation in a given DER installation otherwise not commercially available, the essential requirements are NOT mandatory, and therefore, they do not need:

- "CE" marking (regarding the EMC Directive)
- Declaration of Conformity
- EMC assessment

For this type of apparatus, it is compulsory to draw up technical documentation identifying the installation into which it is incorporated, its EMC characteristics, and the precautions to be taken in order to not compromise the conformity of the given installation (e.g. requirements for cabling, earthing, bonding, protection distances, etc).

Examples: specific apparatus made according particular specifications, generic apparatus adapted to the needs of a specific location, small series-made apparatus necessitating appropriate EMC adjustments at the final location, etc.

b) The rest of the apparatus making part of a fixed installation, including those already placed in the market, must fulfil all the relevant provisions for apparatus.

2.3 Relevant documents

[1] "Directive 2004/108/EC of the European Parliament and the Council of 15 December 2004 on the approximation of the laws of the Member States relating to electromagnetic compatibility and repealing Directive 89/336/EEC", Official Journal of the European Union of 31 December 2004, pp L 390/24 to L 390/37.

[2] "Council Directive 89/336/EEC on the approximation of the laws of the Member States relating to electromagnetic compatibility", Official Journal of the European Communities (OJ) No. L 139, May 3, 1989.

A table and a diagram are presented in the next pages for summarizing the procedures and requirements explained above.

Table 1 – Summary of the procedures and requirements to be applied in the field of the EMC Directive and CE mark

Products	CE-marking	DoC	Protection Requirements	Specific Requirements for Fixed Installations	EMC Assessment	Technical Documentation
passive devices*						
finished appliance for end user (apparatus)	X	X	X		X or harmonised standards	X
finished appliance for assembler						
components or sub-assemblies for end user (apparatus)	X	X	X		X or harmonised standards	X
components or sub-assemblies for assembler						
apparatus for a given fixed installation						X
mobile installations (apparatus)	X	X	X		X or harmonised standards	X
fixed installations			X	X		X

* not liable to generate electromagnetic disturbance, not liable to be affected by such disturbance.

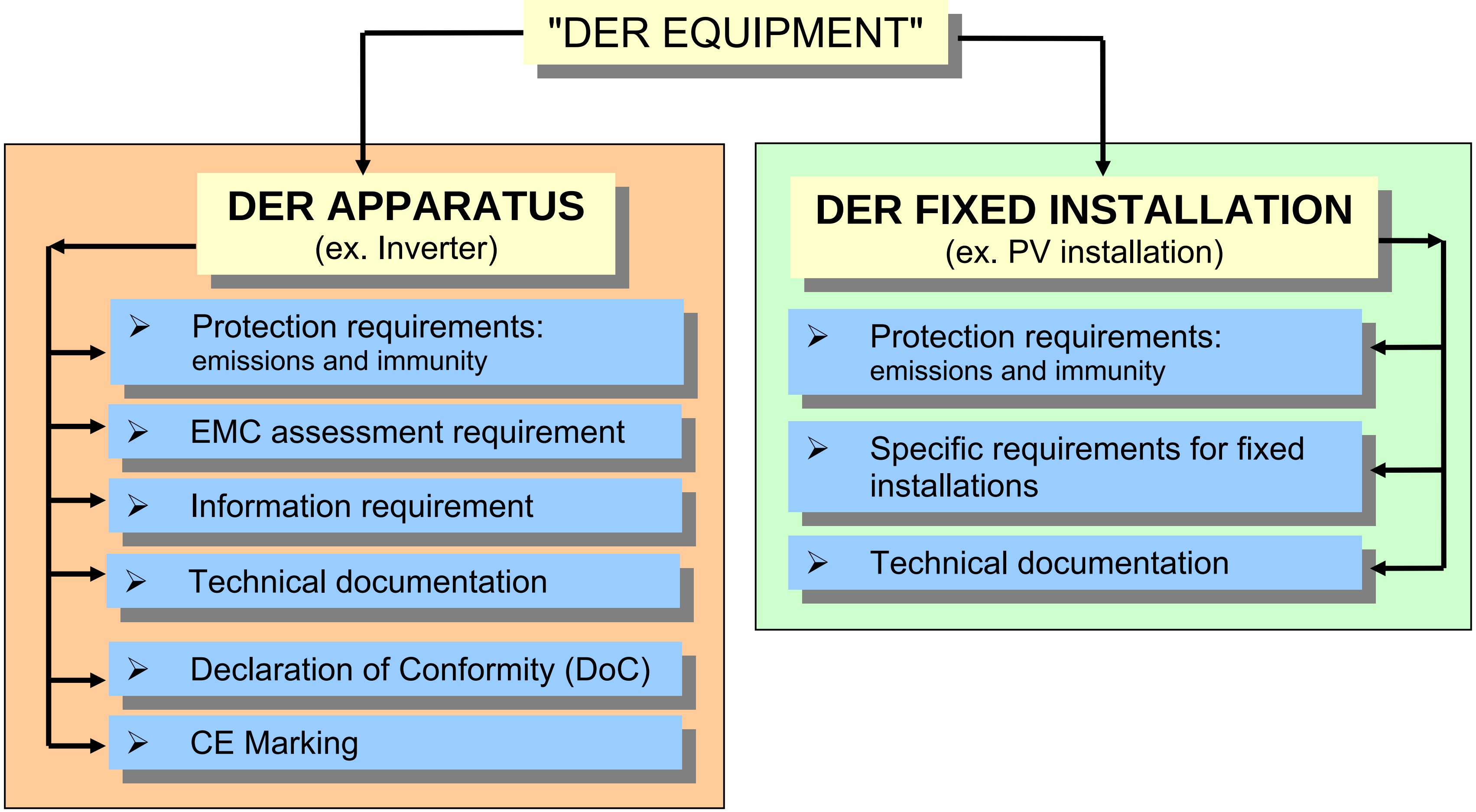

Figure 2 – Summary of the procedures and requirements in the field of the EMC Directive and CE mark to be applied to DER equipment classified as apparatus and fixed installation

3. EMC REQUIREMENTS FOR DER

Apart from the procedures to be fulfilled according to the applicable legislation, Network Operators (NO) establish the requirements that are not totally defined in the regulatory documents and that must be met by the DG owners. Consequently, a project must be presented to the electricity Distribution Company regarding the parts that may affect interconnection conditions and electricity supply security (EMC requirements included).

On the other hand, many DG (from 16A per phase at LV up to 10MW at HV) connections are based on particular conditions, in the frame of the legal requirements, but **defined case by case**. As one of the most important barriers in this context, the lack of adequate standards, technical requirements and procedures for the assessment of the connection and the electrical interconnection itself has been identified by many of the involved stakeholders.

The company has the right of verifying interconnection installations and all elements affecting supply before commissioning.

A new standardisation work has recently been launched at European level, for the connection of micro-generators to the LV network (prEN 50438, Requirements for the connection of micro-generators in parallel with public low-voltage distribution networks); the draft standard which is currently under vote covers the connection of micro-generators (up to 16 A) to the LV network, and in particular:

- Interface protection
- Power quality
- Operation of the generator
- Commissioning

Apart from this standard (already to be approved), no detailed procedures are defined for commissioning of the DG unit. The detailed connection requirements are usually determined jointly between the NO and the operator of the plant, based on the requirements and definitions of the grid code and national standards.

A relevant work dealing with testing and certification procedures regarding EMC requirements caused by DERs is the IEEE 1547.1 Standard. The resultant document identifies 4 different kinds of tests (Sections 5-8) that should be performed:

i. **Type Tests**: They are performed on a representative unit typically at a test laboratory.
ii. **Production Tests**: Verify the operability of every unit of interconnection equipment manufactured for customer use.
iii. **Commissioning Tests**: Testing after the interconnection system is installed and is ready for operation, based on written procedures provided by equipment manufacturers or system integrators, and approved by equipment owner and Area EPS operator (verifications and inspections, field conducted type/production tests, unintentional islanding functionality, cease to energize functionality).
iv. **Periodic Interconnection Tests**: At the time of commissioning, a written “Periodic Interconnection Test” procedure will be agreed on by the equipment owner and the Area EPS operator. The procedure will describe a test process to verify that all interconnection-related protective functions and associated batteries are functional.

The content of the chapter is focused and divided taking into account the different EMC phenomena that can happen in a DG installation: emissions of and immunity against electromagnetic perturbations.

3.1 Emissions

This chapter is divided into and analyzes in detail:

1. Harmonics, considered as low frequency emissions.
2. Voltage fluctuations, like flicker, also considered low frequency emissions.
3. High frequency emissions, divided into conducted and radiated ones.

3.1.1. Harmonics

3.1.1.1. DC current injection

In the Annex A.1 experiences on the DC current injection are described.

3.1.1.1.1. Relevant documents

[1] Identification of general safety problems, definition of test procedures and design measures for protection, DISPOWER Deliverable 2.3, Contract No. ENK5-CT-2001-00522
[2] Engineering recommendation G5/4, February 2001: Planning levels for harmonic voltage distortion and the connection of non-linear equipment to transmission systems and distribution networks in the United Kingdom
[3] Engineering recommendation G83/1 September 2003: Recommendations for the connection of small-scale embedded generators (up to 16 A per phase) in parallel with public low-voltage distribution networks
[4] IEEE 1547:2003, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems
[5] DIN VDE 0126:1999, Automatic disconnecting facility for photovoltaic installations with a rated output smaller than 4.6 kVA and a single-phase parallel feed by means of an inverter into the public low-voltage mains
[6] OVE/ÖNORM E 2750:2004, Photovoltaic Power Systems – Safety and erection requirements
[7] UL 1741:2001, Inverters, Converters, and Controllers for Use in Independent Power Systems
[8] IEEE 519:1992, IEEE Recommended Practises and Requirements for Harmonic Control in Electrical power Systems.
[9] IEEE 1547:2003, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems
[10] Application Guide for Distributed Generation Interconnection: 2003 Update - The NRECA Guide to IEEE 1547, Resource Dynamics Corporation, April 2003
[11] EN 61000-3-2, Limits for harmonic current emissions (equipment input current up to and including 16 A per phase)
[12] prEN 50438, Requirements for the connection of micro-generators in parallel with public low-voltage distribution networks
[13] IEEE 1547.1, IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems
[14] EN 61000-4-13:2003, Testing and measurement techniques – Harmonics and interharmonics including mains signalling at AC power port, low frequency immunity tests

3.1.1.1.2. Background

The injection of DC current by distributed generators into distribution networks has received increasing attention due to the importance of converter-based generators. The possibility that a DC-component (offset) on voltage or current will appear and flow into the grid has therefore to be considered.

- “Symmetrical” DC current is a component flowing in live and neutral conductors. Symmetrical DC current may be for example generated by loads using half-wave rectifiers (light dimmer, power supply for household appliances) or PWM inverters.
- “Unsymmetrical” DC current is a residual component which can be generated by earth faults in DG installations using DC sources and inverters without galvanic separation or by earth leakage currents in the DC circuit of the inverter.

The scope of the present work is limited to symmetrical DC current which will be referred to as DC current.

DC injection may result from the circuit design (e.g. asymmetry due to the dispersion of components' characteristics) or from an internal fault arising.

The major concerns related to the injection of DC current into the AC network are the following:

- Impact on the operation of distribution transformers (saturation).
- Impact on protective devices, mainly on Residual Circuit Breakers (RCD).
- Impact on energy meters.

The first issue receives the greatest attention and is mentioned in several standards for DER components as the reason to impose limits of DC current. Investigations on these three aspects are provided in [1].

3.1.1.1.3. Testing and Conformance Assessment

Very few standards provide precise assessment procedures to measure the DC current injection. The only exception is the standard IEEE 1547.1 ([13]). This standard specifies that the tests should be performed at 33%, 66% and 100% of the rated current:

- RMS current and voltage must be recorded in order to verify that they are within the specified range (5 %).
- The DC current component is considered as the components with a frequency less than 1 Hz). The averaging window has to be between 1 and 60 cycles.
- The absolute value of the DC component has to be averaged for the whole observation time, normalised to the rated current, and compared to the limit of 0,5 %.

3.1.1.1.4. Applicable limits

Currently, this issue is already covered in various interconnection standards. However, the range of limits specified in these documents ([3], [4], [5], [6]) is rather broad: from 20 mA [3] to 5 % of the nominal current, not exceeding 1 A [6].

EN 61000-3-2 ([11]) does not provide any limit for DC current drawn by loads, but specifies limits for even harmonics. Engineering Recommendation G5/4 [2] does not specify any limit for DC current emissions; it just mentions that DC emissions are deprecated.
On the other hand, national standards, guidelines or codes which specify a maximum DC injection do not always specify the maximum time for disconnection in case the DC component reaches the limit (e.g. [3]).

In the power quality section of [12], DC injection is addressed. However, due to a lack of consensus on this issue, the following generic text has been used: "For inverter based systems only symmetrical control as defined in IEV 161-07-11 is permitted. Systems which inject DC current by design (e.g. half wave operation) are not permitted".

This shows that some work is still needed to reach a consensus on the use of meaningful limits for DC injection.

3.1.1.1.5. Challenges

- How to measure DC component (DC may be in fact very low frequency AC (0,2-0,5 Hz)):
- Observation time/averaging?
- How to make the measurement (e.g. FFT, sliding average)?

- Should the DC component be measured with a sinusoidal supply voltage or with a distorted voltage? (this question should also be raised in the work on harmonic emission)
- What should be the targeted accuracy for the measurement?
- How should test procedures look like?
- Under specified normal operating conditions should the “normal” DC level be measured?
- How to simulate in a standardised way internal failures?
- What limit would be meaningful? (no negative effects on network components and not too restrictive limit which can not be reasonably achieved)

3.1.1.2. Higher order harmonics

3.1.1.2.1. Relevant documents

[1] "Directive 2004/108/EC of the European Parliament and the Council of 15 December 2004 on the approximation of the laws of the Member States relating to electromagnetic compatibility and repealing Directive 89/336/EEC", Official Journal of the European Union of 31 December 2004, pp L 390/24 to L 390/37.
[2] IEC 61000-3-2: Limits – Limits for harmonic current emissions (equipment input current ≤16 A per phase).
[3] IEC 61000-3-4: Limits – Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A.
[4] IEC 61000-3-6: Electromagnetic compatibility (EMC) - Part 3: Limits - Section 6: Assessment of emission limits for distorting loads in MV and HV power systems - Basic EMC publication.
[5] IEC 61000-3-12: Limits - Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16 A and ≤ 75 A per phase.
[6] IEC 61000-4-7: Electromagnetic compatibility (EMC) Part 4-7: Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto.
[7] EN 50160: Voltage characteristics of electricity supplied by public distribution systems.
[8] EN 61400-21: Wind turbine generator systems – Measurement and assessment of power characteristics of grid connected wind turbines.
[9] IEEE recommended practice and requirements for harmonic control in electrical power systems. ANSI-IEEE Std 519.
[10] IEEE standard for interconnecting distributed resources with electric power systems. IEEE Std 1547-2003.
[11] IEEE recommended practice for utility interface of photovoltaic (PV) systems. IEEE Std 929-2000.
[12] Ferrandis F.: National Legislation, Standards and Codes of Practice for DG connection in Spain. IBERDROLA, Technical Report, 2005.

3.1.1.2.2. General requirements

Plants must inject no harmonics that cause the harmonic level in the grid surpass the allowable caps (common requirement).

At *high and medium voltage,* the connection of DG plants to the grid will be always carried out by means of transformers with one of its windings connected in delta.

No specific recommendations on interharmonics are provided in the documents.

For small generators, it is easier to find simplified practices for the assessment of the connection and standardized requirements for protection. The emission standards (IEC & EN) formulated for nonlinear load are also used in some countries to assess emission of DG connected on LV level (with power electronic interface e.g. PV) – IEC 61000-3-2, IEC 61000-3-12.

The connection of larger units is usually assessed case by case, taking into account the network configuration at the envisaged point of coupling, capacity and technology of the plant and the operating conditions. The approach for evaluating the acceptability of distorting DG depends on the agreed power of the source, the power of the harmonic-generating equipment and the system characteristics. The objectives is to limit the injection from the total load of individual DG to levels that will not result in voltage distortion levels that exceed the planning levels. The injection of disturbances to the grid in levels higher than the permitted, allows the electric company to disconnect the DG installation under certain conditions and complying with certain procedures.

3.1.1.2.3. Testing and Conformance Assessment

No procedures are given for testing (common practice) harmonics emissions of DER installations. The only exception are wind turbines. For them the measurement procedures, test conditions and test equipment are described in the standard EN 61400-21 [8].

No requirements are given dealing with obligatory voltage monitoring (common practice).

IEC 61000-4-7 standard [6] defines the measurement instrumentation intended for testing individual items of equipment in accordance with emission limits given in certain standards (for example IEC 61000-3-2 and IEC 61000-3-12) as well as for the measurement of harmonic currents and voltages in actual supply systems.

3.1.1.2.4. Applicable limits

IEC 61000-3-4 Limits – Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A

Table 2 – Current emission limits for single phase, inter phase and unbalance three phase system equipment

Minimal R_{sce}[1]	**Admissible individual harmonic current I_n/I_1 %**						**Admissible harmonic current distortion factors %**	
	I_3	I_5	I_7	I_9	I_{11}	I_{13}	***THD***	***PWHD***
66	23	11	8	6	5	4	25	25
120	25	12	10	7	6	5	29	29
175	29	14	11	8	7	6	33	33
250	34	18	12	10	8	7	39	39
350	40	24	15	12	9	8	46	46
450	40	30	20	14	12	10	51	51
600	40	30	20	14	12	10	57	57
The relative values of even harmonics up to order 12 shall not exceed 16/*n* %. Linear interpolation between successive R_{sce} values is permitted. In the case of unbalanced three phase equipment, these values apply to each phase.								
I_1 = reference fundamental current; I_n = harmonic current component.								

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[1] Short circuit ratio: the following definitions apply for this characteristic value of a piece or a customer's installation.
Rsce=Ssc/(3 Sequ) for single phase equipment
Rsce=Ssc/(2 Sequ) for interphase equipment
Rsce=Ssc/Sequ for all three phase equipment

Table 3 – Current emission limits for balanced three-phase equipment

Minimal R_{sce}	**Admissible individual harmonic current I_n/I_1 a %**				**Admissible harmonic current distortion factors %**	
	I_5	**I_7**	**I_{11}**	**I_{13}**	***THD***	***PWHD***
66	14	11	10	8	16	25
120	16	12	11	8	18	29
175	20	14	12	8	25	33
250	30	18	13	8	35	39
350	40	25	15	10	48	46
450	50	35	20	15	58	51
600	60	40	25	18	70	57
The relative values of even harmonics up to order 12 shall not exceed 16/*n* %. NOTE Linear interpolation between successive R_{sce} values is permitted.						
I_1 = reference fundamental current; I_n = harmonic current component.						

IEC 61000-3-6 Electromagnetic compatibility (EMC) - Part 3: Limits - Section 6: Assessment of emission limits for distorting loads in MV and HV power systems - Basic EMC publication

Table 4 – Indicative values of planning levels for harmonic voltage (in percent of the nominal voltage) in MV, HV and EHV power systems

Odd harmonics						Even harmonics		
non multiple of 3			multiple of 3					
Order h	Harmonic voltage %		Order h	Harmonic voltage %		Order h	Harmonic voltage %	
	MV	HV+EHV		MV	HV+EHV		MV	HV+EHV
5	5	2	3	4	2	2	1,6	1,5
7	4	2	9	1,2	1	4	1	1
11	3	1,5	15	0,3	0,3	6	0,5	0,5
13	2,5	1,5	21	0,2	0,2	8	0,4	0,4
17	1,6	1	>21	0,2	0,2	10	0,4	0,4
19	1,2	1				12	0,2	0,2
23	1,2	0,7				>12	0,2	0,2
25	1,2	0,7						
>25	0,5(25/h)	0,5(25/h)						
NOTE – Total harmonic distortion (THD): 6,5% in MV networks and 3 % in HV networks								

IEC 61000-3-12 Limits - Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16 A and ≤ 75 A per phase

Table 5 – Current emission limits for equipment other than balanced three-phase equipment

Minimal R_{sce}	**Admissible individual harmonic current I_n/I_1 [a] %**						**Admissible harmonic current distortion factors %**	
	I_3	I_5	I_7	I_9	I_{11}	I_{13}	***THD***	***PWHD***
33	21,6	10,7	7,2	3,8	3,1	2	23	23
66	24	13	8	5	4	3	26	26
120	27	15	10	6	5	4	30	30
250	35	20	13	9	8	6	40	40
≥ 350	41	24	15	12	10	8	47	47

The relative values of even harmonics up to order 12 shall not exceed 16/*n* %. Even harmonics above order 12 are taken into account in *THD* and *PWHD* in the same way as odd order harmonics.

NOTE Linear interpolation between successive R_{sce} values is permitted. See also Annex B.

I_1 = reference fundamental current; I_n = harmonic current component.

Table 6 – Current emission limits for balanced three-phase equipment

Minimal R_{sce}	**Admissible individual harmonic current I_n/I_1 [a] %**				**Admissible harmonic current distortion factors %**	
	I_5	I_7	I_{11}	I_{13}	***THD***	***PWHD***
33	10,7	7,2	3,1	2	13	22
66	14	9	5	3	16	25
120	19	12	7	4	22	28
250	31	20	12	7	37	38
≥350	40	25	15	10	48	46

The relative values of even harmonics up to order 12 shall not exceed 16/*n* %. Even harmonics above order 12 are taken into account in *THD* and *PWHD* in the same way as odd order harmonics.

NOTE Linear interpolation between successive R_{sce} values is permitted. See also Annex B.

I_1 = reference fundamental current; I_n = harmonic current component.

Table 7 – Current emission limits for balanced three-phase equipment under specified conditions

Minimal R_{sce}	Admissible individual harmonic current I_n/I_1 [a] %				Admissible harmonic current distortion factors %	
	I_5	I_7	I_{11}	I_{13}	*THD*	*PWHD*
33	10,7	7,2	3,1	2	13	22
≥120	40	25	15	10	48	46
The relative values of even harmonics up to order 12 shall not exceed 16/*n* %. Even harmonics above order 12 are taken into account in *THD* and *PWHD* in the same way as odd order harmonics. NOTE Linear interpolation between successive R_{sce} values is permitted. See also Annex B.						
I_1 = reference fundamental current; I_n = harmonic current component.						

EN 50160: Voltage characteristics of electricity supplied by public distribution systems

Table 8 – Values of individual harmonic voltages at the supply terminals for orders up to 25 given in percent of the nominal voltage, in LV and MV power systems

Odd harmonics				Even harmonics	
non multiple of 3		multiple of 3			
Order h	Harmonic voltage %	Order h	Harmonic voltage %	Order h	Harmonic voltage %
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,3	6	0,5
13	3	21	0,2	8	0,5
17	2	>21	0,2	10	0,5
19	1,5			12	0,2
23	1,5			>12	0,2
25	1,5				
>25	1.3(25/h)				
NOTE – Total harmonic distortion, THD, of the supply voltage (including all harmonics up to the order 40): ≤ **8%**					

EN 61400-21 Wind turbine generator systems – Measurement and assessment of power characteristics of grid connected wind turbines

…….

This part of IEC includes procedures for assessing compliance with power quality requirements, including estimation of the power quality expected from the wind turbine type (of any size, three-phase greed connection) when deployed at a specific site, possible in groups.

….

For a wind turbine with power electronic converter (see notes 1, 2, 3 and 4), the wind turbine’s emission of harmonic currents during continuous operation shall be stated. These shall be stated for harmonics up to 50 times the fundamental grid frequency (see note 5), as the individual harmonic currents and the maximum total harmonic current distortion. The individual harmonic currents shall be given as a 10 min average data for each harmonic order at the output power giving the maximum individual harmonic current. The values shall be specified in a table as a percentage of rated current. Harmonic current below 0,1 % of the rated current for any of harmonic orders need not be specified.

NOTE 1: harmonic emission have been reported from a few installations of wind turbines with induction generators but without power electronic converters. There is however no agreed procedure for measurement of harmonic emissions from induction machines. Further, there is no known instance of customer annoyance or damage to equipment due to harmonic emissions from such turbines. This standard therefore does not require measurement of harmonic emissions from such wind turbines.

NOTE 2: The synchronous generator generates a voltage with a waveform depending on the shape of the magnetic field in the air-gap and the regularity of its stator winding. For a wind turbine with a synchronous generator directly connected to the grid, the waveform should comply with the requirements in IEC 60034-1.

NOTE 3: Harmonics are considered harmless as long as the duration is limited to a short period of time. Experience with "soft-start" power electronic units in wind turbines has not generally shown that the short-duration harmonic emission cause problems. Hence, this standard does not require specification of short-duration harmonics caused by wind turbine start-up or other switching operations.

NOTE 4: There has been a reported problem with unnecessary operation of earth-leakage protection on low-voltage circuit possibly due to harmonic current emissions during starting of a wind turbine. The issue may be considered in a future issue of this standard.

NOTE 5: Power electron converters operating with switching frequencies in the kHz range may emit harmonics above 50 times the fundamental grid frequency. The issue of harmonics above 50 times the fundamental grid frequency is under consideration … .

The measurement procedures, test conditions and test equipment are described in the standard.

Harmonic emissions are measured only for wind turbines with a power electronic converter. The maximum harmonic currents generated by the wind turbine during continuous operation shell not exceed the above limits. The harmonic currents shall be measured in accordance with IEC 61000-4-7. The highest accuracy class as defined in IEC 61000-4-7 shall be applied. Results shall be based on observation times of 10 min (see note).
The measurement procedure shall be suitable for wind turbines, i.e. where the magnitude of the harmonic currents produced can be expected to change over periods of a few seconds.

NOTE: Ten minute average data are applied instead of shorter-term data because 10 min average data are easier to measure, and because the results are expected to be very similar to shorter-term data.

IEEE 1547-2003 IEEE standard for interconnecting distributed resources with electric power systems

When the DER is serving balanced linear loads, harmonic current injection into the Area EPS at the PCC shall not exceed the limits stated below in Table 3. The harmonic current injections shall be exclusive of any harmonic current due to harmonic voltage distortion present in the Area EPS without the DER connected.

Table 9-Maximum harmonic current distortion in percent of current (I)[a]

Individual harmonic order h (odd harmonics)	**$h < 11$**	**$11 \leq h < 17$**	**$17 \leq h < 23$**	**$23 \leq h < 35$**	**$35 \leq h$**	**Total demand distortion (TDD)**
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

[a] I = the greater of the Local EPS maximum load current integrated demand (15 or 30 minutes) without the DER unit, or the DER unit rated current capacity (transformed to the PCC when a transformer exists between the DER unit and the PCC).

[b] Even harmonics are limited to 25% of the odd harmonic limits above.

IEEE 929-2000 IEEE recommended practice for utility interface of photovoltaic (PV) systems

The PV system output should have low current-distortion levels to ensure that no adverse effects are caused to other equipment connected to the utility system. The PV system electrical output at the PCC should comply with Clause 10 of IEEE Std 519-1992 and should be used to define the acceptable distortion levels for PV systems connected to a utility. The key requirements of this clause are summarized in the following:

- Total harmonic current distortion shall be less than 5% of the fundamental frequency current at rated inverter output.
- Each individual harmonic shall be limited to the percentages listed in Table 1. The limits in Table 1 are a percentage of the fundamental frequency current at full system output. Even harmonics in these ranges shall be <25% of the odd harmonic limits listed.

Table 9-Distortion limits as recommended in IEEE Std 519-1992 for six-pulse converters

Odd harmonics	Distortion limit
3rd -9th	<4.0%
11th -15th	<2.0%
17th -21st	<1.5%
23rd -33rd	<0.6%
Above the 33rd	<0.3%

These requirements are for six-pulse converters and general distortion situations. IEEE Std 519-1992 gives a conversion formula for converters with pulse number greater than six.

3.1.1.2.5. Challenges

The challenges will be named following the discussion process within the DERlab working group “EMC for DER”.

3.1.2. Voltage Fluctuations, Flicker

In Annex 2, information about assessment methods, possible causes of voltage fluctuations and flicker and possible solutions for flicker mitigation is given.

3.1.2.1. Introduction

Since there is a significant overlap between the terms “voltage fluctuations” (or “rapid voltage changes”) and “voltage variations” we will limit the use of the term “voltage fluctuations” to those changes in voltage magnitude that (potentially) lead to light flicker with incandescent lamps. Voltage fluctuations are quantified through the “short-term flicker severity” (P_{st}) and the “long-term flicker severity” (P_{lt}).

Voltage fluctuations are almost exclusively a concern for lighting load, so we do not need to consider the impact of voltage fluctuations on Distributed Resources (DR) or DG units (immunity). We do however need to consider DER units as a potential source of voltage fluctuations (emission).

3.1.2.2. Relevant documents

A list of relevant documents which should be taken into account is given below:

- A new EMC directive [1].
- IEEE and IEC Standards [2]-[13].
- Publications, recommendations and guidelines [14]-[24].

[1] "Directive 2004/108/EC of the European Parliament and the Council of 15 December 2004 on the approximation of the laws of the Member States relating to electromagnetic compatibility and repealing Directive 89/336/EEC", Official Journal of the European Union of 31 December 2004, pp L 390/24 to L 390/37.

[2] IEC 61000-3-3 (1994), Part 3: Limits – Section 3: Limitation of voltage fluctuations and flicker in low-voltage supply systems for equipment with rated current ≤ 16A.

[3] IEC 61000-3-5 (1994), Part 3: Limits – Section 5: Limitation of voltage fluctuations and flicker in low-voltage power supply systems for equipment with rated current greater than 16 A.

[4] IEC 61000-3-7 (1996), Part 3: Limits – Section 7: Assessment of emission limits for fluctuating loads in MV and HV power systems – Basic EMC publication.

[5] IEC 61000-3-11 (2000), Part 3: Limits – Section 11: Limitation of voltage changes, voltage fluctuations and flicker in low voltage supply systems for equipment with rated current < 75 A and subject to conditional connection.

[6] IEC 61000-4-15(1997), Part 4: Testing and measurement techniques – Section 15: Flickermeter-Functional and design specifications.

[7] IEC 61400-21(2001): Wind turbine generator systems - Measurement and assessment of power quality characteristics of grid connected wind turbines.

[8] IEEE Std 1547-2003 for Interconnecting Distributed Resources with Electric Power Systems.

[9] IEEE 1547.1- 2005, Standard for Conformance Tests Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems.

[10] IEEE Std 519-1992, Recommended practice and requirements for harmonic control in electric power systems.

[11] IEEE Flicker Task Force P1453, Recommended Practice for Measurement and Limits of Voltage Flicker on AC Power Systems.

[12] IEEE Std 141-1993, Recommended practice for electric power distribution for industrial plants.

[13] IEEE Std 929-2000, IEEE Recommended Practices for Utility Interface of Photovoltaic (PV) Systems.

[14] N. Jenkins, R. Allan, P. Crossley, D. Kirschen, G. Strbac, Embedded generation, Institution of Electrical Engineers, London, 2000. Chapter 5: Power quality.

[15] Application Guide for Distributed Generation Interconnection: 2003 Update, The NRECA Guide to IEEE 1547, www.nreca.org/Documents/PublicPolicy/DGApplicationGuide-Final.pdf , April 2003.

[16] N.A. Kasmas, S.A. Papathanassiou, “Evaluation of the voltage change factor k_U for DG equipped with synchronous generators”. Under review for publication in *Electric Power Systems Research.*

[17] A. Larsson, “Flicker emission of wind turbines caused by switching operations”, *IEEE Transactions on Energy Conversion*, Vol. 17, No. 1, March 2002, pp. 119 –123.

[18] A. Larsson, Flicker emission of wind turbines during continuous operation, IEEE Transactions on Energy Conversion, Vol.17, no.1 (March 2002), pp.114-118.

[19] T. Sun, Power quality of grid-connected wind turbines with DFIG and their interaction with the grid. Aalborg University of Technology, Institute of Energy Technology, Aalborg, Denmark: May 2004. PhD thesis.

[20] T. Thiringer, T. Petru, S. Lundberg, Flicker contribution from wind turbine installations, IEEE Transactions on Energy Conversion, Vol.19, no.1 (March 2004), pp.157-163.

[21] T. Thiringer, T. Petru, C. Liljegren, Power quality impact of a sea located hybrid wind park, IEEE Transactions on Energy Conversion, vol.16, no.2 (June 2001), pp.123-127.

[22] Z. Saad-Saoud, N. Jenkins, Models for predicting flicker induced by large wind turbines, IEEE Transactions on Energy Conversion, vol.14, no.3 (September 1999), pp.743-748.

[23] C. Vilar, J. Usaola, H. Amaris, A frequency domain approach to wind turbines for flicker analysis, IEEE Transactions on Energy Conversion, Vol.18, no.2 (June 2003), pp.335-341.

[24] M.P. Papadopoulos, S.A. Papathanassiou, S.T. Tentzerakis, N.G. Boulaxis, Investigation of the flicker emission by grid connected wind turbines, Int Conf Harmonics and Quality of Power, 1998.

3.1.2.3 Testing and certification methods

A complete procedure is given for testing (common practice) voltage fluctuations wind turbine generator systems. For them the measurement procedures, test conditions and test equipment are described in the standard EN 61400-21 [8].

Apart from that, other DG installations lack such a complete procedure.

IEC 61000-4-7 standard [6] gives a functional and design specification for flicker measuring apparatus intended to indicate the correct flicker perception level for all practical voltage fluctuation waveforms.

3.1.2.4 Applicable limits

Regarding switching operations, the limits imposed depend on the voltage level (LV or MV) where the installation is connected, the size of the equipment and the frequency of the operations. Taking into account the requirements of [2]-[5], the limits of Table 1 can be set for the relative (%) voltage change (see also Fig. 1).

Table 10- Magnitude limits for rapid voltage changes

		Frequency of switching operations, *r* (h^{-1}: *per hour,* d^{-1}: *per day)*		
LV		$r > 1$ h^{-1}	2 d^{-1} < r < 1 h^{-1}	$r < 2$ d^{-1}
	Steady-state change, d_c	≤ 3 %		
	Maximum change, d_{max}	≤ 4 %	≤ 5.5 %	≤ 7 %
MV		r>10 h^{-1}	1 h^{-1}<r≤10 h^{-1}	r≤1 h^{-1}
	Steady-state change, d_c	-		
	Maximum change, d_{max}	≤ 2 %	≤ 3 %	≤ 4 %

Limits for flicker emissions are the same for normal operation and switching events. At the LV level, limits stipulated in [2] are $P_{st} \leq 1$ and $P_{lt} \leq 0.65$. At the MV level, the determination of limits is left to the utilities, which set the planning levels for their grids. Indicative values for planning levels in MV systems, according to [10], are $P_{st} \leq 0.9$ and $P_{lt} \leq 0.7$.

3.1.2.5 Challenges

The challenges will be named following the discussion process within the DERlab working group “EMC for DER”.

3.1.3. High frequency emissions

Due to the special nature of DER equipment, which can be also installed in domestic locations (ex. PV installations), rather than the industrial environment or others, it is more advisable to consider the domestic environment for emission requirements (stricter than the industrial one). In this regard, the reference generic standard is [1].

Where a relevant dedicated product or product-family EMC emission standard exists, this shall take precedence over all aspects of these generic standards [1] or [2].

3.1.3.1. Relevant documents

[1] EN 61000-6-3, "Electromagnetic Compatibility (EMC) – Part 6-3: Generic standards – Emission standard for residential, commercial and light-industrial environments".
[2] EN 61000-6-4, "Electromagnetic Compatibility (EMC) – Part 6-3: Generic standards – Emission standard for industrial environments".
[3] EN 55011, “Industrial scientific and medical (ISM) radio-frequency equipment - Electromagnetic disturbance characteristics - Limits and methods of measurement”.
[4] CISPR 16-X-X Standards family, “Radio disturbance and immunity measuring apparatus, methods of measurements, uncertainties, statistics and limit modelling”.

3.1.3.2 Testing and certification methods

As previously mentioned in chapter 2, “Certification procedures in the European Union according to the new EMC directive”, generic electric or electronic equipment (like DER) can be classified into apparatus and fixed installations.

Apparatus (for example, a commercial inverter) can be tested and certified to comply with the EMC Directive taking into account the emission limits stated in EN 61000-6-3 (residential environment) or in EN 61000-6-4 (industrial environment). EN 55011 (CISPR 11) and CISPR 16 standards specify the measurement procedures (common practice). Then, if a sample taken from a group of equipment is certified to comply with the EMC Directive, then the rest of equipment of the group, with the same design, are also supposed to comply (if a production quality assurance scheme is implemented).

There are no concrete standards providing limits to certify if fixed installations (for example a single wind turbine or even a complete wind farm) comply with the EMC Directive. Please refer to the procedure described in 2.2 and 2.3 for this case. Anyway, if a fixed installation needs to be EMC evaluated, EN 55011 standard can give some guidance on how to proceed in-situ (common practice) and some reference limits. However, this assessment will be valid for this concrete installation. Following the same example, a similarly designed and built wind turbine installed in other location (even if its design is the same) should also be tested/evaluated.

The testing of conducted emissions requires a LISN (Line Impedance Stabilization Network) or a CISPR RC voltage probe, specified in CISPR 16. The testing of radiated emission can be performed with different antennas (the most common is the bilog antenna) and requires a semi-anechoic chamber or an open area test site (OATS).

On the other hand, in terms of conducted high frequency emissions Network Operators care that their communication channels (Power Line Communicactions, SCADAs…) are not interfered by the DER equipment connected to the electric network.

3.1.3.3 Conducted emissions

Table 11- Frequency ranges, limits and standards related to high frequency conducted emissions tests

Port	Frequency range	Limits	Basic standard	Applicability note	Remarks
AC mains	0.15 MHz – 0.5 MHz limits decrease linearly with log. frequency	66 dBµV – 56 dBµV quasi-peak 56 dBµV – 46 dBµV average	CISPR 22, Class B		The statistical evaluation in the basic standard applies
	0.5 MHz – 5 MHz	56 dBµV quasi-peak 46 dBµV average			
	5 MHz – 30 MHz	60 dBµV quasi-peak 50 dBµV average			
	0.15 MHz – 30 MHz	See basic standard, clause: discontinuous interference	CISPR 14		
Signal control, DC power input, DC power output and other	0.15 MHz – 0.5 MHz Limit decreasing linearly with log. frequency	40 dBµA – 30 dBµA quasi-peak 30 dBµA – 20 dBµA average	CISPR 22 Amend. 1, Class B	See note 2	Current probe measurement with line terminated to reference plane via 150 Ω
	0.5 MHz – 30 MHz	30 dBµA quasi-peak 20 dBµA average			

Note 1: Applicable to apparatus covered within the scope of IEC 61000-3-3. Limits for apparatus not currently covered by IEC 61000-3-2 and IEC 61000-3-3 are under consideration.

Note 2: For guidance only; data will be reviewed when the relevant basic standard is published.

3.1.3.4 Radiated emissions

Table 12- Frequency ranges, limits and standards related to high frequency radiated emissions tests

Port	Frequency range	Limits	Basic standard	Applicability note	Remarks
Enclosure	30 MHz – 230 MHz 230 MHz – 1000 MHz	30 dBµV at 10 m 37 dBµV at 10 m	CISPR 22, Class B	See note	The statistical evaluation in the basic standard applies

Note: Applicable only for apparatus containing processing devices, e.g. microprocessors, operating at frequencies greater than 9 kHz.

3.1.3.4. Challenges

The challenges will be named following the discussion process within the DERlab working group “EMC for DER”.

3.2. Immunity

3.2.1 Introduction

The technical specification [1] is supposed to be the base document for the next generic standard for immunity in this type of environment. Obviously, it is not an EMC harmonised standard in the EU yet.

Other phenomena covered by [1]:

- Radiated radiofrequency electromagnetic fields, 80 MHz – 3000 MHz (IEC 61000-4-3)
- Electrostatic discharge –ESD- (IEC 61000-4-2)
- Fast transient/burst –EFT- (IEC 61000-4-4)
- Conducted radiofrequency disturbances (IEC 61000-4-6)
- Surges (IEC 61000-4-5)
- Power frequency magnetic field (IEC 61000-4-8)
- Damped oscillatory wave (IEC 61000-4-12)
- Mains frequency voltage (IEC 61000-4-16)
- Ripple on DC power supply (IEC 61000-4-17)

3.2.2 Relevant documents

[1] IEC TS 61000-6-5, "Electromagnetic Compatibility (EMC) – Part 6-5: Generic standards – Immunity for power stations and substation environments", 2001.

3.2.3 Voltage dips and interruptions

3.2.3.1. Relevant documents

[1] IEC 60050, *International Electrotechnical Vocabulary*

[2] EN 50160:1999, *Voltage characteristics of electricity supplied by public distribution systems*

[3] IEEE P1433, *A standard Glossary of Power Quality Terminology*

[4] *Voltage dips and short interruptions in medium voltage public electricity supply systems*, UNIPEDE DISDIP study, 1991

[5] EPRI Distribution System Power Quality Monitoring Project (EPRI DPQ Project), http://www.electrotek.com/PROJECTS/DPQ/Dpq.htm

[6] IEC 61000-2-8: 2000, *Voltage dips and short interruptions on public electric power supply systems with statistical measurement results*

[7] Characteristics and target values of the voltage supplied by the Hydro-Québec medium and low voltage systems, Hydro-Québec Report number 30012-01-02

[8] J.V. Milanovic, R. Gnativ, *Characteristics of Voltage Sags in Radial Networks With Dynamic Loads And Embedded Generators*

[9] S. Z. Djokic, et al., *Sensitivity of personal computers to voltage sags, short interruptions*, IEEE Transactions on Power Delivery, Vol. 20, No. 1, Jan. 2005, pp. 375-383

[10] S. Z. Djokic et al., *Sensitivity of AC adjustable speed drives to voltage sags, short interruptions and under- voltage transients*, IEEE Transactions on Power Delivery, Vol. 20, No. 1, Jan. 2005, pp. 494-505

[11] A. Mansoor et al., *Effects of Unsymmetrical Voltage Sags on Adjustable Speed Drives*, Proceedings of the Southern African Power Quality Conference, May 12 - 14, 1997

[12] Luis Guasch et al., *Effects of unsymmetrical voltage sags on induction motors*

[13] S. Z. Djokic et al. *Sensitivity of AC coil contactors to voltage sags, short interruptions and under-voltage transients*, IEEE Transactions on Power Delivery, Vol. 19, No. 3, July 2004, pp. 1299- 1307

[14] P. Pohjanheimo and M. Lehtonen, *Equipment Sensitivity to Voltage Sags – Test Results for Contactors, PCs and Gas Discharge Lamps*

[15] Math H.J. Bollen, *Understanding Power Quality Problems – Voltage sags and interruptions*, IEEE press series on power engineering

[16] *Identification of general safety problems, definition of test procedures and design measures for protection*, DISPOWER Deliverable 2.3, Contract No. ENK5-CT-2001-00522

[17] EN 61000-4-11:2004, *Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests*

[18] IEC 61000-4-34: 2005, *Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests for equipment with input current more than 16 A per phase*

[19] EEG generators (under the Renewable Energy Law Regime) connected to the High Voltage. Guide for the connection and operation of renewable energy generators connected to the high voltage network – enlargement of the grid code, VDN, August 2004

[20] Resolución de 4 de Octubre de 2006, de Secretaría General de Energía, por la que se aprueba el procedimiento de operación 12.3. Requisitos de respuesta frente a huecos de tensión de las instalaciones eólicas (Resolution of 4th October of 2006, of the Energy General Secretary, by which the 12.3 operation procedure is approved. Requirements of wind farms reaction against voltage sags).

[21] IEC 61000-4-29, *Testing and measurement techniques - Voltage dips, short interruptions and voltage variations on d.c. input power port immunity tests*

3.2.3.2. Background

Definition: “A sudden reduction of the voltage at a point in an electrical system followed by a voltage recovery after a short period of time from a few cycles to a few seconds.” (IEV, [1]).

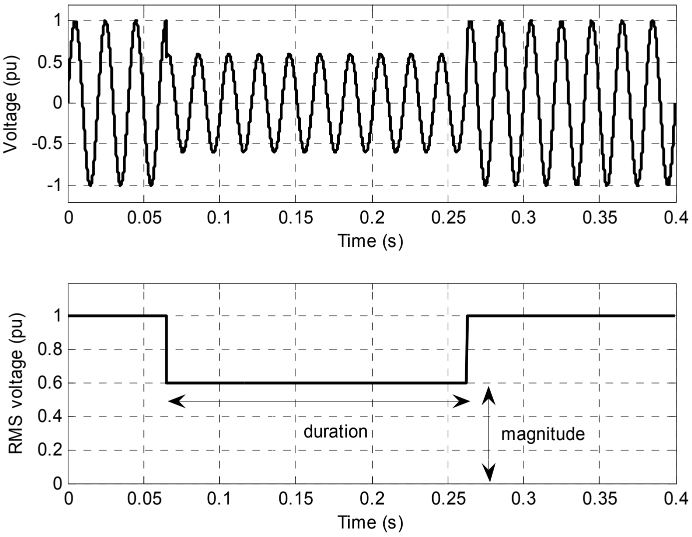
Another definition can be found in EN 50160 ([2]) and in IEEE P1433 ([3]). These definitions differ in the limit made between voltage dip and short interruption: a level of 1 % of the voltage is mentioned in EN 50160, while IEEE 1433 uses 10 %.

These definitions correspond to a two-dimensional representation of voltage dips: the magnitude (expressed in percent of the voltage for example) and the duration (in cycles or milliseconds). However, voltage dips are much more complex phenomena. The way of characterising voltage dips can be extended to the following parameters:

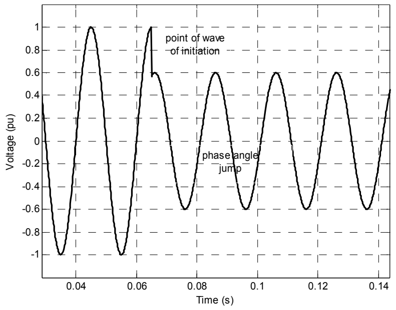
- Magnitude
- Duration
- Point on wave of dip initiation/ of voltage recovery
- Phase angle jump

Figure 3 provides an illustrative example where these parameters are shown.

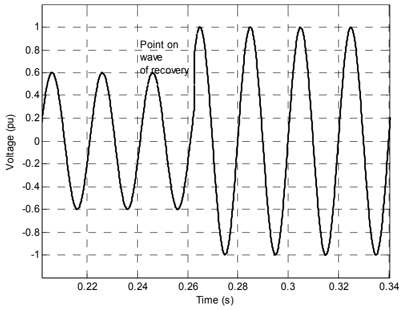
Figure 3 – Illustrative example of the voltage dip parameters



Voltage dips characteristic parameters (synthetic event)



Point on wave of dip initiation and phase angle jump



Point on wave of voltage recovery

3.2.3.4. Testing and conformance

Testing is the most reliable way to get information on equipment sensitivity to voltage sags. Two standards are available for testing appliances’ immunity to voltage dips:

- IEC 61000-4-11 ([17]) for equipment up to 16 A per phase.
- IEC 61000-4-34 ([18]) for equipment above 16 A per phase.

The first standard ([17]) defines preferred test levels and durations for various electromagnetic environment classes (see Table 1).

Table 13- Preferred test levels and durations (for equipment connected to 50 Hz supply), source: [17]

Classes	Test level and durations for voltage dips (50 Hz)									
	Point 1		Point 2		Point 3		Point 4		Point 5	
	Mag.	Dur.	Mag.	Dur.	Mag.	Dur.	Mag.	Dur.	Mag.	Dur.
Class 1	Case by case according to the equipment requirements									
Class 2	0%	½ cy.	0%	1 cy.			70%	25 cy.	80%	250 cy.
Class 3	0%	½ cy.	0%	1 cy.	40 %	10 cy.	70%	25 cy	80%	250 cy.

Class 1 corresponds to protected supply, Class 2 to points of common coupling (PCC), and Class 3 to industrial points of coupling (IPC).

[17] is usually used for testing inverter-based DER connected to the LV network.

On the other hand, ride-thru requirements are requested for generators connected to the transmission network in some countries (e.g. [19]). This document specifies that generators connected to the transmission system shall not disconnect from the network for some voltage disturbance. This requirement is illustrated on Figure 3: the generator must operate in the domain above the curve.

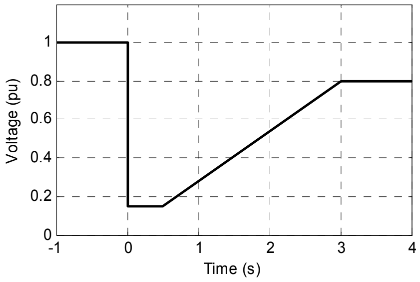


Figure 4 – Ride-thru requirements requested for generators connected to the transmission network according to [19].

Ride-thru requirement of renewable energy generator connected to the transmission network (source [19])

3.2.3.5. Challenges

The following questions have been partially addressed in previous research but should be raised and investigated into details through research activities:

- Is there a need for a DER standard specifying immunity levels?
- Is there a need for a DER standard specifying a test procedure with common test levels?

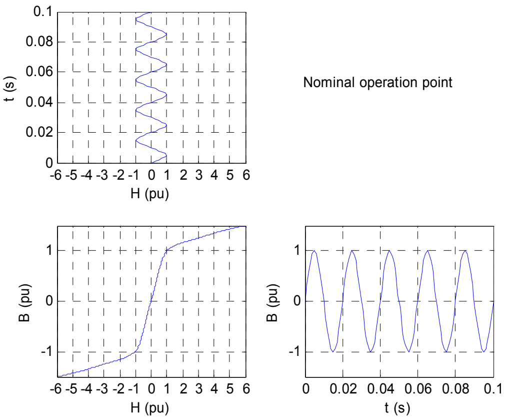
- Are the current standards appropriate to assess the immunity of DER components to voltage dips?
- Should test procedures go beyond the current approaches (i.e. also assess the effect of phase angle jumps and point on wave)?
- Is it possible to address all DER components by the same way and in the same standard?
- How to define the performance criteria (e.g. disconnection, power reduction, power decrease to zero)
- Interconnection protections have a significant impact on the immunity of DER components to voltage dips. In the absence of common requirements for protections, how should this be addressed?
- Power electronic converters are widely used for interconnecting DER to the network. Should test procedures address the “primary” energy source, and how?

ANNEX

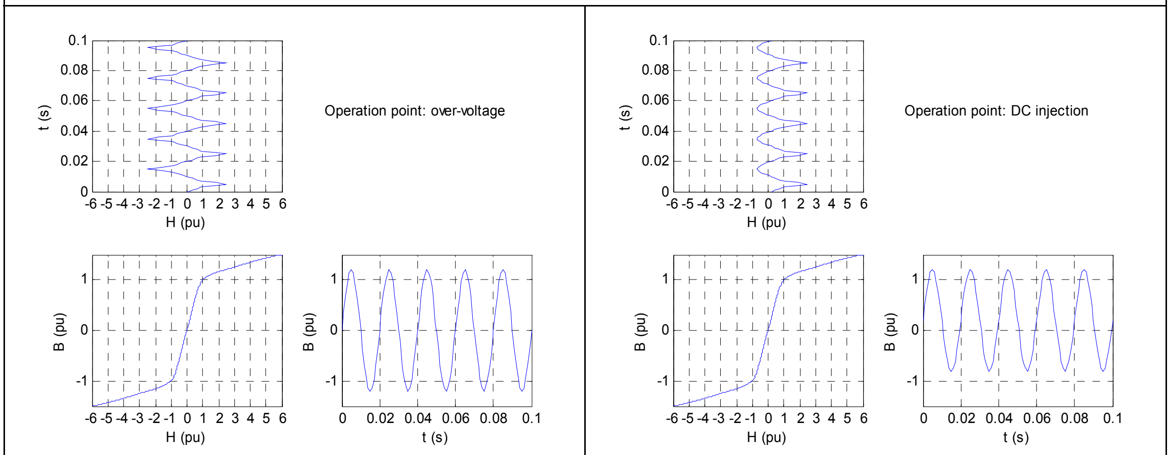
A.1. Experiences on DC current injection

A.1.1. Experiences on transformers. Possible effects on distribution transformers, proposed limit

As already mentioned, the major concern related to the injection of DC current is the saturation of distribution transformers. Figure 1 illustrates the saturation phenomenon.



A: nominal point



B: over-voltage

C: DC injection

Figure A.1 - Core magnetisation characteristics (source: [1])

In [1], the results of detailed investigations are presented. On the basis of laboratory measurements performed on various distribution transformers, some levels for DC injection are proposed: 0.5 % of the rated current with an exception for micro-generators for which the limit of 100 mA should be used.
This limit has been following the following scheme:

- Investigate the effects of DC current on the operation of distribution transformers (i.e. harmonic distortion, losses and noise).
- Choose a criterion: which level of DC is acceptable for typical distribution transformers and find the corresponding limit of DC current
- Translate the maximum value of DC current which is acceptable for distribution transformers to an emission limit for inverter-connected generators.

For the last step, micro-generators have been considered separately. Indeed, in the case of the connection of large number of small units (e.g. up to 16 A per phase), the DC injection will statistically tend to zero. Taking a 95 % confidence level allows setting a realistic limit for small generators.

A.1.2. Experiences on inverters. Typical levels for small inverters

[1] also provides the results of tests performed on a set of photovoltaic inverters with an output power smaller than 5 kW. Tests have been performed with a sinusoidal supply voltage as well as with distorted supply voltage containing even harmonics. The levels mentioned in the standard EN 61000-4-13 ([13]) have been used for testing (e.g. 3% for the 2nd, 1.5% for the 4th, 6th and 8th. The test results show that with a sinusoidal voltage waveform, most of the tested inverters have a DC component below 100 mA. Furthermore, except for one device, the presence of even harmonics on the voltage does not lead to any increase of the DC injection. This means that under normal operation (excluding an internal failure), inverters generate only a low level of DC component.

A.2. Supplementary information on voltage fluctuations

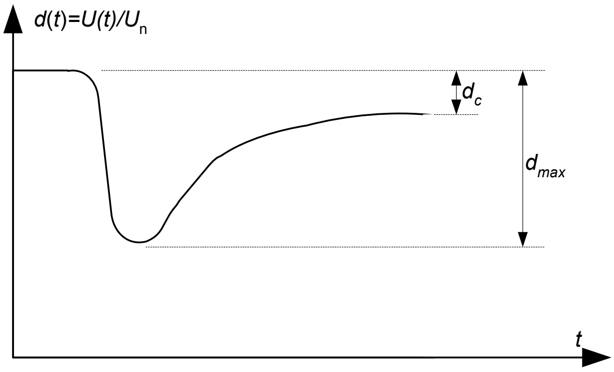
A.2.1. Assessment methods

A.2.1.1. Switching operations

An evaluation of the expected voltage change (Fig. 1) at the PCC at the cut-in of a DG unit is given by:

$$d_{\max}(\%) = 100 \cdot k_U(\psi_k)\frac{S_n}{S_k} \tag{1}$$

where $k_U(\psi_k)$ is the voltage change factor defined for wind turbines in [7] (and evaluated for synchronous generators in [16]) included in their test certificates as a function of the angle ψ_k of the short-circuit impedance Z_k of the grid. For simplified calculations, k_U can be set equal to the ratio of the equipment starting current to its rated current, ranging from less than 1 to higher than 8, depending on the type of equipment and the starting method used.



Fast voltage change pattern and characteristics.

Equation (1) is applied for the single unit in the power station, which creates the largest disturbance. Summation rules for simultaneous switching of equipment need not be applied, due to the very low probability of coincident events. For the case of wind turbines, flicker emissions resulting from switching operations can be calculated as [7],[17]:

$$P_{st} = \frac{18}{S_k}\left(\sum_{i=1}^{N} N_{10,i}\left(k_{f,i}(\psi_k)\cdot S_{n,i}\right)^{3.2}\right)^{1/3.2} \quad \text{and}$$
$$P_{lt} = \frac{8}{S_k}\left(\sum_{i=1}^{N} N_{120,i}\left(k_{f,i}(\psi_k)\cdot S_{n,i}\right)^{3.2}\right)^{1/3.2} \tag{2}$$

where N is the number of generators operating in parallel, $S_{n,i}$ the rated capacity and $k_{f,i}(\psi_k)$ the flicker step factor of unit i (defined in [13]). $N_{10,i}$ and $N_{120,i}$ are the maximum number of switching operations that can take place in a 10-min and a 120-min interval for unit i. If the flicker factor is unavailable, the flicker has to be evaluated either by the shape characteristics and the frequency of the disturbance ([8] provides useful guidance), or by simulation using a software implementation of the flickermeter algorithm [6].

The following rule is commonly applied for the summation of flicker due to switching operations (used also for P_{lt}):

$$P_{st} = \sqrt[3]{\sum_i P_{st,i}^3} \tag{3}$$

where the exponent may also be 3.2 instead of 3.0, as in (2).

A.2.1.2. Variations in generated power

Flicker values (from measurements or simulations) due to variations in output power of wind turbines of various types can be found in the literature [18]-[24]. Most of these studies consider only one wind turbine. When several turbines are connected close to each other, the flicker level will be higher than with one turbine. Fortunately they will not simply add. A simple approach proposed in [7] for the total P_{st} level is the following expression:

$$P_{st} = \sqrt{\sum_{i=1}^{N} P_{st,i}} \tag{4}$$

with $P_{st,i}$ the P_{st} contribution from each individual turbine.

Another approach recommended in [7] for the expected flicker emissions of wind turbine generators is to use the flicker coefficient $c(\psi_k,v_a)$, dependent on the average annual wind speed v_a at the wind turbine installation site and the grid short circuit impedance angle ψ_k:

$$P_{st} = P_{lt} = c(\psi_k, v_a)\frac{S}{S_k} \tag{5}$$

For the total flicker emissions of a wind farm comprising N wind turbines, the following relation is used:

$$P_{st} = P_{lt} = \frac{1}{S_k}\sqrt{\sum_{i=1}^{N}\left(c(\psi_k, v_a)\cdot S_{n,i}\right)^2} \tag{6}$$

A.2.2. Possible causes of voltage fluctuations and flicker

Voltage fluctuations and flicker are normally due to:

I. Switching operations (starting, stopping or switching between a small and a large generator).

II. Fast variations in generated power (mainly wind and solar power). Wind turbines produce a continuously varying output. In [14], three time-scales are distinguished (where is also pointed out that the increased emission will at least be partly compensated by the increase in fault level due to the installation of the generators):
   - Variations with a frequency of several Hz due to the turbine dynamics.
   - Periodic power pulsations at the frequency at which the blades pass the tower, typically around 1 Hz for a large turbine. These are referred to as 3p-oscillations for three-blade turbines.
   - Slower variations due to changes in wind speed (turbulent and gusty winds). This type of flicker is proportionately reduced when more wind turbines are connected together due to the non-coincident nature of wind gusts.

III. Dynamic interaction with other loads and utility system equipment (e.g. voltage regulators, switched capacitors, generators etc). For example, it is possible for output fluctuations of a DG (even smoother ones from solar or wind systems) to cause hunting of an upstream regulator and, while the DG fluctuations alone may not create visible flicker, the hunting regulator may create visible flicker.

IV. Dynamic interactions with other DG units.

A.2.3. Possible solutions for flicker mitigation

General proposed solutions are to avoid placement of DG units at feeder locations that fail flicker screening tests (if possible), to limit frequency of system starts and stops as well as output variations and to use improved fuel, maintain engine & controls to prevent misfiring and unintended rapid output fluctuations for reciprocating engines.

Possible solutions for flicker caused by DG starting are the soft starting by using inverters (limited rate of change of power output at starting), a careful designation of synchronous machines (voltage matching and phase angle synchronization) and induction machines (speed matching, limitation of inrush current and reduced voltage start).

For flicker caused by interactions between DGs, or DGs and voltage regulators or other devices, control settings or DG operating mode and control system can be suitably adjusted. Another possible solution is an integrated control of system voltage and reactive power management, especially for significant DG penetration.

Other flicker solutions are:

- Advanced inverter control algorithms of inverter-type DGs can have a significant beneficial effect on flicker if they are operated as controlled voltage sources and/or limit the rate of power change function (at all times).

Static VAR Compensators (SVC), generator stabilizers (for synchronous rotating equipment) and beefed up distribution system (lower impedance) or reconfigured distribution system.

A.3. Supplementary information on immunity to voltage dips

A.3.1. Origin and statistics of voltage dips

The basic cause of voltage dips is a sudden and large increase of current flow through the system impedances which results in a large voltage drop. This sudden change can have mainly two origins: short circuits and switching of large loads (e.g. induction motor starting), the first one causing more severe events.

Various studies provide some statistics on voltage dips (e.g. [4], [5], [6], [7]). Most studies conclude stating that results present considerable variations on the number of voltage dips experienced by a customer: this number can range from some tens to some several hundreds per year. The type of network (overhead/underground/mixed) as well as external factors (e.g. weather) has an important influence on these statistics. However, the great majority of voltage dips have a magnitude of about 80 % and duration of 4 to 10 cycles [8]).

A.3.2. Concern and relevance of voltage dips

Voltage dips and short interruptions are widely considered to be the most serious power quality disturbances due to their effect on sensitive processes. Depending on equipment sensitivity, voltage dips may have effects as severe as those of short interruptions: a voltage dip may result in equipment failure.

For distributed generators, the nature of the problem is partly different. In addition to the possible internal effects that voltage dips may have on distributed generators (e.g. over-current, unbalance), voltage dips may also cause network disturbances through there effect on distributed generators (external effects). A special concern in this context is the loss of generation. The disconnection of a significant amount of distributed generation resulting from a voltage dip could have a major impact on the network operation, in particular in scenarios with large DG penetration.

As the penetration of distributed generation increases, the philosophy of disconnecting “at first sign of trouble” is not acceptable anymore. Frequent disconnections of distributed generators may have negative effects on:

- the generator itself
    - temporary cease of feed-in (which can last much more than the disturbance itself) with the following consequences:
        - ✓ energy and revenue loss
        - ✓ owner’s impression of malfunction which may go beyond the real prejudice (dissatisfaction)
    - repeated stress on components with possible lifetime reduction
- the network operation, for example:
    - power quality disturbance (caused by the disconnection, e.g. voltage variations)
    - stability problems (for large penetrations)

A3.3. Possible effects of voltage dips on DER equipment

Various studies have been dedicated to the determination of the sensitivity of equipment to voltage dips ([9], [10], [11], [12], [13], [14]). These studies focused on sensitive equipment like computers, gas discharge lamps, contactors and adjustable speed drives.

As illustration, voltage dips can have the following effects on adjustable speed drives ([15]):

- Trip of the drive protection to protect the power electronic components

- Malfunction due to too low DC bus voltage
- Over current trip of the drive due to the increase of current flow during and after the event
- Malfunction of the process driven by the motor due to a drop of speed.

In [16], the results of detailed investigations made on photovoltaic inverters are provided. Figure 2 shows for example the sensitivity curves of 12 commercial photovoltaic inverters.

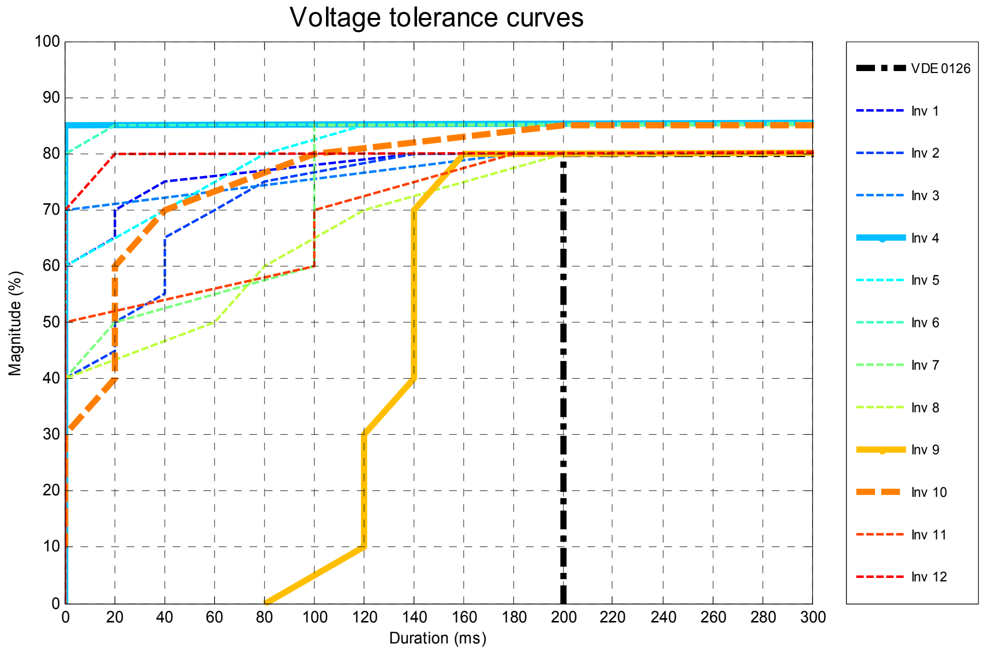


Figure 2 - Voltage tolerance curves of the 12 inverters ([16])

In [16], further provides the most common causes of the observed behaviour:

- Under voltage protection trip (the most frequent).
- AC current control problem and over current at voltage recovery (poor control).
- Trip due to the monitoring of DC component (“unsymmetrical” current fed and interpreted as a DC component which forces disconnection).
- Switch-off of the whole inverter (even the electronic supply) meaning a very long starting procedure.