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On Adaptation of Electric Vehicle and Microgrid Issues to EMC-Power Quality Standards

M. N. Moschakis[1,*], E. L. Karfopoulos[2], E. I. Zountouridou[2], S. A. Papathanassiou[2]

[1]Department of Electrical Engineering, Technological Educational Institute of Larissa, 41110, Greece
[2]School of Electrical and Computer Engineering, National Technical University of Athens, 15773, Greece

Abstract This paper deals with the adaptation of Microgrid and Electric Vehicle (EV) concepts to grid standards related to power quality. It presents a review of recent progress on power quality standards including standards on converters and Electric Vehicles. Power quality issues and relevant standards taking into account the operation of Electric Vehicles are examined for interconnected and islanded (microgrid) mode of operation. Taking into account results from various research studies including EV connection and microgrid operation but also power quality requirements in various countries, recommendations on the adaptation of microgrid-EV concepts to power quality standards are given.

Keywords electric vehicle, microgrids, dispersed generation and storage, electromagnetic compatibility, power quality

1. Introduction

There are three types of Electric Vehicles (EVs): pure battery, hybrid and fuel cell EVs. Battery and hybrid plug-in EVs can act as prosumers that consume or deliver power to the grid while fuel cell EVs can only inject power to the grid. EVs are connected to the grid through a power electronic converter in a single- or three-phase arrangement. The connection of a large number of EVs into the power grid may raise a certain number of problems which, if not properly addressed, may reduce the quality of supply on the network. The degradation of the power quality may affect the installations of the network users and prevent the network operator from meeting its obligations. Moreover, EVs may be affected by power quality-electromagnetic compatibility (EMC) phenomena arising by other network users or by network disturbances[1]-[4]. On the other hand, EVs with proper modification may be used to improve power quality performance of distribution networks[5].

Power quality requirements for consumers of electricity are included in the existing grid standards and can be adopted in case of producers of electricity. As regards European countries, they have incorporated in a great extent the European norms related to power quality requirements for network users and Distribution Generation (DG) units in their national grid codes. As EVs present either network users or DG units, they will be subject to similar requirements[6].

* Corresponding author:
mmoschakis@teilar.gr (M. N. Moschakis)
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Special attention should be given in case of microgrids especially in islanded mode of operation. Current standards depend mainly on the traditional configuration of grids. The concept of smart grids with an increased amount of DG units connected in Medium Voltage (MV) or Low Voltage (LV) networks should be taken into account in future amendments of existing standards or in the formulation of new standards related with power quality issues[7]. EMC-Power Quality and Smart Grid issues are also discussed in[20] and proper actions are suggested.

In the current paper, EMC-Power quality issues and standards are considered taking into account penetration of EVs and microgrid operation. Based on the current and previous research studies, recommendations on proper action within standardization are given for the adaptation of EV-microgrid concepts to future editions of new or existing power quality standards.

2. Standards on EMC-Power Quality

2.1. European Norm EN 50160

The main European Norm (EN) dealing with supply voltage characteristics is the EN 50160[8]: “Voltage characteristics of electricity supplied by public distribution networks”. This document has been prepared by CENELEC and provides the main requirements concerning the supplier’s side and characterizes voltage parameters of electrical energy in public distribution systems. According to standard EN 50160, the *supplier* is the party who provides electricity via a public distribution system and the *user* or *customer* is the purchaser of electricity from a supplier.

EN 50160 applies only under normal operating conditions.

It provides definitions, limits and indicative values for a number of power quality phenomena in LV and MV networks. In LV networks, the *nominal voltage of the system Un* is considered and, in MV networks, the *declared supply voltage Uc*, which is normally the nominal voltage or a different voltage agreed between the supplier and the user.

The limits set by EN50160 concern the following parameters: power frequency, supply voltage variations, harmonics voltage, supply voltage unbalance, flicker and mains signalling. For example, the limits set for supply voltage variations is: “During each period of one week 95%, the 10-minute mean rms values of the supply voltage shall be within the range of *Un* ±10% in LV networks and *Uc* ±10% in MV networks”.

The indicative values concern the following parameters: rapid voltage changes, supply voltage dips, short and long interruptions, temporary and transient overvoltages. For example, the indicative value for supply voltage dips is: “The expected number of voltage dips in a year may be from up to a few tens to up to one thousand. The majority of voltage dips have duration of less than 1 second and a depth of less than 60% of *Un* (of *Uc* in MV)”.

As we already mentioned, EN 50160 does not apply under abnormal operating conditions. Moreover, it provides only indicative values for the so-called voltage events, which is not useful for regulatory purposes. The only useful values for voltage quality regulation are the limits set for the so-called voltage variations. However, even these are not always satisfactory. For the purpose of defining voltage quality standards that differ from the EN 50160, regulators are also engaged together with CENELEC (in addition to the work carried out individually) in a joint effort to improve the existing technical norms[9]-[12]. In 2007, the European Regulatory Group for Electricity and Gas (ERGEG) published a consultation paper on this subject with a number of recommendations to CENELEC for the improvement of EN 50160[13].

Most of the European countries have adopted EN 50160 standard. However, a number of European countries have introduced voltage quality standards that tighten the requirements contained in the EN 50160 (France, Hungary, Norway, Portugal, and Spain). Some differences are elaborated below[11],[12]:

- *France*. Contracts for MV customers contain the voltage variation limit Uc ±5% for 100% of the time, where Uc must be in the range ±5% around Un for 100% of the time. Concerning voltage variations on MV and LV networks, 10 minute mean values of voltage variations shall be within ±10% of the corresponding nominal value. Moreover, the threshold between interruption and dips is 8% of the contractual voltage.
- *Hungary*. For LV networks, 10 minute mean values of the supply voltage variations shall be within Un ±7.5% for 95% of the week and within Un ±10% for 100% of the week. For LV networks, each 1 minute mean value of supply voltage variations shall not be above Un +15% and not below Un -15%.
- *Portugal*. For Extra High Voltage (EHV) and HV networks, the Quality of Service Code establishes that the value of Uc shall be within the range of Un±7%. Under normal operating conditions, during each period of 1 week, 95% of the 10 minute mean RMS values of the supply voltage shall be within the range of Uc ±5%.
- *The Netherlands*. For LV and MV networks, supply voltage variations shall be within Un ±10% for 95% of the week and within Un + 10% / -15% for 100% of the time with no exceptions for long lines or non-interconnected areas.
- *Norway*. For LV networks, the network companies shall ensure that supply voltage variations at the points of connection are within Un ±10% for 100% of the time, measured as 1 minute mean values.
- *Spain*. For LV and MV networks, supply voltage variations in the points of connection shall be within Uc ±7% for 95% of the time. For supplies to distributors who are fed through 1-36 kV networks, the tolerances above shall be reduced to 80%.

2.2. IEC 61000 series of Standards

Apart from EN 50160, a series of standards have been developed on Electromagnetic Compatibility (EMC) issues by the International Electrotechnical Commission (IEC). Electromagnetic compatibility is defined as *the ability of equipment to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment*. EMC seeks what is sought also for the utilization of electricity by users’ appliances, namely, that the generation of disturbance must be limited and equipment must be capable of tolerating a reasonable level of disturbance.

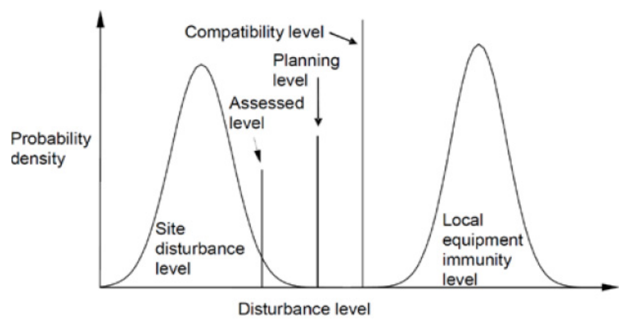

Figure 1. EMC concepts with time statistics in a site within a network[20]

These problems are summarized in the IEC 61000 series of EMC standards[14], in which limits of conducted disturbances are characterized. They include standards establishing limits for the *emission* of and *immunity* from disturbances, as well as numerous other supporting standards and technical reports describing the electromagnetic environment and phenomena found in it, methods of measurement and test, mitigation etc. Among them are standards for *compatibility levels*, which are reference values established to enable emission and immunity limits to be coordinated with each other and with the actual disturbance levels to be expected or regarded as acceptable in the various environments. Additionally to the compatibility levels, so-called *planning levels* have been defined. They represent levels, set by the network operator for their single supply network, which is aimed at not getting exceeded, being lower than the standardized compatibility levels. That is, planning levels are defined with a margin in relation to compatibility levels, as indicated in Figure 1.

Most of IEC standards have become European Norms (IEC/EN). In Table 1, a list of published IEC/EN Standards and Technical Reports (TR or TS) of different types are presented with basic information (Standard No., Title, Publication Year and Stability Date). The Stability Date refers to the year up to which the publication will remain unchanged. At this date, the publication will be reconfirmed, withdrawn or replaced by a revised edition or amended. If there is a revision or amendment on-going then this is given under the publication and entitled "Work in progress"[14].

For the connection of Distribution Generation (DG) units, most of the European countries have also set power quality requirements, which normally present an adoption of IEC 61000 series applied to DG units. These standards have been partly or fully incorporated to national grid codes. The adoption of IEC standards may differ to some extent for various reasons such as the voltage levels, grid configuration and architecture, type of DG units or loads etc. A technical report has been published by CIGRE that includes a review on connection criteria of DG units with reference to power quality requirements in various European countries[6].

Table 1. EN and IEC Standards on EMC-Power Quality

Standard No.	Title (Publication Year / Stability Date)
EN 50160:	Voltage characteristics of electricity supplied by public distribution networks (2007 / 2010)
IEC/TR 61000-1-4:	Historical rationale for the limitation of power-frequency conducted harmonic current emissions from equipment, in the frequency range up to 2 kHz (2005/ 2010)
IEC/EN 61000-2-2:	Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems (2002 / 2012)
IEC/EN 61000-2-4:	Compatibility levels in industrial plants for low-frequency conducted disturbances (2002 / 2012)
IEC/TR 61000-2-6:	Assessment of the emission levels in the power supply of industrial plants as regards low-frequency conducted disturbances (1995 / 2011)
IEC/TR 61000-2-8:	Voltage dips and short interruptions on public electric power supply systems with statistical measurement results (2002 / 2012)
IEC/EN61000-2-12:	Compatibility levels for low-frequency conducted disturbances and signalling in public medium-voltage power supply systems (2003 / 2012)
IEC/EN 61000-3-2:	Limits for harmonic current emissions - Equipment input current ≤ 16 A per phase (2009 / 2011)
IEC/EN 61000-3-3:	Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection (2008 / 2011)
IEC/TS 61000-3-4:	Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A (1998 / 2015)
IEC/TS 61000-3-5:	Limitation of voltage fluctuations and flicker in low-voltage power supply systems for equipment with rated current greater than 75 A (2009 / 2015)
IEC/TR 61000-3-6:	Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems (2008 / 2012)
IEC/TR 61000-3-7:	Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems (2008 / 2012)
IEC/EN61000-3-11:	Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems - Equipment with rated current ≤ 75 A and subject to conditional connection (2000 / 2012)
IEC/EN61000-3-12:	Limits for harmonic currents produced by equipment connectedto public low-voltage systems with input current > 16 A and ≤75 A per phase (2004 / 2010)
IEC/TR61000-3-13:	Assessment of emission limits for the connection of unbalanced installations to MV, HV and EHV power systems (2008 / 2012)
IEC/EN 61000-4-4:	Electrical fast transient/burst immunity test (2004 / 2011)
IEC/EN 61000-4-5:	Surge immunity test (2005 / 2012)
IEC/EN 61000-4-6:	Immunity to conducted disturbances, induced by radio-frequency fields(2008/ 2013)
IEC/EN 61000-4-7:	General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto (2009 / 2010)
IEC/EN61000-4-11:	Voltage dips, short interruptions and voltage variations immunity tests (2004/ 2015)
IEC/EN61000-4-13:	Harmonics and interharmonics including mains signalling at a.c. power port, low frequency immunity tests (2009 / 2012)
IEC/EN61000-4-14:	Voltage fluctuation immunity test for equipment with input current not exceeding 16 A per phase (2009 / 2012)
IEC/EN61000-4-15:	Testing and measurement techniques - Section 15: Flickermeter - Functional and design specifications (2003 / 2010)
IEC/EN61000-4-16:	Test for immunity to conducted, common mode disturbances in the frequency range 0 Hz to 150 kHz (2002 / 2014)
IEC/EN61000-4-17:	Ripple on d.c. input power port immunity test (2009 / 2011)
IEC/EN61000-4-27:	Unbalance, immunity test for equipment with input current not exceeding 16 A per phase (2009 / 2012)
IEC/EN61000-4-28:	Variation of power frequency, immunity test for equipment with input current not exceeding 16 A per phase (2009 / 2012)
IEC/EN61000-4-29:	Voltage dips, short interruptions and voltage variations on d.c. input power port immunity tests (2000 / 2012)
IEC/EN61000-4-30:	Power quality measurement methods (2008 / 2012)
IEC/EN61000-4-34:	Voltage dips, short interruptions and voltage variations immunity tests for equipment with mains current more than 16 A per phase (2009 / 2012)
IEC/EN 61000-6-1:	Immunity for residential, commercial and light-industrial environments (2005/2011)
IEC/EN 61000-6-2:	Immunity for industrial environments (2005 / 2011)

2.3. IEEE Standards related to Power Quality Issues

Apart from European standards, some countries have adopted parts of other international standards in cases not covered by the European standards, such as standards published by IEEE (Institute of Electrical and Electronics Engineers). A relevant standard with the interconnection of DG units, power quality requirements and behaviour of DG units after disturbances is the standard IEEE 1547[15]. This standard has been used by European countries e.g. for limitation of DC injection. Moreover, some IEEE standards have adopted IEC standards, e.g. IEEE Std 1453 on flicker issues have adopted IEC 61000-4-15 standard. The main IEEE standards on power quality issues are[15]:

- IEEE 519 (1992): Recommended Practices & Requirements for Harmonic Control in Electrical Power Systems.
- IEEE 1346 (1998): IEEE Recommended Practice for Evaluating Electric Power System Compatibility With Electronic Process Equipment.
- IEEE 1159-2009: Recommended Practice for Monitoring Electric Power Quality.
- IEEE 1250 (2011): Guide for Identifying and Improving Voltage Quality in Power Systems.
- IEEE 1547-2003: Standard for Interconnecting Distributed Resources with Electric Power Systems.
- IEEE 1409 (2012): IEEE Draft Guide for the Application of Power Electronics for Power Quality Improvement on Distribution Systems Rated 1 kV Through 38 kV.

3. Electric Vehicles and Power Quality

3.1. Standards on EVs and Power Quality Issues

In the last years, IEC have issued a small number of standards related with EVs. Standards on EVs with reference to power quality issues are the followings[14]:

- IEC 61851-21 (2001): Electric vehicle conductive charging system - Part 21: Electric vehicle requirements for conductive connection to an a.c./d.c. supply. It gives the EV requirements for conductive connection to an ac or dc supply, for ac voltages up to 690 V and for dc voltages up to 1000 V, when the electric vehicle is connected to the supply network. It has references to EMC standards, specifically, IEC 61000-2-2, 3 (all parts), 3-2, 4 (all parts), 4-1, 4-2, 4-3, 4-4, 4-5, 4-11. Its contents include EMC issues and, specifically, immunity and generated electromagnetic disturbances.
- IEC 61851-22 (2001): Electric vehicle conductive charging system - Part 22: AC electric vehicle charging station. This part of IEC 61851, together with part 1, gives the requirements for ac electric vehicle charging stations for conductive connection to an electric vehicle, with ac supply voltages up to 690 V. It has references to IEC 61000- 2-2, 3-2, 4-1, 4-2, 4-3, 4-4, 4-5, 4-11 and includes EM environmental tests. Specifically, immunity to EM disturbances and emitted EM disturbances.

Standards on EVs have also been published by other organizations such as the Society of Automotive Engineers (SAE). SAE has issued the standard J2894-2011 on Power Quality Requirements for Plug-In Electric Vehicle Chargers and a few more standards on EVs. Moreover, SAE and IEEE association have established a partnership in vehicular technology related to the Smart Grid in order to create a more efficient and collaborative standards-development environment. The IEEE Std 2030-2011 has been developed, which is the first all-encompassing IEEE standard on smart grid interoperability, taking into account the connection of EVs.

As power electronics converters constitute a crucial part of EV connection to the power grid, standards on converters with reference to EMC issues are also important. Standards IEC 60146-1-1 and IEC 60146-2 can be considered as relevant[14] as they have references to EMC issues such as harmonics and other EMC aspects, EMC tests, immunity requirements and tests, and emission tests.

3.2. Adapting EV-Microgrid Concepts to Power Quality Standards

Electric Vehicles act either as simple loads or DG units. The main characteristics of EVs include the mobility, the consuming/generating variability and the use of power electronic interface systems for the connection to the power grid.

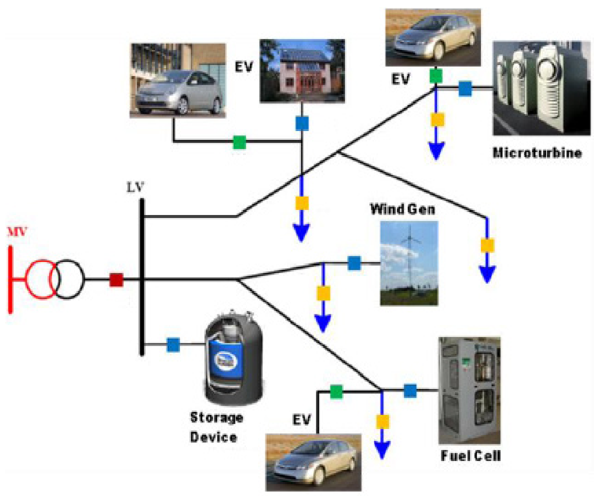

Figure 2. Typical Structure and Elements of a Microgrid with EVs

Looking to EV as a simple load, it represents a large amount of consumed power, which easily can approach half the power consumed in a typical domestic household at peak load[1]. Thus it is easy to foresee major congestion problems in already heavily loaded grids and voltage profile problems in predominantly radial networks, particularly if the peak load periods coincide with EV charging periods. The same characteristics apply when EVs operate as DG units. A typical structure and elements of a microgrid that includes EVs is shown in Figure 2.

The connection of EVs to distribution networks may raise certain power quality issues. The operation of EVs may cause power quality problems to other network users through emission of disturbances to the grid but also EVs may be affected by network disturbances. Therefore, emission limits and a certain level of immunity are required. On the other hand, EVs through their power electronic interface and proper control or modification may help to limit or even to avoid voltage deviations or disturbances[5].

The severity of these phenomena depends largely on the short-circuit power (fault level) available at the connection point of EVs, that is the charging stations of one or a fleet of EVs. Therefore, especially on weak grids this may be one of the limiting factors which determines the number and size of EVs that can be connected.

In migrogrid operation, there are two modes of operation: interconnected and non-interconnected (islanded) mode of operation. Micro-grids can be defined as low voltage distribution networks comprising various distributed generators (DG), storage devices and controllable loads (L) that can be operated interconnected or isolated from the main distribution grid as a controlled entity. A possible configuration of a microgrid with EVs formulated temporarily after a fault at the transmission system is depicted in Figure 3.

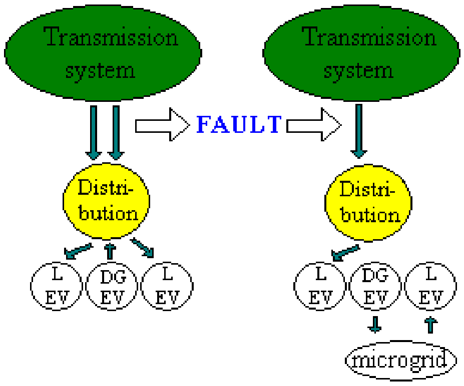

Figure 3. Power system with microgrids before and after a fault at transmission level

The main power quality parameters for interconnected and islanded mode of operation of an electrical network are discussed below taking into account mainly the impact of fault level. In interconnected mode of operation, fault level is an issue mainly for weak grids as regards power quality parameters. In islanded mode of operation, the fault level may be significantly lower and the power quality requirements may differ.

Frequency Variations

In interconnected systems, large frequency variations occur very rarely due to severe disturbances and not by the operation of EVs or other DG units. In non-interconnected systems such as microgrids in islanded mode of operation, frequency variations occur regularly by the connection of a large number of EVs at the same time. EN 50160 defines limits from the supplier's point of view for interconnected and non-interconnected systems and IEC 61000-2-2 defines emission and immunity levels for equipment connected in LV networks. A study on the impact of EVs during microgrid operation on frequency variations is performed in[2]. It is shown that no violation of maximum allowable limits occurs but also that EVs with certain modifications may contribute to alleviation of frequency variations.

Voltage Variations

As EVs draw or inject power to the grid, they may cause a reduction or rise in voltage. The effect is more severe in interconnected weak grids or islanded grids but also for lower-size feeders, low-load situations and for EVs connected far away from the main substation. The variability in energy consumption/generation and the stochastic nature of EV connection also contributes to the appearance of voltage variations. In[21], it is shown that a high penetration of EVs, may cause a violation of the maximum allowable voltage drop limits, especially for rural distribution systems.

Rapid Voltage Changes or Voltage Fluctuations

The simultaneous connection of a large number of EVs that draw or inject power to the grid may cause rapid voltage changes (voltage fluctuations). The same parameters as in voltage variations affect the severity of rapid voltage changes.

Flicker

Voltage fluctuations due to the operation of EVs or other DG units may lead to flicker. Flicker is influenced from the same parameters as voltage fluctuations and voltage variations. Flicker may also be caused by interharmonics emitted by power electronic interfaces used for the connection EVs and other DG units or equipment.

Unbalance

EVs may be connected to the grid in a single-phase or three-phase arrangement. Single-phase connections may cause unbalance to the network voltage. In LV networks or microgrids, the unbalance ratio may be higher. Moreover, EV power electronic interfaces may be affected by the system voltage unbalance. In[21], it is shown that a high penetration of EVs, may cause a violation of the maximum allowable voltage unbalance limits, especially for rural distribution systems.

Voltage Dips (Sags)

The connection of EVs is unlikely to cause voltage dips (voltage magnitude lower than 90% of the nominal voltage). Only in extreme cases of simultaneous connection of a large number of EVs drawing power from the system, a voltage dip may occur. Parameters that influence the severity of voltage dips for these reasons are similar with voltage variations or fluctuations. However, the operation of EVs when connected to a charging station may be influenced by voltage dips e.g. due to faults, and therefore an immunity level is required. IEC 61000-6-1 and 2 define immunity levels to voltage dips for electrical and electronic apparatus. In a microgrid, the duration of a voltage dip due to upstream faults on the main grid will be much lower as the microgrid will be rapidly disconnected from the main grid in case of such disturbances.

Short Interruptions

Short interruptions are a situation where the voltage drops to very low value (1 to 10% of the nominal voltage). They are usually caused by faults and, as for voltage dips, their duration is reduced in microgrid operation since the microgrid will be rapidly disconnected from the main grid. IEC 61000-6-1 and 2 define immunity levels to short interruptions for electrical and electronic apparatus.

Temporary Overvoltages (Swells)

Similarly with voltage dips, the connection of EVs is unlikely to cause temporary overvoltages (or voltage swells). Only in extreme cases of simultaneous connection of a large number of EVs injecting power to the system, a voltage swell may occur. Parameters that influence the severity of voltage swells for these reasons are similar with voltage variations or fluctuations.

Transient Overvoltages

Transient overvoltages may influence the operation of EVs, therefore a certain level of immunity is required. IEC 61000-6-1 and 2 define immunity levels to transient overvoltages for electrical and electronic apparatus.

Table 2. Summary and Comparison of Applicable Standards (EN 50160 and IEC 61000 only)

Parameter	EN 50160	IEC 61000-x-y
Frequency Variations	LV, MV: Mean value of fundamental measured over 10s 1.Interconnected systems: ±1% for 95% of a week -6%/+4% for 100% of a week 2.Non-interconnected systems: ±2% for 95% of a week ±15% for 100% of a week	IEC 61000-2-2: LV: 2% (emission and immunity limits)
Voltage Variations	LV (Un), MV (Uc): ±10% for 95% of week, 10-min mean rms values	± 10% applied for 15 minutes
Rapid Voltage Changes (Voltage Fluctuations)	LV (Un): 5% normal, 10% infrequently MV (Uc): 4% normal, 6% infrequently	IEC 61000-2-2 (Compatibility levels): 3% normally, 8% infrequently IEC 61000-3-3: 3% normal, 4% max. IEC 61000-2-12: 3% IEC 61000-3-7: Planning levels IEC 61000-3-11: Emission limits IEC61000-4-14, 4-15 (Immunity levels and measurements)
Flicker	LV, MV: Plt ≤ 1 for 95% of a week	IEC 61000-2-2: Pst < 1.0, Plt < 0.8 IEC 61000-3-3: Pst < 1.0, Plt < 0.65 IEC 61000-3-7 (Planning levels) IEC 61000-4-14, 4-15 (Immunity levels and measurements)
Harmonics	LV (Un), MV (Uc): Limits for harmonics up to the 25th are presented in a Table. THD < 8% (harmonics up to the 40th)	IEC 61000-2-2: 6%-5th , 5%-7th , 3.5%-11th , 3%-13th, THD <8% IEC 61000-3-2: 5% -3rd , 6% - 5t^{h} , 5% -7th , 1.5% -9th , 3.5% -11th , 3% -13th , 0.3% - 15th , 2% - 17th
Interharmonics	-	IEC 61000-2-2: 0.2% (Indicative value)
Unbalance	LV, MV: up to 2% for 95% of week, mean 10 minutes rms values, up to 3% in some areas	IEC 61000-2-2 (Compatibility levels): 2% IEC 61000-2-12 (Compatibility levels): 2%, IEC 61000-4-27 (Immunity requirements and measurements)
Voltage Dips (Sags)	LV (Un), MV (Uc): Duration <1s, depth <60% (majority of dips).	IEC 61000-6-1, 6-2 (Immunity levels): up to 30% for 10 ms, up to 60% for 100 ms IEC 61000-6-2 (Immunity levels): up to 60% for 1000 ms
Short Interruptions	LV, MV: (up to 3 minutes) few tens - few hundreds/year Duration (70% of them) < 1 s	IEC 61000-6-1, 6-2: 95% reduction for 5 s
Long Interruptions	LV, MV: (Longer than 3 minutes) <10-50/year	-
Temporary Overvoltages (Swells)	LV: <1.5 kV rms MV: 1.7 Uc (solid or impedance earth) 2.0 Uc (unearthed or resonant earth)	-
Transient Overvoltages	LV: generally < 6kV (occasionally higher), rise time: ms - μs. MV: not defined	IEC 61000-6-1, 6-2: ±2 kV, line-to-earth, ±1 kV, line-to-line, 1.2/50(8/20) Tr/Th μs
Mains Signalling	LV, MV: Over 99% of a day, the 3 second mean of signal voltages must be less than or equal to defined values (in a figure). E.g., in LV networks, 5% of Un for frequencies between 1 and 10 kHz.	IEC 61000-2-2 (Compatibility levels)

Mains Signalling Voltage

A signalling system may sometimes be implemented on the distribution network. Ripple signals may be transmitted on the grid, for instance to give information on applicable prices or changes in price (from day to night, peak prices), or to control the switching on or off of certain loads, e.g. street lighting. The connection of EVs or other DG plants modifies the network impedances especially when considering large generating plants. This phenomenon may cause a modification in the harmonic resonance conditions near the connection point and the ripple signal may thus be affected.

Harmonics

Harmonics are also important issues[16,17] due to the wide use of power electronics converters as an interface between the EVs and the grid. EVs present another type of harmonic current sources connected to the grid as shown in Figure 4. In islanded operation the harmonic distortion may be higher than in interconnected operation due to the lower fault level and other reasons. Moreover, the harmonic resonance frequency during islanded mode of operation may be shifted to lower frequencies. In[21], it is shown that for high penetration of EVs and other harmonic sources connected on a distribution system, the maximum allowable voltage THD limits may be exceeded.

Interharmonics

Interharmonics may also be produced by power electronics converters, which may also cause flicker as we mentioned above. However, due to the lack of experience in this field, it is presently difficult to assess to what extent interharmonics are really an issue. Nevertheless, limits have been specified in IEC standards and national grid connection criteria for DG units, which are also applicable to EVs.

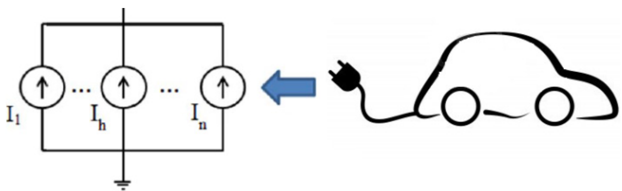

Figure 4. EVs as multiple harmonic current sources.

DC Injection

DC components injected into AC low voltage network are another important power quality but also safety and protection issue. DC injection is mainly caused by faulty operation of power electronic converters. It is crucial to separate symmetrical DC, flowing in phase and neutral conductors from unsymmetrical leakage current, flowing from phase to ground. The latter has fundamentally different implications, mainly related to electric shock and corrosion issues whereas the first is relevant for the components inserted in the network such as distribution transformers.

DC injection is normally an issue during abnormal conditions. When transformerless power electronic converters are used for the interconnection of DG units, the DC current will flow to the grid affecting the operation of other network or user equipment. When a transformer is used between the grid and the converter, only the transformer will be influenced by the DC current. In LV grids and microgrids, interconnection is usually implemented without a transformer, so special attention should be given.

DC injection is an emerging issue for standardization as no current IEC standards refer to this power quality parameter. However, other international standards such as IEEE 1547 define limits for DC injection. IEEE 1547 defines that: “The DR (Distributed Resource) and its interconnection system shall not inject DC current greater than 0.5% of the full rated output current at the point of DR connection”. European national grid codes have set limits for DC injection especially for photovoltaic (PV) installations. For example, in Germany: “The maximum DC current in PV installations connected in LV grids is 1A, above which the PV installation should be disconnected”. Maximum DC current levels vary in a wide range from levels as low as 20 mA up to 1 A or 0,5% up to 5% to various European national and International standards. For microgrid operation, a fixed planning level of DC injection should be set. A level in the range of the excitation current of the distribution transformer, which will not adversely affect transformer operation, could be a solution.

3.3. Summarization and Comparison of EN50160 and IEC Standards on EMC-Power Quality

Table 2 summarizes the applicable standards for EVs and power quality requirements including emission and immunity limits. Only EN 50160 and IEC standards are included. IEEE and other standards, such as those mentioned in the previous Section for standards on EVs and converters with references to electromagnetic compatibility issues, are not included.

4. Conclusions

EVs may cause power quality problems but they are also affected by power quality phenomena. Emission limits and immunity levels are need to be set prior to connection of EVs to distribution networks taking into account the characteristics of EVs to act either as user or producer of electricity. The mobility, generating/consuming variability and the use of power electronic interface systems should also be taken into account.

Current norms and standards on power quality requirements may be partly or fully adopted for the integration of EV concepts following the paradigm for network users and DG units. These standards have also been adopted by a number of countries with a few differences and/or extra requirements depending on the voltage levels, grid architecture and configuration, types of loads etc. It has been shown that limits set by EMC-Power Quality standards can be violated by a medium or high penetration of EVs for traditional electrical networks.

Moreover, special attention should be given for the connection of EVs in future electrical grids such as microgrids. Microgrids operating either in interconnected or islanded mode introduce special characteristics. International and national power quality standards apply mainly for the traditional configuration of grids, so proper changes on these standards should be issued.

In the current document, an effort has been made to analyze the impact on EMC or power quality parameters for grids with EVs and for power systems enabling microgrid operation. For the adaptation of microgrid-EV concepts to EMC-power quality standards the following actions are needed:

1. A full convergence of EMC and Power Quality issues.
2. A better definition of planning levels.
3. A methodology to apportion available emission and immunity levels of electrical networks in order to meet planning levels.
4. A complete guide for network operators in order to meet EMC-Power Quality requirements taking into account a high penetration of EVs and smart grid or microgrid operation.

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