Modelling of emission of PV inverters and Electric vehicles based on measurements

Panel on Harmonics from 2 kHz to 150 kHz: Immunity, Emission, Assessment and Compatibility

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Agenda

- **Some background**
- Electric vehicle chargers
- Photovoltaic inverters
- Basic modelling approach
Mysterious interference effects

My hood dryers switching on and off without interaction ...

If I want a coffee, I only get water, but fortunately only during the daytime ...

My cooker is whistling ... but only annoying melodies.

If my colleague connects his EV, my one stops charging.

You can be lucky, my EV does not start charging at all.

It sounds funny ... as long as you are not affected yourself.

... fortunately up to now it is yet rare, but still there ...

Further information can be found in the study reports developed by CENELEC SC205A TF EMI
Increasing importance of supraharmionics

- **Increase of emission** due to the increasing number of electronic equipment with higher switching frequencies

- **Increase of interferences** although equipment is marked with CE sign (e.g. audible noise, additional heating, malfunctions, ...)

- **Gap in standardization** (Urgent necessity for compatibility levels, emission limits and immunity limits)
  But work has started now (e.g. SC77A, CENELEC SC205A, ...)

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*Solar farmer close to Dresden*

*Fleet charging*
Ongoing standardization activities (SC77A)

**Compatibility level (WG8):**
- Intensive discussion between stakeholders
- Trade-off between protection of PLC and reasonable limits for other equipment required

**Emission limits (WG1):**
- Task force on 2-150 kHz
- Emission limits for lamps and induction cookers

**Immunity limits (WG6):**
- IEC 61000-4-19 released
- Very high requirements even for equipment for public networks

**Measurement issues (WG1):**
- IEC 61000-4-30 Ed.3 (informative annex)
- Discussion of different methods (with/without gaps, 200Hz/2kHz bands)

Complicated discussion because of the required signal-to-noise ratio between non-intentional and intentional emission

No complete framework yet available
Impact on other equipment

- Even small levels can cause interferences with customer complaints
- Increased current due to high frequency distortion of supply voltage might cause additional thermal stress (and unobvious life time reduction?)

Spectrum with customer complaints

Impact of 3 kHz voltage on compact fluorescent lamp
Classification of supraharmonic emission

**Duration of emission:**
- *Short time* (once for several seconds or minutes)
- *Long time* (multiple hours or longer)
  - Continuous occurrence (emission without interruptions)
  - Discontinuous occurrence (repeating emission)

**Characteristic of emission:**
- *Constant emission*
  No significant change in magnitude and/or frequency within one fundamental cycle (very rare)
- *Varying emission*
  Noticeable changes within one fundamental cycle
- *Transients*
  Very short time of the fundamental period (might occur together with varying or constant emission)
Analysis domain

Time domain analysis

Transients

Varying emission

Frequency domain analysis

Constant emission

Emission of a SMPS with active PFC in time-domain and frequency domain
Method for measurement in frequency-domain

**Acquisition**
- Sampling 1MS/s, 16bit per channel
- Storing raw data for 1…3.1s interval per min

**Digital high pass filter**
- 2kHz, 3rd order, elliptic

**Windowing**
- 200ms, rectangular

**DFT**

**Aggregating**
- to 200Hz bands

**RMS averaging**
- for each 1…3.1s interval

**IEC 61000-4-7 annex B**

**Post processing**
- Storing results

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**Graphical illustration:**

- Recording window
  - 1…3.1s interval
  - 200ms intervals
  - Quadratic averaging

- Time axis
  - 1 min intervals

- FFTs for each interval
Impact factors on emission of EV and PV

- **Device itself (primary emission)**
  - Circuit topology
  - Output impedance
  - Operating point
    (charging state for EV; solar irradiation for PV; ...)

- **Network (transfer)**
  - Grid impedance
  - Voltage distortion
  - Voltage magnitude

- **Other Devices (secondary emission)**
  - Switching frequency
  - Input impedance
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Example emission of an EV

Charging power and spectrogram for a particular EV

- Emission (frequency and level) depends on state of charge
- Highest emission usually
  - during operation with maximum charging current
  - at switching frequency
Variation of magnitude at switching frequency

Time-dependency of the emission levels at switching frequency for four different EV types

Highpass filtered current waveform of a fast charging station

- Significant variation of emission level at switching frequency during the charging cycle possible (EV 1 and 3)
- Considerable time-variation of supraharmonic emission
Spectral behavior

*Spectra of four different EVs at maximum charging current*

- Different characteristics for different EV types in terms of switching frequencies, magnitudes at switching frequency, level of time-variation

**Single generic model is not sufficient**
Classification of supraharmonic emission

<table>
<thead>
<tr>
<th>No significant emission</th>
<th>Significant emission</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bandwidth</strong></td>
<td><strong>Behaviour at switching frequency (magnitude and frequency)</strong></td>
</tr>
<tr>
<td>Narrow</td>
<td>Constant</td>
</tr>
<tr>
<td>Wide</td>
<td>Variable (discrete)</td>
</tr>
<tr>
<td></td>
<td>variable (continuous)</td>
</tr>
</tbody>
</table>

**Characterization in frequency domain (based on authors findings)**

*Spectrogram with narrow, continuous-variable emission*

*Spectrogram with wide, discrete-variable emission*
Survey of emission at switching frequency

Emission at switching frequency for 10 EVs in grid and 10 EVs in lab

- High diversity of emission magnitudes and frequencies between different EV types
- Significant dependency on network impedance at switching frequency (mostly determined by closeby equipment; no far propagation)
Input impedance characteristic of two EVs

- Different input impedance behavior of the EVs due to different circuit designs
- Significant variation of resonances in frequency and magnitude
- Work on output impedance characterisation still ongoing
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Example emission of a PV inverter

1. Switching frequency at about 16 kHz
2. Two operating states (Inverters are switched off during nighttime)
3. Almost constant emission at switching frequency during the day
Example emission behavior of a specific PVI

**Spectra of three different PVIs**

*at rated power injection*

- Lab measurement at three inverters (< 10 kW) with different topologies
- Equal testing conditions
- Differences between the inverters in magnitude and switching frequency
- Typical switching frequency (1st emission band) in the range of 15kHz ... 20kHz

**Single generic model is not sufficient**
Variation behavior of supraharmonic emission

- Significant variation but no extreme transients
- No zero-crossing oscillation
Impact of AC- and DC-voltage on emission level

- Two different operation areas for this specific PV inverter
- Variation of magnitude at switching frequency ($U_{B1}^{P0C}$) by up to 100 % (Laboratory measurements at reference impedance acc. to IEC 60725)
Input impedance characteristic of one PVI

- Multiple resonances with distinctive minima and maxima (as identified for EVs)
- Interaction of different impedance characteristics has significant impact on levels and propagation of supraharmonics
- Studies at FH Biel show that impedance depends also on operating state
Inverter A: Current source behavior

Inverter B: Source with impedance behavior

Inverter C: Voltage source behavior

- Different source behavior
- Model of output impedance is necessary for realistic studies and emission limit assessments
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- Modelling approaches
Modelling requirements

• Individual models for each EV / PV type (probabilistic parameter variation for devices of same type)

• Models has to include dependencies from many input factors, like
  – Supply voltage magnitudes
  – Output impedance
  – Operating conditions
  – ...

• Exact knowledge of (time-varying) connection point impedance

No single generic model

No simple constant voltage or current source models

Modelling seems to be complex and time-intensive
Modelling methodologies

- Component-based **time-domain models**
  - Exact knowledge of circuit design and control software required
  - Network simulation quickly slows down with increasing number of models
  - Very time-intensive model development
  - High accuracy in case of good quality of information

- Measurement-based **frequency-domain models**
  - Powerful teststand required (usually limited in maximum power)
  - Model accuracy is linked to comprehensiveness of measurements and information about impedances of the teststand
  - Quick increase of complexity of measurements and their analysis

*Are the classical ways of modeling useful applicable to suprahrenonics?*
Initial modelling approach in frequency-domain

**Source model**

- Only for switching frequency
- Non-constant voltage source based on lookup tables

**Sink model**

- Frequency-dependent input impedance only for the most common operating state
First modeling results

Output impedance identification by stepwise variation of network impedance

- Good accuracy for single device
- Still high errors for interaction between two devices

A lot of work is still required ...
Please, are encouraged to try yourself

- More than 10 labs from all over the world
- More than 500 different devices
- EV and PV measurements are included within the next weeks

Web-based platform for exchanging measurements of harmonic emission of electronic equipment

http://panda.et.tu-dresden.de
Thank you for your attention!

Power Quality should not be an excuse for blocking new technologies, but this does not mean no care at all.

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