Harmonic Distortion Compliance Assessment and Renewable Generators

Issues and Proposed Update

Context

- More and more inverters are connecting to the grid
- Their harmonic frequency behaviour is different from traditional rectifiers
- Fair assessment of added distortion is required for:
  - Commissioning
  - Periodic compliance check
  - Distortion allocation planning for the future
- Can we use current standards for this assessment? It’s getting harder…
- Measurement-based compliance decisions: clear pass/fail?
- Are shunt filters at plant level still the answer to distortion?

Issues and updates

Issues:

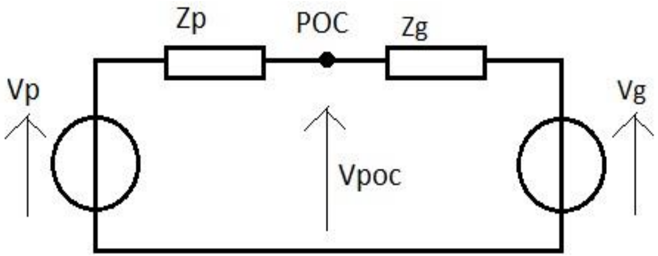
1. Grid and load interaction, contribution and amplification: what can a shunt filter do?
2. Measurement uncertainty: can’t run from it
3. Compliance assessment: is summation law still usable?

Updates:

1. Agree on what contribution is, and on what a filter can do
2. Estimate uncertainty for a fair assessment
3. Estimate grid impedance, validate model, use for compliance

Issue 1: contribution and amplification

- Harmonic current injected by:
  - Rectifiers: related to DC-side current, not AC-side voltage
  - Inverters: depends also on AC harmonic voltage, **they have an output filter**
- **Inverters' impedance interacts with grid impedance:**



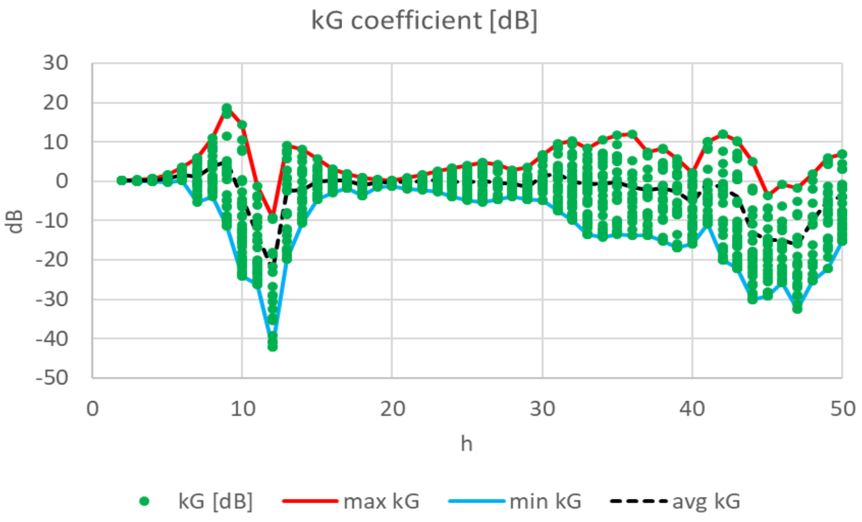
$$V_{POC} = V_p \frac{Z_g}{Z_p + Z_g} + V_g \frac{Z_p}{Z_p + Z_g}$$

$$V_{POC} = V_p k_p + V_g k_g$$

$$V_{POC}(V_g = 0) = V_p k_p; \quad V_{POC}(V_p = 0) = V_g k_g$$

Issue 1: contribution and amplification

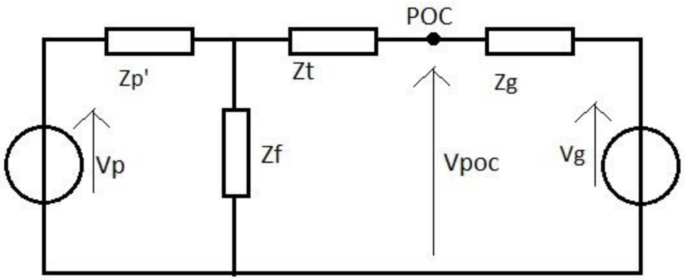
- |**kG**| can be <>1 (<> 0 dB)
- Even if V_p = 0, connecting the plant can change harmonic content of V_{poc}
- Can this be defined as contribution?
- Can proponents control it? Can they change **Zp** so that |**kG**|<1 ⍰ **Zg** ∈ polygons?
- What if plant is *attenuating* grid distortion? *Negative* contribution? Is it a *service*? See plot…



Example of kG in dBV: green dots stacked at each frequency are the values of kG for each polygon impedance point at that frequency

Issue 1: shunt filter at plant level vs amplification

- Classic shunt filter: low-Z trap for emissions
- Plant tries to change **Zp** via a shunt filter
- |**Zf**| = 0: ideal filter? No: possible resonance between **Zt** and **Zg**!
- Can **Zf** make **Zp** larger? Not always! E.g. if **Zp** is resistive
- Updates necessary:
  - Ideal shunt filter may not exist
  - Some emission/amplification remains
  - *Trade off and scenario-based design*



$$k_g = \frac{Z_p'//Z_f + Z_t}{Z_p'//Z_f + Z_t + Z_g}$$

$$k_g|_{Z_f=0} = \frac{Z_t}{Z_t + Z_g}$$

Issue 2: harmonic measurement uncertainty

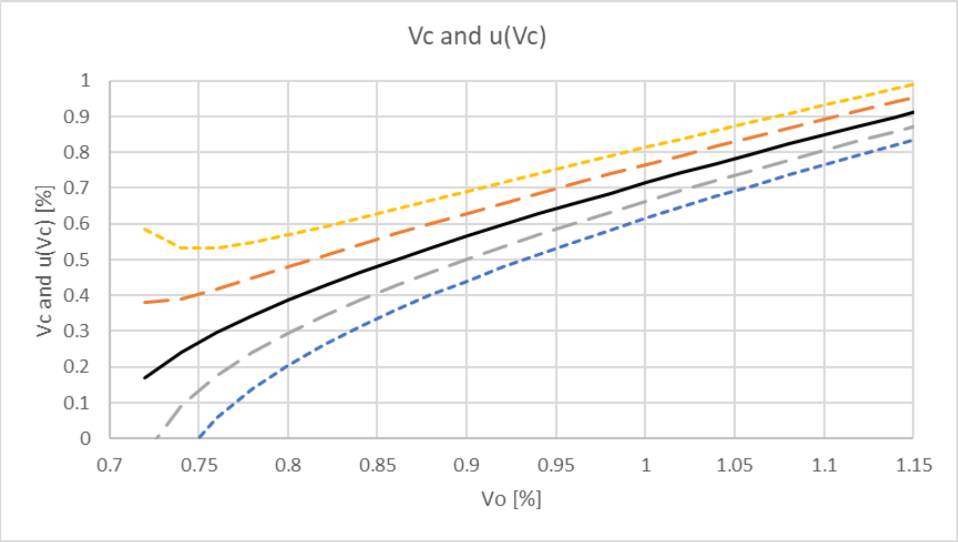
- Summation law (IEC61000-3-6): $U_h = \sqrt[\alpha]{\sum_i U_{h,i}^{\alpha}}$; with sources and weights (see before): $V_{POC} = \sqrt[\alpha]{\left(|\boldsymbol{V_p k_p}|\right)^{\alpha} + \left(|\boldsymbol{V_g k_g}|\right)^{\alpha}}$
- Invert to calculate contribution: $V_{POC,contrib.} = \sqrt[\alpha]{V_{POC,op}^{\alpha} - V_{POC,backg}^{\alpha}}$, where “op” means plant operating, and “backg” distortion before connection
- Contributed V_{poc} used for compliance assessment in “hold-point” testing
- *Questions:*
  - What is the *uncertainty* of contribution?
  - *$$$ depend on it!* Is uncertainty low enough for a *clear pass/fail?*

Issue 2: effect of background distortion uncertainty

- Use Guide to the expression of uncertainty in measurement (GUM 2008)
- Example: background V_b = 0.7%, V_{op} = 0.8%: uncertainty of contribution $u(V_c)$ vs uncertainty of background $u(V_b)$:

$u(V_b)$	$u(V_c)$
0.05%	±0.1%
0.1%	±0.2%

- $u(V_c)$ can make a *pass/fail unclear*
- Consider *probability of risk and severity of consequence for V_c > allocation*



Background: 0.7%; operation V_o: between 0.72% and 1.15%
Solid line: calculated contribution V_c
Uncertainty of V_c from uncertainty of V_b:

- $u(V_b)$ = 0.05%: long dash
- $u(V_b)$ = 0.1%: short dash

Issue 2: estimate background distortion uncertainty

- Key question: how *well* does the 95th percentile of the background of "yesterday" estimate the 95th percentile of "today"?
- How *confident* am I in stating: "They are close enough"?

Try this: at any node in the network:

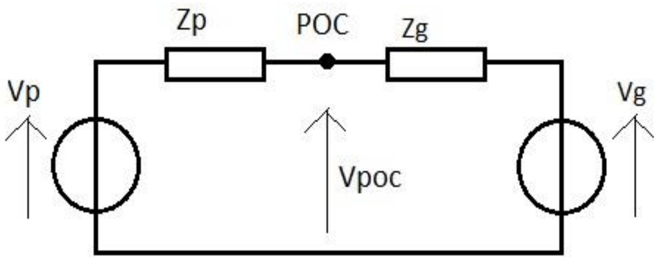
1. Measure distortion for subsequent 2 weeks' periods for 1 year
2. Take the 26 95th percentiles
3. Calculate variance of the 26 points: estimate of the uncertainty of V_b

Question: is this uncertainty *low enough* to achieve a clear pass/fail from the calculated contribution?

Issue 3: grid impedance and contributed distortion

Alternative method to estimate contributed distortion: use a **harmonic model**.

- Can be used for calculating the contribution of **Vp** alone
- The amplification of **Vg** can be estimated from $\boldsymbol{k_G = Z_p/(Z_p + Z_g)}$
- However… one needs to know **Zp** and **Zg**
- **Zg** can be especially tricky…
- ...but there are methods in literature to estimate its value



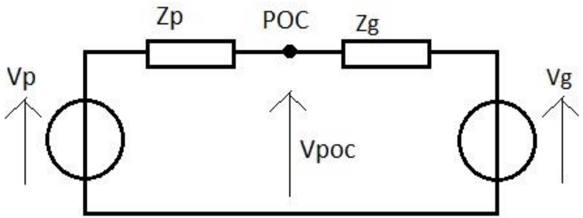
$$\boldsymbol{V_p = V_{POC} + Z_p I_{POC}}$$

$$\boldsymbol{V_{POC}(V_g = 0) = \frac{Z_g}{Z_p + Z_g} V_p}$$

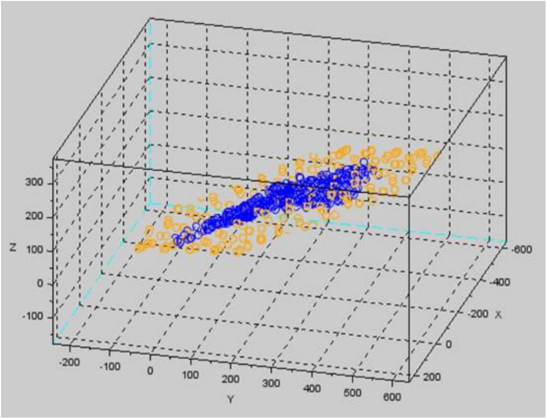
Issue 3: estimating grid impedance

Calculate “differential impedance” across two subsequent measurement intervals:

- Key: one distortion source must vary more than the other
- If V_p varies more than V_g, $Z_{diff} \approx Z_g$
- If V_g varies more than V_p, $Z_{diff} \approx Z_p$
- Literature gives examples of the application
- Variations can be created on purpose
- **A model can be used to estimate contribution!**
  - **In commissioning and for ongoing compliance**



$$\boldsymbol{Z}_{diff} = \frac{d\boldsymbol{V}_{POC}}{d\boldsymbol{I}_{POC}}$$



X = $\mathrm{Re}(I_{poc})$, Y = $\mathrm{Im}(I_{poc})$, Z = $\mathrm{Re}(V_{poc})$

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Conclusions

- A shunt filter may not solve amplification: a **trade-off** is important
  - Also, managing grid impedance from NSP side is an option
- Summation law: need a background, but what is its **uncertainty**? Estimate for fair decisions
- Model-based approach instead: create a **validated harmonic model** (through impedance measurement) and **distribute it** to proponents
- **Rule change**: allow other methods to be used, not just single standard
- Publish **distortion trends** and **allocations outlook** if they are becoming limiting factors in the uptake of inverter-based generation
- Distortion attenuation: can it become a **service** in a **market**?

Questions

Propagating uncertainty

- JCGM 100:2008 (GUM 1995 with minor corrections): Evaluation of measurement data – Guide to the expression of uncertainty in measurement
- Section 5.1: determining combined standard uncertainty, uncorrelated variables
- Assuming uncertainty in previously measured background's, and uncertainty of plant's contribution plus new background, are uncorrelated (some approximation here: in fact there are periodic trends in the background)

$$u_c^2(y) = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)$$

$$y = f(x_1, x_2, \dots x_i \dots x_n)$$

$$V_{POC,contrib.} = \sqrt[\alpha]{V_{POC,op}^{\alpha} - V_{POC,backg}^{\alpha}}$$

$$V_c = f(V_o, V_b) = (V_o^{\alpha} - V_b^{\alpha})^{\frac{1}{\alpha}}$$

$$\frac{\partial f}{\partial V_o} = V_o^{\alpha-1} \cdot (V_o^{\alpha} - V_b^{\alpha})^{\frac{1-\alpha}{\alpha}} = c_o \qquad \frac{\partial f}{\partial V_b} = -V_b^{\alpha-1} \cdot (V_o^{\alpha} - V_b^{\alpha})^{\frac{1-\alpha}{\alpha}} = c_b$$

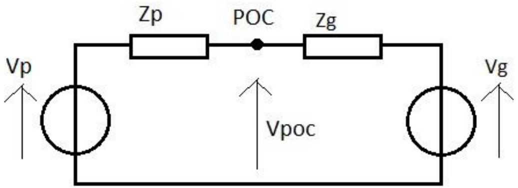
$$u_c^2(y) = c_o^2 u^2(V_o) + c_b^2 u^2(V_b)$$

For $\alpha = 1$: $c_o = 1, c_b = -1$

For $\alpha = 1.4$: $c_o = \frac{V_o^{0.4}}{(V_o^{1.4} - V_b^{1.4})^{0.2857}}$, $c_b = -\frac{V_b^{0.4}}{(V_o^{1.4} - V_b^{1.4})^{0.2857}}$

For $\alpha = 2$: $c_o = \frac{V_o}{\sqrt{V_o^2 - V_b^2}}$, $c_b = -\frac{V_b}{\sqrt{V_o^2 - V_b^2}}$

Estimating grid impedance: example



$$V_{POC} = V_p \frac{Z_g}{Z_p + Z_g} + V_g \frac{Z_p}{Z_p + Z_g}$$

$$V_{POC} = V_p k_p + V_g k_g$$

$$I_{POC} = V_p \frac{1}{Z_p + Z_g} - V_g \frac{1}{Z_p + Z_g}$$

$$I_{POC} = V_p k_c - V_g k_c$$

$$V_p = V_{p0} + V_p(t); \qquad V_g = V_{g0}$$

$$\begin{cases} V_{POC} = k_1 V_{p0} + k_1 V_p(t) + k_2 V_{g0} = k_1 V_p(t) + A \\ I_{POC} = k_c V_{p0} + k_c V_p(t) - k_c V_{g0} = k_c V_p(t) + B \end{cases}$$

$$\begin{cases} dV_{POC} = V_{POC}(t_2) - V_{POC}(t_1) = k_1 \cdot \left(V_p(t_2) - V_p(t_1)\right) = k_1 dV_p \\ dI_{POC} = I_{POC}(t_2) - I_{POC}(t_1) = k_c \cdot \left(V_p(t_2) - V_p(t_1)\right) = k_c dV_p \end{cases}$$

Where **A** and **B** are the sum of the constant terms. A “differential” impedance that considers two pairs of $\mathbf{V_{POC}}$ and $\mathbf{I_{POC}}$ observations at two different times can be written as:

$$Z_{diff} = \frac{dV_{POC}}{dI_{POC}} = \frac{k_1}{k_c} = Z_g$$

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Some literature

- **Uncertainty:** Working Group 1 of the Joint Committee for Guides in Metrology (JCGM/WG 1), "Evaluation of measurement data — Guide to the expression of uncertainty in measurement", 2008
- Evaluation of **grid impedance:**
    - Duan 1 Serfontein, D., Rens, J., Bothe, G., Desmet, J. "Continuous Event-Based Harmonic Impedance Assessment Using Online Measurements", in IEEE Transactions on Instrumentation and Measurement, vol. 65, no. 10, October 2016
    - Duan 1 Serfontein, D., Rens, J., Bothe, G., "Harmonic Impedance Assessment Using Prevailing Phasors", in proceedings of 18th International Conference on Harmonics and Quality of Power (ICHQP), Ljubljana, Slovenia, 2018
- **Summation law:**
    - IEC61000-3-6:2012
    - Germain Beaulieu, Robert Koch, Mark Halpin, and L. Berthet, "Recommended methods of determining power quality emission limits for installations connected to EHV, HV, MV and LV power systems," presented at the 19th International Conference on Electricity Distribution, Vienna, Austria 21-24 May, 2007