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Impact of modern power electronic household equipment on harmonic resonance in residential LV networks

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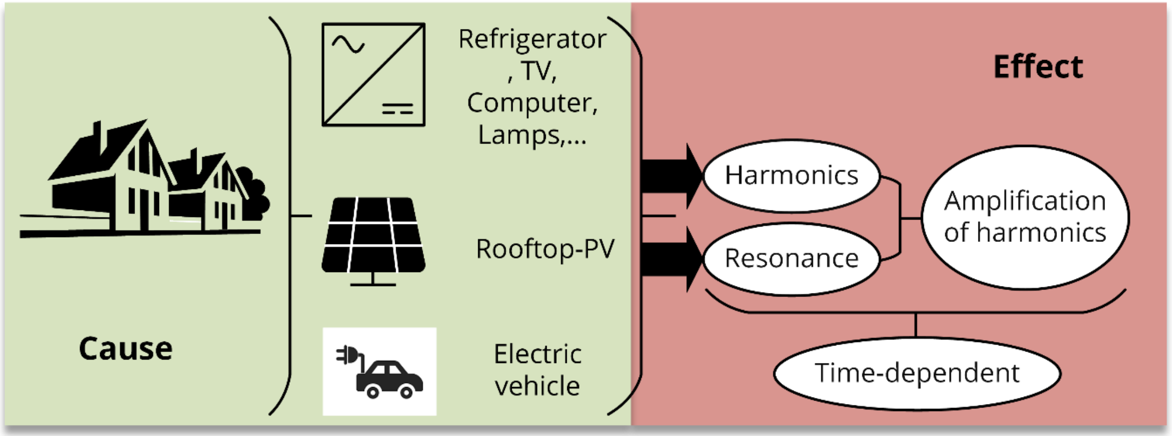
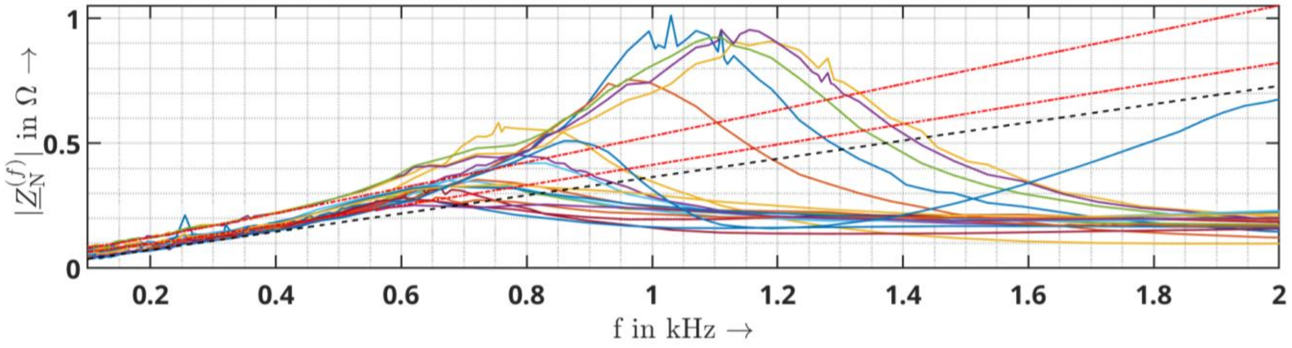
Introduction

- Power electronic-based equipment are increasing in residential low-voltage networks
- **Basis:** These equipment exhibit capacitive behaviour in the 100 Hz – 2 kHz frequency range
- **Consequence:** They interact with distribution transformer impedance producing **harmonic resonance**
- Harmonic resonance: higher impedance magnitude
- **Effects:** Harmonic resonance amplifies prevailing emission levels
- **Need:** Accurate models of household equipment to analyse resonance characteristics and harmonic propagation

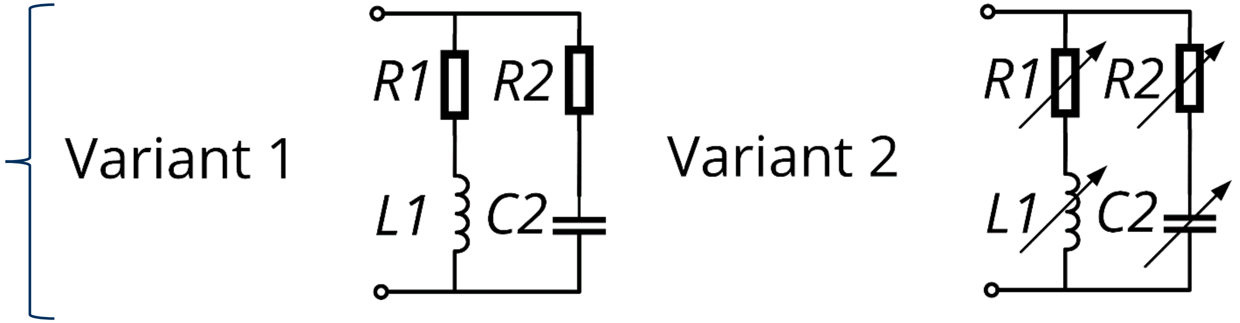


Network harmonic impedance from various public LV network measured at busbar



Introduction

- Generic models do not adequately represent:
  — time-varying mix of household equipment
  — evolution impact of such mixtures on resonances



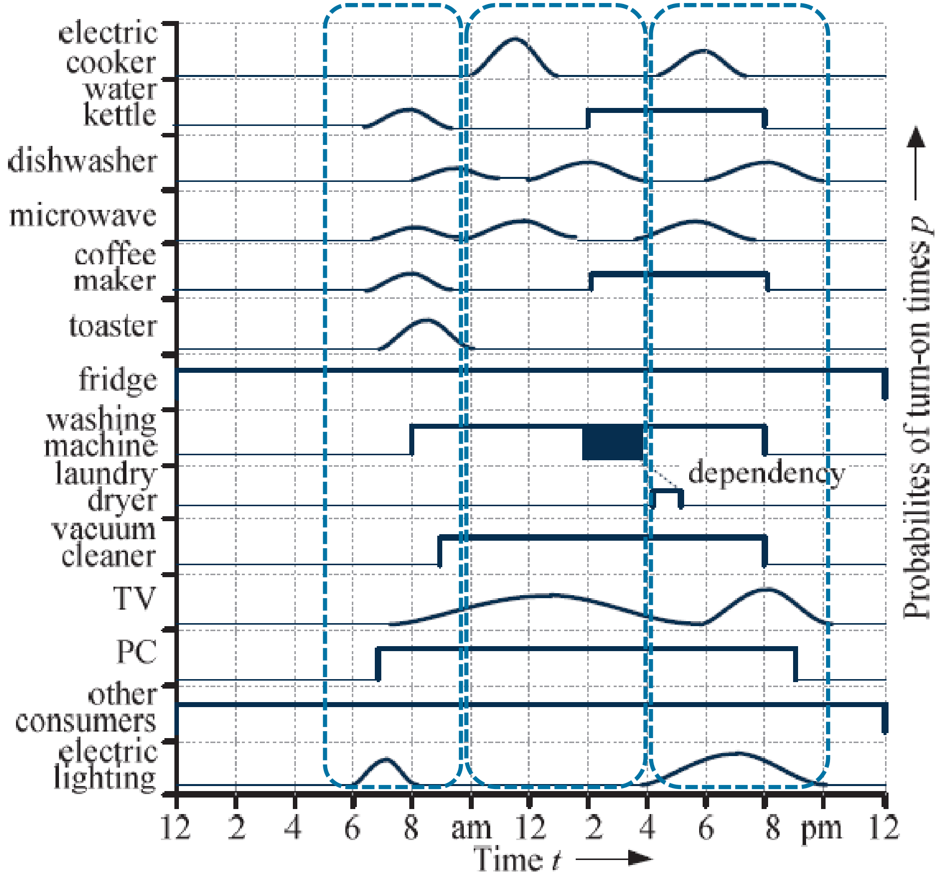
Work‘s focus

- To identify time-dependent mix of household equipment
- To analyse the evolution impact of such mixtures on resonances
- To model such mixtures for network-level simulation study

Modelling approach

- Simultaneous connection of many devices
- Time-dependent combination of devices: morning, noon, evening, and night
- Load demand at fundamental frequency also changes
- Device operation state decided by two factors: user‘s manual control and internal operating point
- LED lamp: only manual operation
- PC/Laptop: manual and internal
- Device selection in a load mixture: probabilistic turn-on time and operational duration—customer behaviour dependent

Probabilistic turn-on times of various household devices



Modelling approach

- Each device's front-end is designed as non-power factor corrected (pfc), passive-pfc, active-pfc, and passive
- Evolution-wise, the topology of devices have changed
- Example: lamps have changed from passive to n-pfc/p-pfc/a-pfc
- Approach specified in [1], provides different time-dependent load mixtures and used in this work
- 9 scenarios: three different loading condition (low, average, and peak) for past, present, and future scenarios

Device (D)	Device name	Past (A)	Present (B)	Future (C)
1	Refrigerator	Passive	Passive/a-pfc	a-pfc
2	Router	N/A	n-pfc	n-pfc
3	Incandescent lamps	Passive	N/A	N/A
4	CFL	N/A	n-pfc	N/A
5	LED	N/A	n-pfc /a-pfc	n-pfc/a-pfc
6	PC	n-pfc	p-pfc/a-pfc	a-pfc
7	Laptop	N/A	n-pfc	n-pfc
8	Hotplate/Water cooker	Passive	Passive	Passive
9	Induction stove	N/A	a-pfc	a-pfc
10	TV	n-pfc	n-pfc/ a-pfc	a-pfc
11	Hair dryer	Passive	Passive	Passive
12	Vacuum cleaner	Passive	Passive/n-pfc	n-pfc

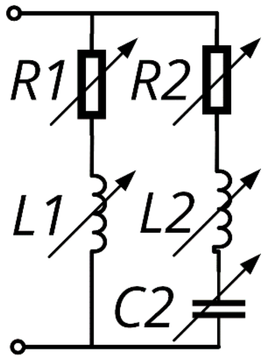
Load scenarios			
Evolution stage (k)	**I (low demand)**	**II (average demand)**	**III (peak demand)**
Past (A)	$D_{A1}+D_{A3}$	$D_{A1}+D_{A3}+D_{A6}$	$D_{A1}+D_{A3}+D_{A6}+D_{A8}$
Present (B)	$D_{B1}+D_{B2}+D_{B4}+D_{B5}$	$D_{B1}+D_{B2}+D_{B4}+D_{B5}+D_{B6}$	$D_{B1}+D_{B2}+D_{B4}+D_{B5}+D_{B6}+D_{B8}+D_{B9}$
Future (C)	$D_{C1}+D_{C2}+D_{C5}$	$D_{C1}+D_{C2}+D_{C5}+D_{C6}$	$D_{C1}+D_{C2}+D_{C5}+D_{C6}+D_{C9}$

Modelling approach

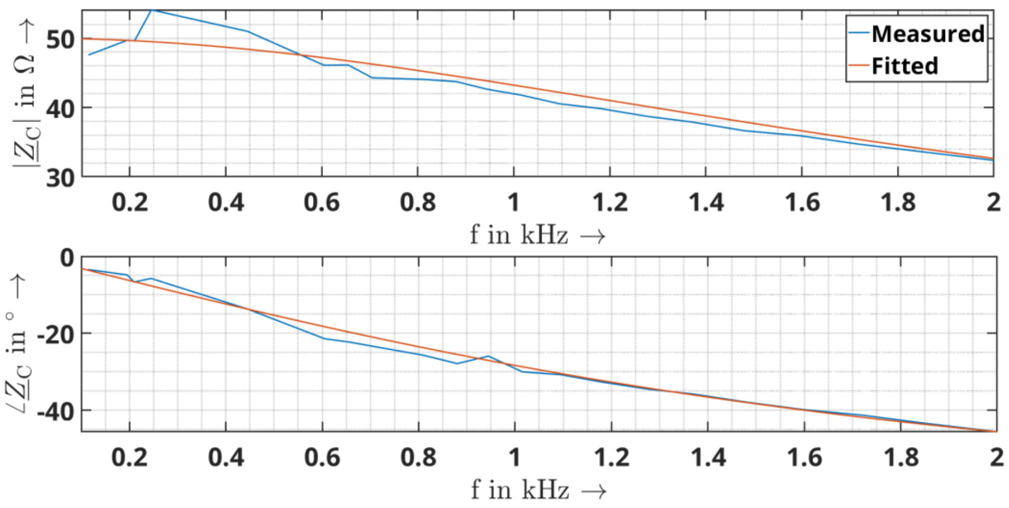
- Load mixtures are recreated in laboratory conditions
- Measured impedances for harmonic frequencies is fitted into RL||RLC using curve-fitting
- Cumulative error between measured and fitted impedance is given by:

$$\delta = \left| \frac{\sum_{h=3}^{39} \left| \underline{Z}_{fit}^{(h)} - \underline{Z}_{mes}^{(h)} \right|}{\sum_{h=3}^{39} \left| \underline{Z}_{mes}^{(h)} \right|} \right| \cdot 100\ \%$$

- R_1, R_2, and C_2 majorly influencing resonance



Measured and fitted impedance of a load mixture



Error for various load scenarios

Scenario	δ (%)
IA	0
IB	7.84
IC	7.48
IIA	20.8
IIB	19.2
IIC	7.89
IIIA	8
IIIB	4.86
IIIC	7.1

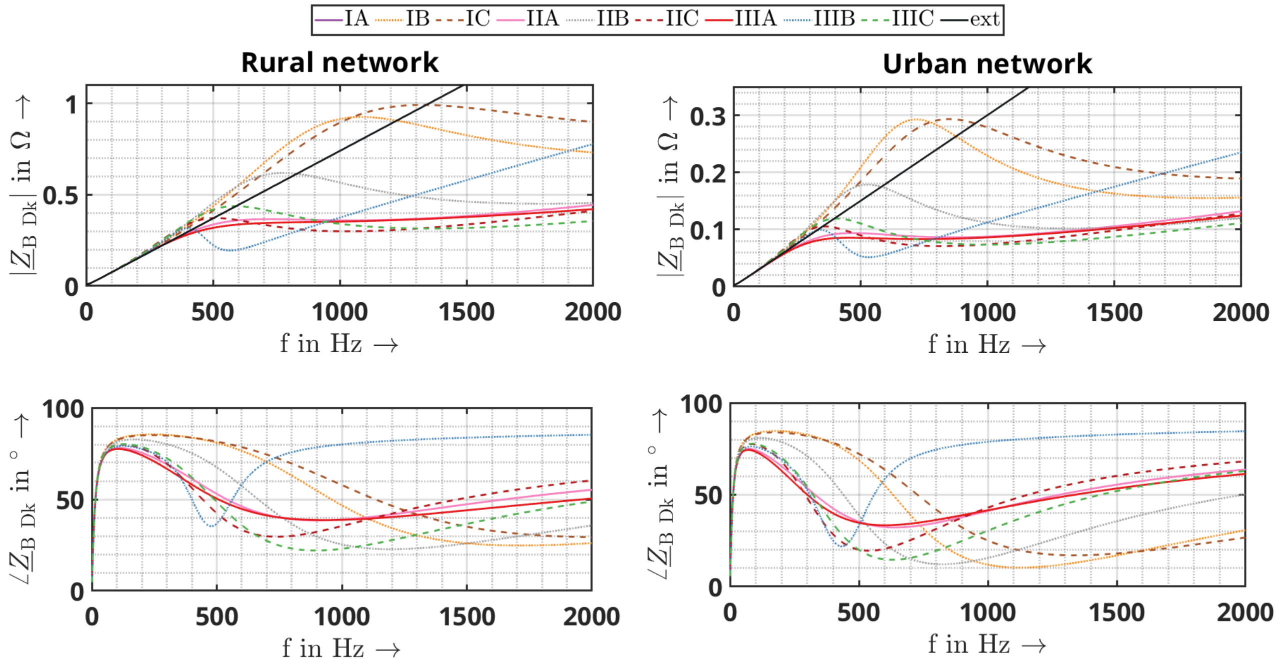
Simulation results

Simulation of two networks [2]:

— Urban network, 630 kVA, 180 users
— Rural network, 250 kVA, 30 users

- Load parameters for each scenario applied to all customers
- No resonances in past scenarios for all load conditions (solid)
- Resonances are possible for present (dot) and future (dashed) scenarios
- Magnitude ratio between the actual and extrapolated busbar impedance $k_{\mathrm{A\,Dk}}$ is used to quantify resonances

Network harmonic impedance simulated at busbar for different load scenarios



Simulation results

Urban and rural networks

- Present and future scenario have equal likelihood for resonance
- Low and medium loading conditions yield stronger resonance intensities
- Increase in loading reduces resonance frequency and intensity

Comparison

- Lower resonance frequency and higher resonance intensity in urban networks
- This is due to higher number of customers and shorted cable length

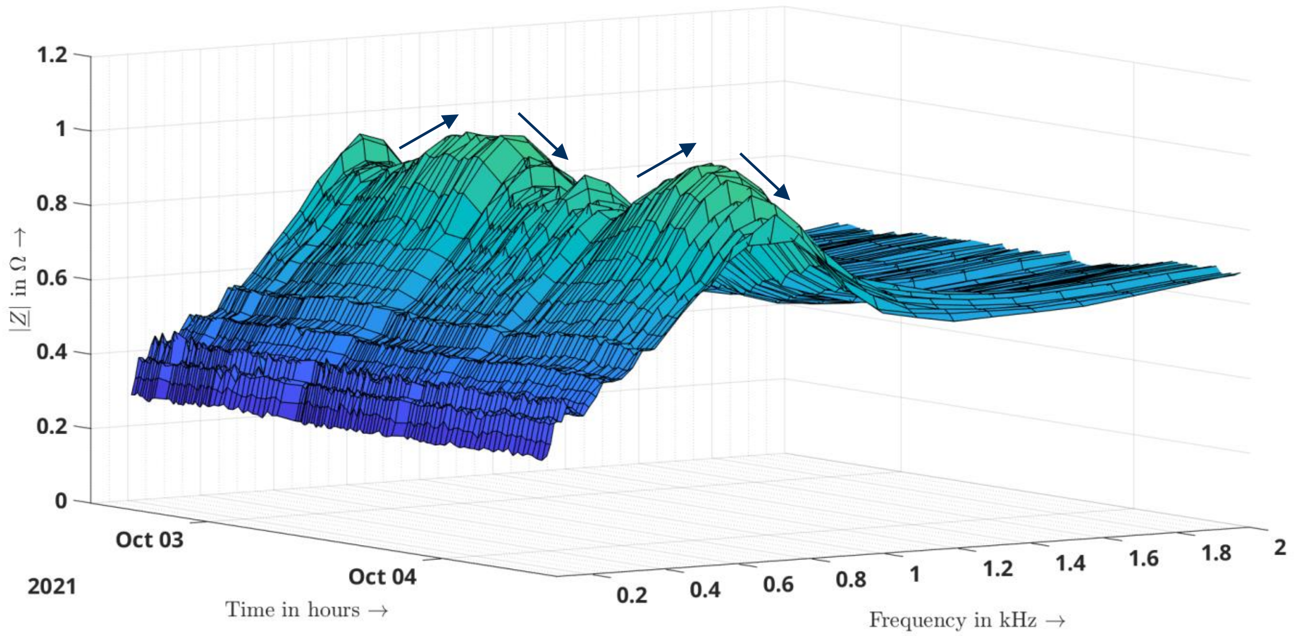
Resonance characteristics for various load scenarios

Scenario	Urban f_r (Hz)	Urban $k_{\mathrm{A\,Dk}}$	Rural f_r (Hz)	Rural $k_{\mathrm{A\,Dk}}$
IA	N/A	N/A	N/A	N/A
IB	608	1.47	810	1.32
IC	656	1.3	881	1.23
IIA	N/A	N/A	N/A	N/A
IIB	412	1.27	569	1.25
IIC	251	1.15	352	1.17
IIIA	N/A	N/A	N/A	N/A
IIIB	N/A	N/A	358	1.14
IIIC	284	1.15	413	1.18

Field measurement results

- Time-dependent characteristics of resonances
- Resonance magnitude highest at night (sleep time)
- Load demand increases from night to day
- Resonance magnitude decreases from night to day
- Consistent characteristics for two consecutive days
- Consistent with the simulation results

Time-dependent resonance characteristics at a PoC in a residential LV network



Summary

- Frequency-domain impedance models for household mixtures representing different time-dependent and evolution stages are derived
- Likelihood of resonances increases in present and future scenarios
- Urban networks are prone to slightly severe resonance compared to rural networks

Future works

- More load mixtures to be recreated and measured in lab
- Disparity in user behaviour: random distribution of load mixtures to different households
- Device tolerance and manufacturer disparity: uniform distribution of load parameters
- Flexible reference public low-voltage network

Important references

[1] J. Dickert and P. Schegner, “A time series probabilistic synthetic load curve model for residential customers,” 2011 IEEE PES Trondheim PowerTech Power Technol. a Sustain. Soc. POWERTECH 2011, pp. 1–6, 2011.

[2] Malekian, K. ; Safargholi, F. ; Küch, K. ; Domagk, M. ; Meyer, J. ; Hoven, M.: Characteristic parameters and reference networks of German distribution grid (LV, MV, and HV) for power system studies. In: ETG Congress 2017 - Die Energiewende, 2017.

Thank you for your attention