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Continuous non-invasive harmonic resonance detection and characterization in residential low-voltage networks

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von der Fakultät Elektrotechnik und Informationstechnik
der Technischen Universität Dresden

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Abstract

Harmonic resonances are increasingly observed in central European residential low-voltage networks. These resonances are caused by increased usage of power-electronic-based equipment such as household appliances, electric vehicle chargers, and photovoltaic inverters. These resonances amplify the prevailing disturbance levels produced by the power-electronic-based equipment thus inducing a cause-effect loop. These equipment are connected and disconnected by the users at various time instances in a day resulting in a time-dependent cause and effect of harmonic resonances. This warrants a continuous detection and characterization of harmonic resonance in residential low-voltage networks. The resonance can be detected by both invasive and non-invasive approaches. The invasive approaches are accurate but are oftentimes costlier and bulkier solutions. Furthermore, as they inject a signal to detect resonances, they may disturb the nominal operation of the network and cannot be continuously used. The non-invasive approaches are more suited for continuous detection and characterization of resonance since they measure only harmonic voltages and currents and do not inject any disturbing signal. However, their typical disadvantages such as less reliability and longer measurement durations need to be addressed.

To develop such a non-invasive technique, simulation models that represent the time-dependent characteristics of harmonic resonance are developed. The simulation models were developed based on extensive field measurements carried out in various central European networks. The accuracy of the models in terms of their capability to represent harmonic resonance characteristics was also assessed based on data obtained from the campaign. Using the simulation models, the characteristics of harmonic resonance for various realistic scenarios were analyzed. Based on the results from this analysis, it was evident that a single measurement location—low-voltage busbar of supply transformer—is sufficient to comprehensively detect and characterize the resonance noninvasively.

Using the insights obtained from the analysis, in this work, a non-invasive technique for continuous detection and characterization of harmonic resonance in residential low-voltage networks is presented. The technique is formulated in three stages based on three indices each detecting a harmonic resonance characteristic. The indices are validated using the simulation model developed and presented in this work. The success rate of the detection and characterization technique is validated using short- and long-term measurement campaigns in residential low-voltage networks, which are also part of the application example of the proposed technique. Based on the results presented in this work, it was evident that the proposed technique is successful in detecting and characterizing their respective harmonic resonance characteristics continuously.

Zusammenfassung

Harmonische Resonanzen werden zunehmend in mitteleuropäischen Niederspannungsnetzen beobachtet. Diese Resonanzen werden durch den verstärkten Einsatz von leistungselektronischen Geräten wie Haushaltsgeräten, Ladegeräten für Elektrofahrzeuge und Photovoltaik Wechselrichtern verursacht. Diese Resonanzen verstärken die vorherrschenden Störpegel, die von den leistungselektronischen Geräten erzeugt werden, und führen so zu einer Ursache-Wirkungs-Schleife. Diese Geräte werden von den Nutzern zu verschiedenen Zeiten am Tag ein- und ausgeschaltet, was zu einer zeitabhängigen Ursache und Wirkung von harmonischen Resonanzen führt. Dies rechtfertigt eine kontinuierliche Erkennung und Charakterisierung von harmonischen Resonanzen in privaten Niederspannungsnetzen. Die Resonanz kann sowohl mit invasiven als auch mit nicht-invasiven Methoden nachgewiesen werden. Die invasiven Verfahren sind zwar genau, aber oft kostspieliger und umfangreicher. Da sie außerdem ein Signal zur Erkennung von Resonanzen einspeisen, können sie den Nennbetrieb des Netzes stören und können nicht kontinuierlich eingesetzt werden. Die nicht-invasiven Ansätze eignen sich besser für die kontinuierliche Erkennung und Charakterisierung von Resonanzen, da sie nur Oberschwingungsspannungen und -ströme messen und kein Störsignal einspeisen. Ihre typischen Nachteile wie geringere Zuverlässigkeit und längere Messdauer müssen jedoch behoben werden.

Um eine solche nicht-invasive Technik zu entwickeln, werden Simulationsmodelle entwickelt, die die zeitabhängigen Eigenschaften der harmonischen Resonanz darstellen. Die Simulationsmodelle wurden auf der Grundlage umfangreicher Feldmessungen entwickelt, die in verschiedenen mitteleuropäischen Netzen durchgeführt wurden. Die Genauigkeit der Modelle in Bezug auf ihre Fähigkeit, die Merkmale der harmonischen Resonanz darzustellen, wurde ebenfalls auf der Grundlage der aus der Kampagne gewonnenen Daten bewertet. Mit Hilfe der Simulationsmodelle wurden die Eigenschaften der harmonischen Resonanz für verschiedene realistische Szenarien analysiert. Anhand der Ergebnisse dieser Analyse wurde deutlich, dass ein einziger Messort - die Sammelschiene des Versorgungstransformators - ausreicht, um die Resonanz umfassend und nichtinvasiv zu erfassen und zu charakterisieren.

Unter Verwendung der aus der Analyse gewonnenen Erkenntnisse wird in dieser Arbeit ein nicht-invasives Verfahren zur kontinuierlichen Erkennung und Charakterisierung von Oberschwingungsresonanzen in privaten Niederspannungsnetzen vorgestellt. Das Verfahren wird in drei Stufen formuliert, die auf drei Indizes basieren, die jeweils eine harmonische Resonanzcharakteristik erkennen. Die Indizes werden anhand des in dieser Arbeit entwickelten und vorgestellten Simulationsmodells validiert. Die Erfolgsrate der Erkennungs- und Charakterisierungstechnik wird anhand von Kurz- und Langzeitmesskampagnen in Niederspannungsnetzen in Wohngebieten validiert, die auch Teil des Anwendungsbeispiels der vorgeschlagenen Technik sind. Die in dieser Arbeit vorgestellten Ergebnisse zeigen, dass das vorgeschlagene Verfahren erfolgreich ist, wenn es um die kontinuierliche Erkennung und Charakterisierung der jeweiligen harmonischen Resonanzcharakteristiken geht.

Nomenclature

Symbols

f	Frequency
R	Resistance
L	Inductance
C	Capacitance
G	Conductance
$\underline{Z}$	Complex impedance
$\underline{U}$	Complex voltage phasor
$\underline{I}$	Complex current phasor
QF	Quality factor
B	Bandwidth
X	Reactance
N	Number of either grid- or customer-side customers
$f()$	function
k	various k parameters
$\boldsymbol{k}$	Array of various values of k parameters
$d-q$	Synchronous reference frame components
δ	Error between the measured and fitted curves
θ	Impedance angles
$\boldsymbol{\theta}$	Array of impedance angles
ψ	Sum of impedance angles
Δ	Indicates the deviation from reference value
n	Grid-side harmonic voltage phasors
m	customer-side current harmonic phasors
par1	Statistical indices of various probability functions
par2	Statistical indices of various probability functions
δ	Error between estimated and measured value for customer models
$\mathbf{a}$(K)	Array of measured harmonic voltage phasors
$\mathbf{B}$(K)	Array of measured harmonic current phasors
$\boldsymbol{c}$	function of grid-side harmonic voltage and impedance
$p1$	Denotes part 1 of harmonic voltage magnitude
$p2$	Denotes part 2 of harmonic voltage magnitude
$p12$	Product of part 1 and part 2 of harmonic voltage magnitude
$p3$	Denotes part 1 of harmonic current magnitude
$p4$	Denotes part 2 of harmonic current magnitude
$p34$	Product of part 1 and part 2 of harmonic current magnitude
pt	Squares of different parts of harmonic magnitude
ρ	Pearson coefficient
cov	Covariance of two random variables
σ	Mean of a variable
P	Active power
Q	Reactive power
$\underline{S}$	Complex power
O	Number of occurrences
tr	Trigonometric entities
SR	Success rate

Superscripts

h	Harmonic order
f	Frequency
hr	Resonant harmonic order
fr	Resonant frequency
50	Fundamental frequency
1	Fundamental harmonic order

Subscripts

C	Customer-side
G	Grid-side
N	Network: parallel of grid-side and customer-side
B	At the LV busbar of an MV/LV distribution transformer
MV	At the MV busbar of an MV/LV distribution transformer
LV	At any LV busbar of a residential LV network
PoC	At a point of customer connection
PoE	Point of evaluation
amp	Amplification
atn	Attenuation
ext	extrapolated
p1	Part 1
p2	Part 2
Z	Used with k factor as resonant amplification factor
pre	Before injection
post	During injection
inj	Used to denote injected signal
mes	Measured
fit	Fitted
ag	denotes aggregated model or associated parameters
u	Upstream MV network
t	Transformer
p	Primary-side of the MV/LV transformer
s	Secondary-side of the MV/LV transformer
f	Feeder parameters
eq	Equivalent from the secondary side of the MV/LV transformer
1	To denote parameters in the first branch of an electrical circuit
2	To denote parameters in the second branch of an electrical circuit
y	resonance or no-resonance scenario
ph	Various phases
$\mathrm{L1, L2, L3}$	phase of line conductors
A	Resonance scenario
D	Non-resonance scenario

F	Feeder in an LV network for resonance studies
$\mathrm{BB}-\mathrm{F}$	LV Busbar of distribution transformer for resonance studies
$\mathrm{B}-\mathrm{F}$	Beginning of a feeder in an LV network for resonance studies
$\mathrm{M}-\mathrm{F}$	Middle of a feeder in an LV network for resonance studies
$\mathrm{E}-\mathrm{F}$	End of a feeder in an LV network for resonance studies
max	denotes maximum value of a given variable
min	denotes minimum value of a given variable
U, I	A part of harmonic phasors belongs to voltage or current
z	To indicate various parts of a harmonic phasor/ power
I	Part 1 of a harmonic phasor/ power
II	Part 2 of a harmonic phasor/ power
III	Part 3 of a harmonic phasor/ power
$\sum$	Sum of all parts of harmonic phasor/ power
P	Active power
Q	Reactive power
ref	Reference
asm	Assumed
est	Estimated
95	95^{th} percentile of an array of values
pf1	To denote a k-parameter in estimated phase angle
pf2	To denote a k-parameter in estimated phase angle
qf1	To denote a k-parameter in estimated phase angle
qf1	To denote a k-parameter in estimated phase angle
bgx	To denote a k-parameter in estimated phase angle
err	To denote error between the estimated and actual phase angle
stage s	stage number
series	To denote series impedance
parallel	To denote parallel impedance

Selected mathematical symbols and functions

$\underline{\chi}$	Complex number, resting phasor
χ	Magnitude of $\underline{\chi}$
$\boldsymbol{\chi}$	Matrix or array of χ
$\lvert\underline{\chi}\rvert$	Absolute value of $\underline{\chi}$
$\angle\underline{\chi}$	Angle, phase, argument of $\underline{\chi}$
$\Re(\underline{\chi})$	Real part of $\underline{\chi}$
$\Im(\underline{\chi})$	Imaginary part of $\underline{\chi}$
$\underline{\chi}^*$	Complex conjugate of $\underline{\chi}$
j	Imaginary unit

List of acronyms

AC	Alternating current
apfc	Active-power factor corrected
BHI	Busbar harmonic impedance
D-A-CH-CZ	Technical rules for the assessment of network disturbances
DC	Direct current
DIBS	Discrete interval binary sequence
DSO	Distribution System Operator
EVC	Electric vehicle chargers
FDI	Frequency-dependent impedance
FDNI	Frequency-dependent network impedance
HV	High Voltage
ICA	Independent component analysis
IGBT	Insulated-gate bipolar transistor
LV	Low voltage
MGS	Modulated gaussian signals
MLBS	Maximum length binary sequence
MOSFET	Metal-oxide-semiconductor field-effect transistor
MV	Medium voltage
NHI	Network harmonic impedance
npfc	Non-power factor corrected
PE	Power electronic
PoC	Point of connection
PoE	Point of Evaluation
ppfc	Passive-power factor corrected
PRBS	Pseudo random binary sequence
PVI	Photovoltaic inverters
VDE	German Association for Electrical, Electronic and Information Technologies
PQ	Power quality

Contents

1. Introduction

Resonance phenomena first gained importance in transmission networks due to subsynchronous oscillations [61, 81] and later in industrial distribution networks [89] and offshore wind parks [66] due to interactions between the reactive power compensation device and feeders and transformers. In these networks, the cause and effects of resonances are well-known, allowing a detailed analysis of their resonance characteristics. Over the past few decades, in residential low-voltage (LV) networks, power electronic (PE)-based appliances are increasingly used by customers [132]. These appliances exhibit capacitive behavior and interact with the feeders and distribution transformer increasing the risk of resonant conditions.

Resonances in any network do not pose any harmonic problem unless they are not excited by the harmonic emission sources. Resonances that occur in residential LV networks are a complex phenomenon that needs to be studied since the elements that produce them are distributed and not concentrated. The PE-based appliances in the residential LV network act as one of the harmonic emission sources that stimulate the resonances. Resonances further amplify these harmonic emission sources and increase harmonic disturbances, inducing a causal effect as depicted in Fig. 1.1. Increased harmonic levels can cause adverse effects such as overheating of cables, overloading of the neutral conductor, damage of capacitors, etc [63]. Therefore, these resonances should be detected in a residential LV network.

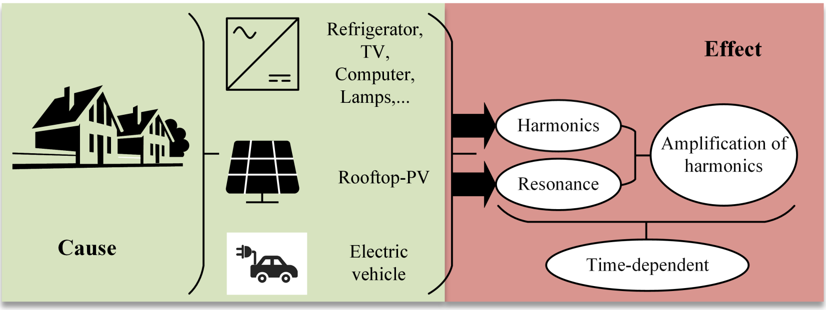

Figure 1.1.: Causal effect of amplification of harmonics due to power-electronic-based residential appliances

The operation of PE-based appliances in residential LV networks is time-dependent. Household appliances, photovoltaic inverters (PVIs), and electric vehicle chargers (EVCs) change their operating point depending on customer usage or environmental conditions. As Fig. 1.1 shows, the resonance characteristics change dynamically due to the time-dependent combination of these electronic power appliances, and thus the amplification of the harmonics. Oftentimes, only a single resonance peak occurs in frequencies less than 2 kHz albeit whose characteristics are time-dependent. Therefore, these varying resonances need to be measured, detected, and characterized continuously. Off-line simulation-based analyses such as resonant mode, eigenvalues, and sensitivity are not suitable for such continuous detection. Impedance measurement techniques — invasive and non-invasive — can be used for such continuous detection of resonances. Invasive techniques disturb the network by injecting a signal to calculate the impedance, resulting in greater accuracy. However, they are not suitable for continuous resonance monitoring as frequent network disturbance is undesirable. Non-invasive techniques observe the harmonic disturbances without disturbing the normal operation of the network. They use complex statistical tools to select data for impedance estimation that satisfy certain threshold criteria. These techniques are less accurate and require a long measurement duration. Despite the accuracy of invasive techniques, non-invasive techniques are best suited for continuous detection of resonances, as they do not disturb the nominal operation of the network. However, such a non-invasive technique capable of continuously characterizing the resonance is not available in the literature.

Once these resonances are detected and characterized, the major application is to damp them either using active or passive approaches. Since the resonating elements are not concentrated in residential LV networks, only active resonance damping solutions are best suited. However, these damping solutions that are commercially available may be expensive for an LV network as the first solution. Whereas, the non-invasive resonance detection and characterization implemented in a cost-effective power quality (PQ) instrument can provide a first insight to the distribution system operator (DSO) on a continuous basis that would allow them to decide if a sophisticated damping solution may be required. In this thesis, the focus is on developing a non-invasive detection and characterization technique that is simple to implement and would provide valuable insights on resonances to the DSO.

Research questions

As the main focus of this thesis is to develop a continuous non-invasive resonance detection and characterization technique for residential LV networks, it should not require a long measurement duration, yet achieve faster and more reliable detection of resonances. To develop and validate this non-invasive technique for resonance detection, the following research questions need to be fulfilled:

1. What are the simulation model requirements to emulate the time-dependent harmonics and resonance characteristics?
2. How do various parameters affect and get affected by resonances?
3. Is a single or multiple measurement point required to be used to effectively detect and characterize resonance?
4. What are the indices with which non-invasive continuous resonance detection and characterization can be achieved?
5. How are the indices used to develop a resonance detection technique and how effective is the proposed technique?

Outline of the thesis

The rest of the thesis is organized into three major parts. Each of the parts aimed to answer the aforementioned research questions.

The first part entails two chapters wherein Chapter 2 presents the overview of resonances. It outlines the causes and effects of resonance and emphasizes the necessity of continuous measurement-based resonance detection and characterization. Chapter 3 presents the state-of-the-art on harmonic resonance detection and modeling. It details the various techniques for continuous resonance detection and characterization in LV networks. It also enunciates the modeling requirements for detecting resonances. It identifies the research gaps concerning the modeling and detection of resonances.

The second part presents the modeling and characteristics of resonances in residential LV networks. Chapter 4 illustrates the simulation models of residential LV networks for resonance studies. The rationale behind the modeling and their specific requirements are also discussed. The models are then validated against field measurement data to ensure they are representative. Chapter 5 characterizes the resonance based on the impact of various parameters such as the power capacity of the network, feeder type, type of load mixture, etc. This chapter also aims to answer the research question of whether single or multiple measurement points are required to detect and characterize the resonance continuously.

The third part presents the mathematical basis, simulation, and field validation of the novel non-invasive continuous resonance detection and characterization technique developed in this thesis. Chapter 6 identifies three indices with which continuous resonance detection and characterization can be achieved. It validates the efficiency of the indices through simulation studies. Chapter 7 presents the technique to detect and characterize the resonance continuously and noninvasively using the indices developed. It further validates the technique for realistic resonance conditions using measurement data from various German residential LV networks. Chapter 8 highlights the salient contribution of this work and concludes the thesis.