Converter Impedance Characterization for Stability Analysis of Low-Voltage DC-Grids

Presented by K. Rykov,
Eindhoven University of Technology,
the Netherlands

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Introduction 1/2

- Growing popularity of DC generation instead of AC
- Wide range of applications of low voltage DC grids
- The paper was written within the EU project "Direct Current Components and Grid"

Nevertheless

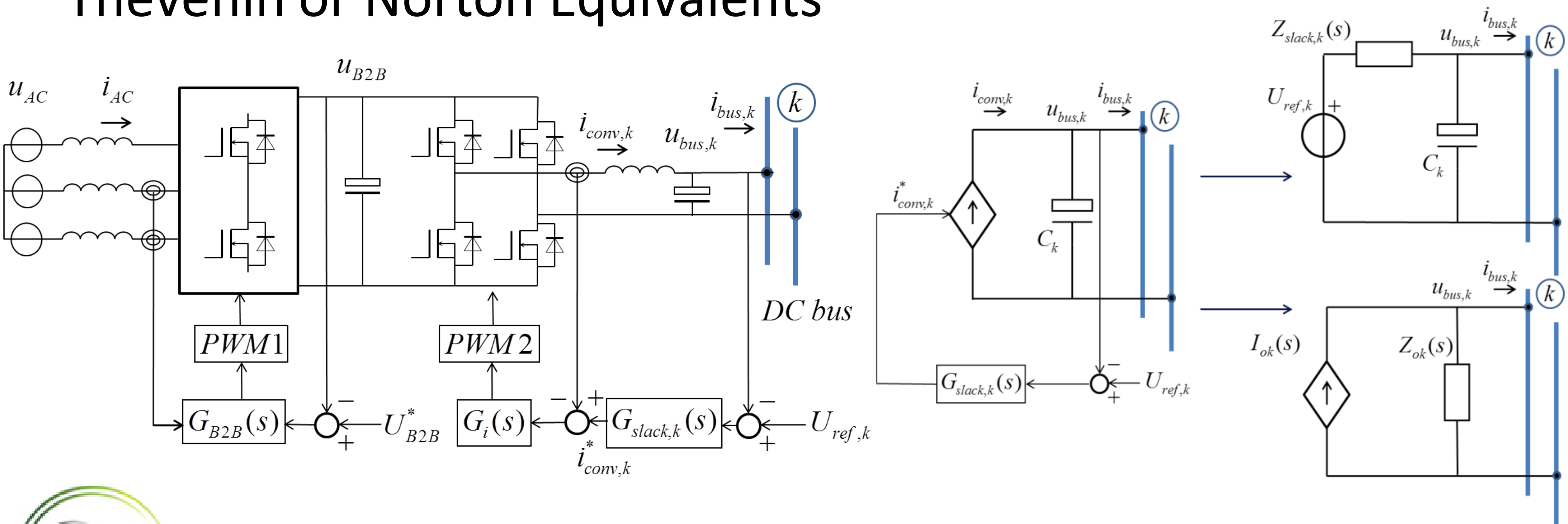
- Interaction among heterogeneous power modules has not been well investigated yet
- Output impedances of power converters combined together may cause resonance issues
- Internal structure of converters including control parameters usually is not known

Introduction 2/2

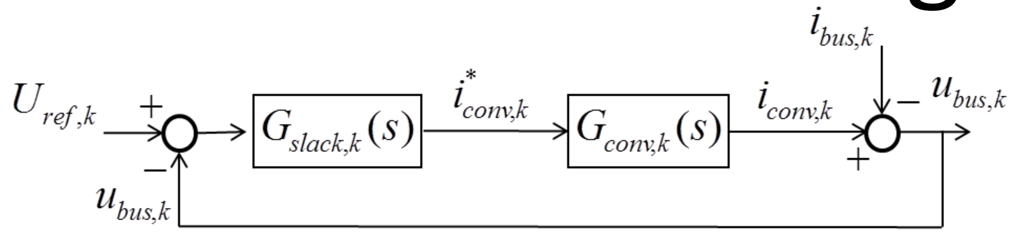
- The paper proposes the technique of experimental impedance identification applied separately to each power module
- Operation of the aggregated system is consequently analyzed

Theoretical Modelling 1/2

- Average models with the switching process neglected, enables the description of a DC-grid by means of linearised transfer functions
- The dynamics of the actively controlled converters can be modelled as equivalent impedances in frequency domain using Thevenin or Norton Equivalents



Theoretical Modelling 2/2



- The transfer function of the PI controller is found to be

$$G_{slack,k}(s) = K_p + \frac{K_i}{s}.$$

- The converter module may be represented by just a unity current gain, including a propagation delay

$$G_{conv,k}(s) = \frac{i_{conv,k}(s)}{i^*_{conv,k}(s)} = \frac{1}{1 + (nT_{sw})s}.$$

- Total transfer function of the slack module and the resulting converter impedance:

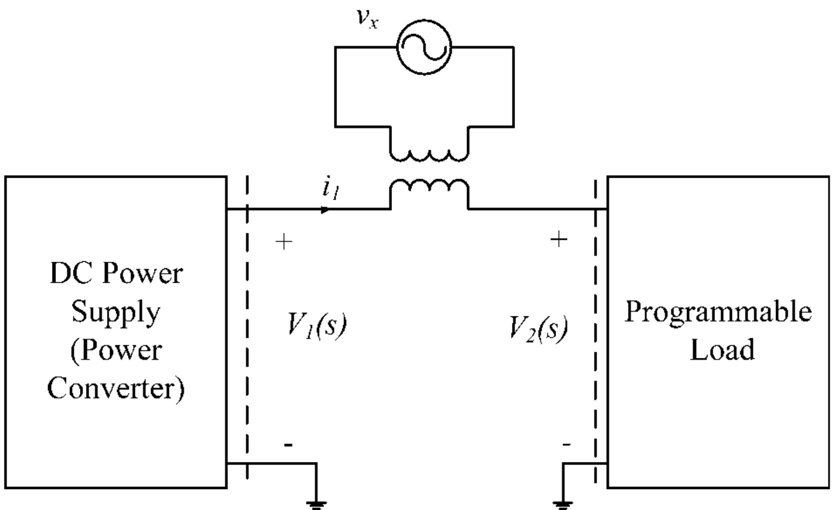
$$G_k(s) = G_{slack,k}(s) \cdot G_{conv,k}(s), \qquad Z_{slack,k}(s) = 1/G_k(s).$$

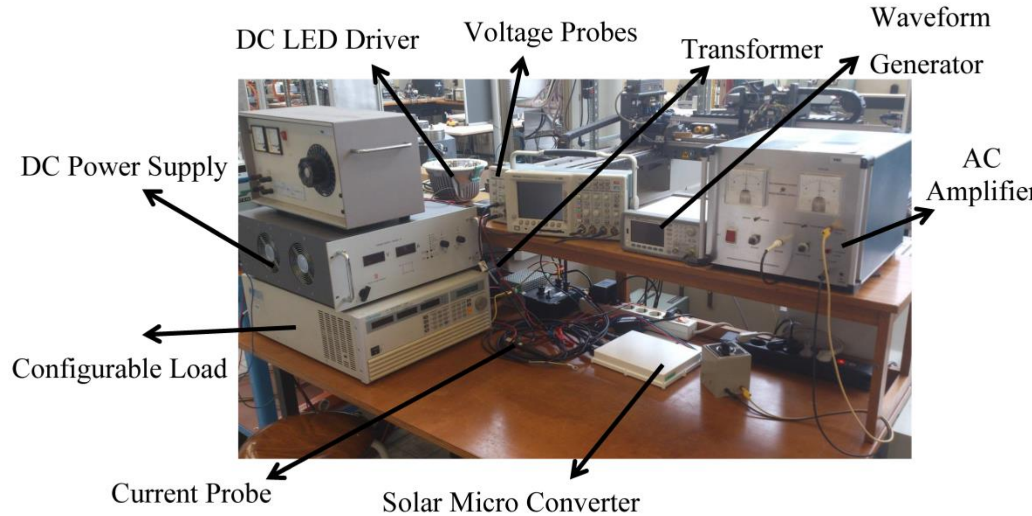
- The Norton equivalent representation of the interface converter:

$$I_{o,k}(s) = \frac{U_{ref,k}(s)}{Z_{slack,k}(s)}, \qquad Z_{o,k}(s) = Z_{slack,k}(s)//[1/sC_k].$$

Experimental Impedance Identification 1/2

- The method is based on injecting of small-signal excitation AC-voltages (≈ 500 mVpp) of different frequencies , subsequent voltage and current measurements and their processing



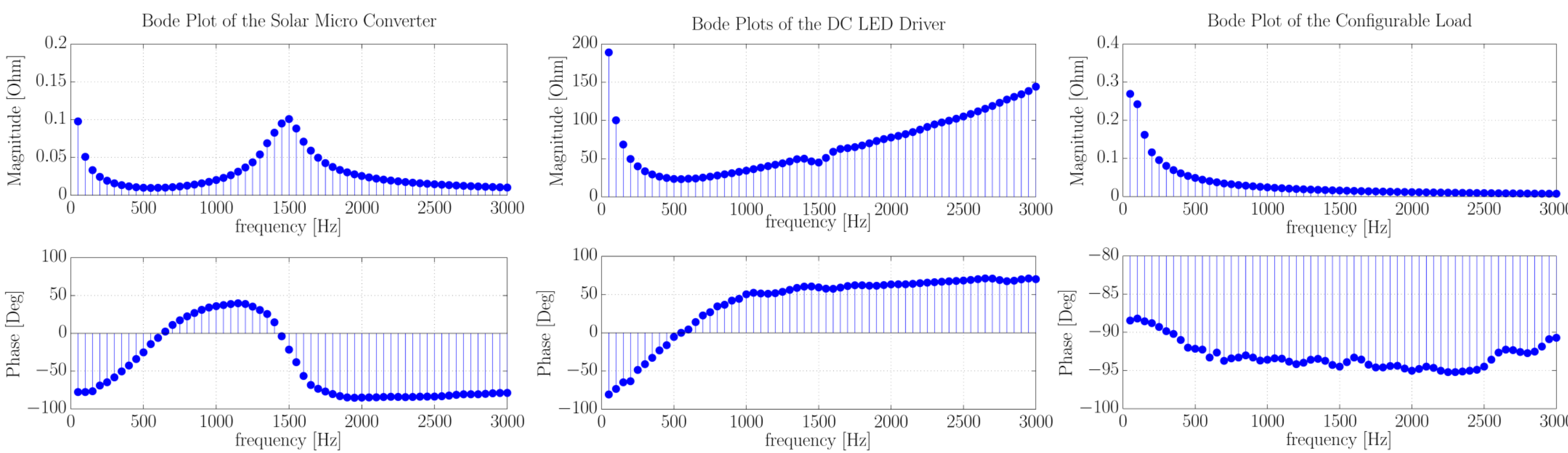


- Equivalent impedances on the source $Z_1(s)$ and the load side $Z_2(s)$

$$Z_1(s) = \frac{\| V_1(s) \|}{\| I_1(s) \|}[\angle V_1(s) + \angle I_1(s)] \qquad Z_2(s) = \frac{\| V_2(s) \|}{\| I_1(s) \|}[\angle V_2(s) - \angle I_1(s)]$$

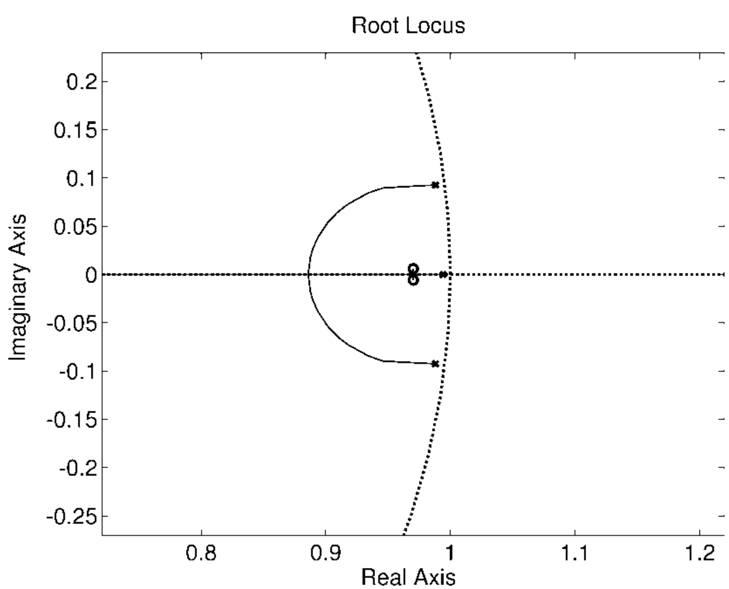
Experimental Impedance Identification 2/2

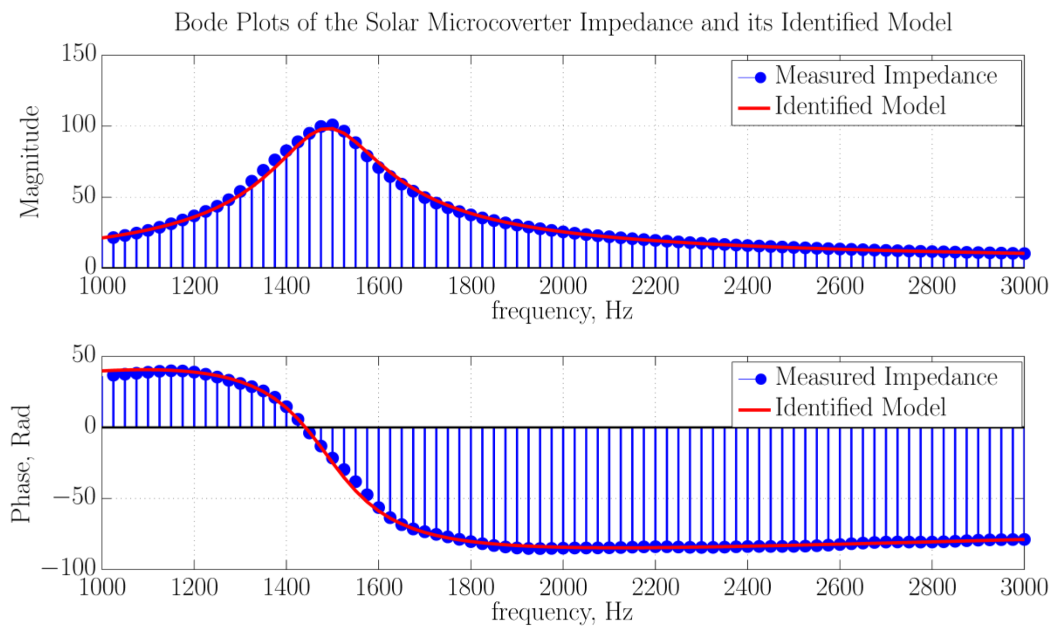
- The technique was applied to three devices:
  - 200 W solar micro converter;
  - 30 W DC LED driver;
  - A configurable load operating at the constant power mode of 500 W.



Polynomial Identification

- Obtained impedance information in the frequency domain can be fitted with a polynomial model for time domain simulations
- Discrete-time model was used: $A(z)y(t) = B(z)u(t) + e(t)$, where polynomials $A(z)$ and $B(z)$ were identified (with a focus on stability)





System Aggregation 1/2

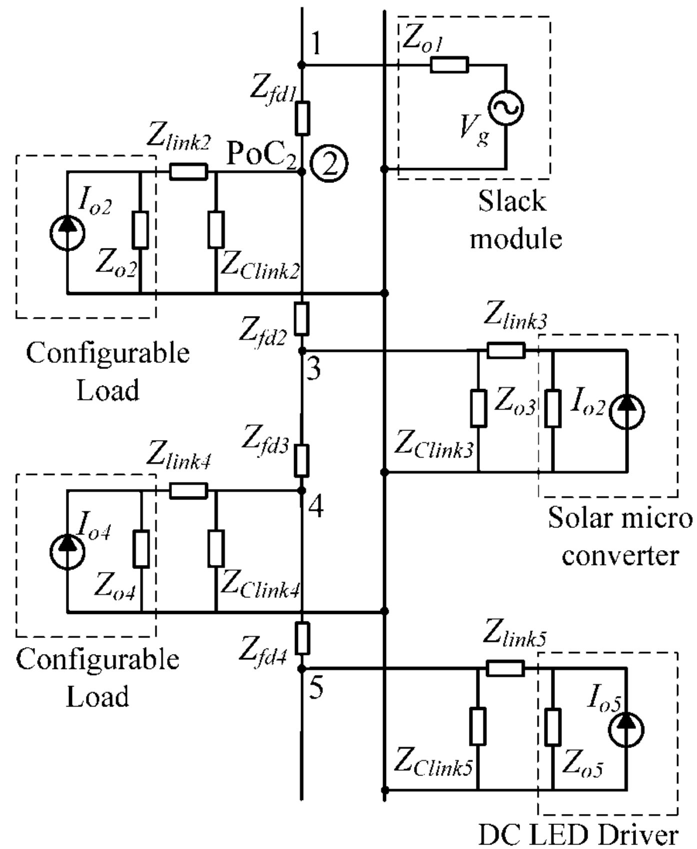
- The system under investigation consists of five power modules
- Let us introduce individual admittances $y_{o,k}(s) = 1/Z_{o,k}$ and admittances of adjacent elements $y_{k(k-1)}(s) = 1/Z_{fd(k-1)}$ for all k = 5 modules.
- The resulting system admittance matrix:

$Y_{1,2}$

$$Y_{5,5} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{15} \\ Y_{21} & Y_{22} & \cdots & Y_{25} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{51} & Y_{52} & \cdots & Y_{55} \end{bmatrix},$$

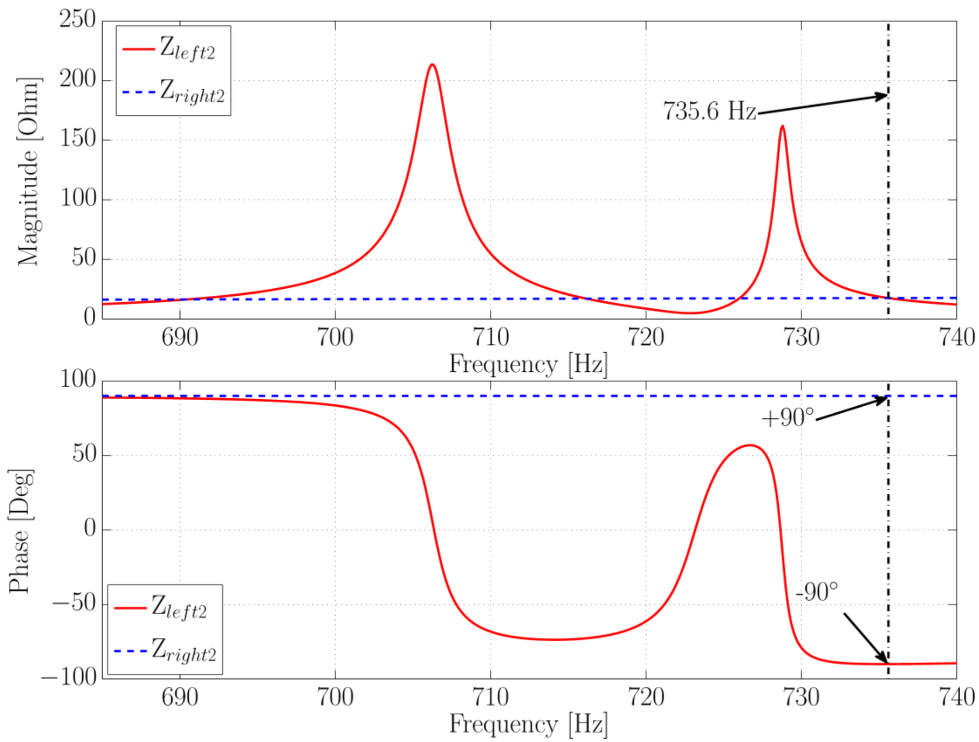
$Y_{2,5}$

where resulting impedance are $Z_{right,2} = 1/Y_{1,2(2,2)}$ and $Z_{left,2} = 1/Y_{2,5(1,1)}$



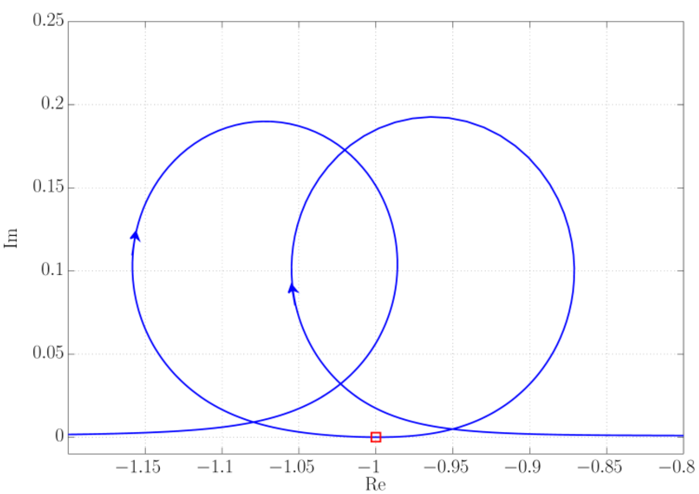
System Aggregation 2/2

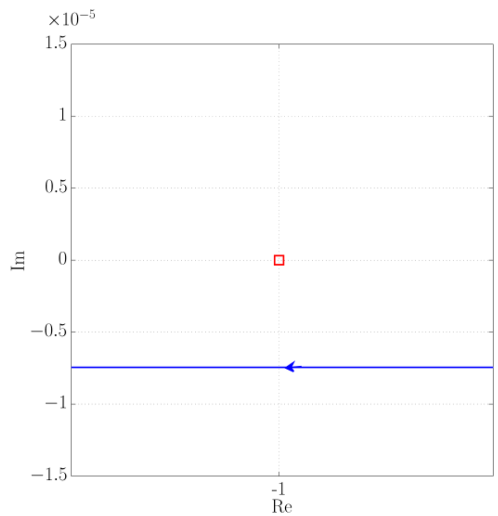
- Potentially dangerous points of possible parallel resonance correspond to the frequencies where magnitudes of both impedances are equal and the phaseshift is 180˚, in other words, where the minimum resistive value is reached. This situation is clearly seen at the point of 735.6 Hz.

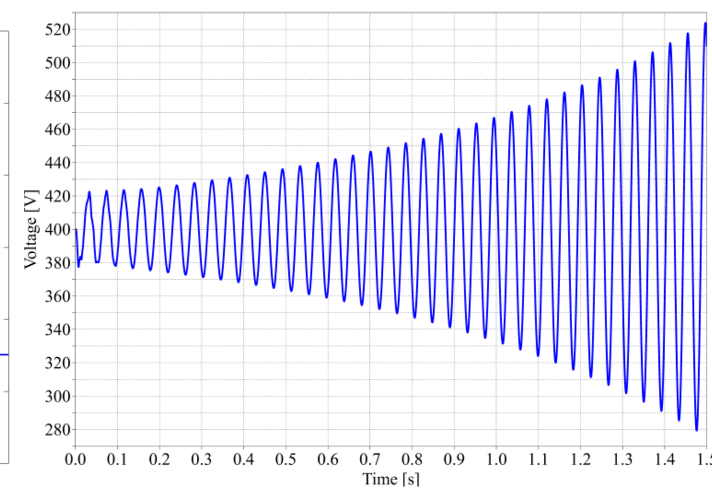


Analysis of Operation 1/2

- Potential voltage instability can be confirmed by the Nyquist stability criterion and time-domain simulations
- The Nyquist diagram with the point (-1; 0) enclosed by the polar plot, and the increasing amplitude of the waveforms indicate that system is unstable.

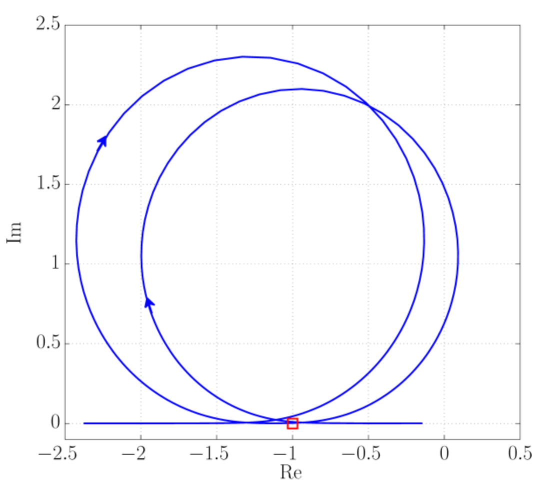


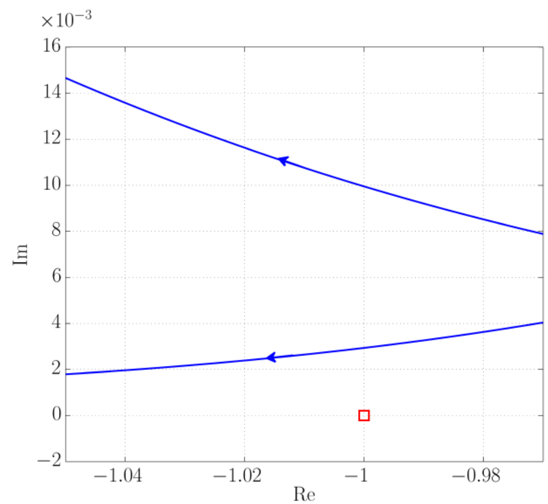


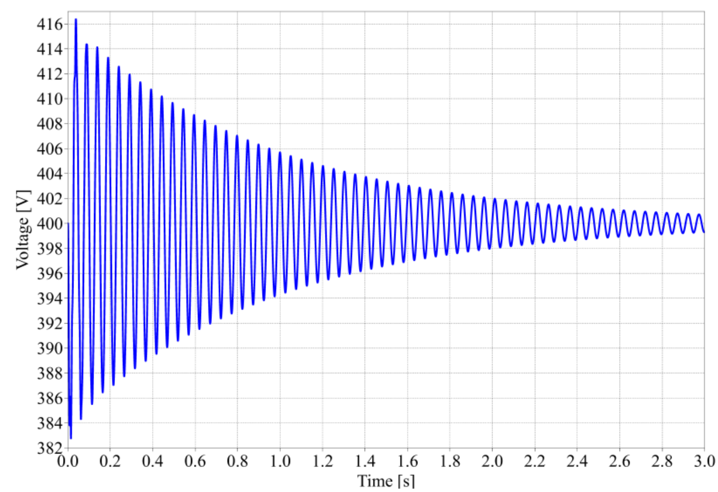


Analysis of Operation 2/2

- The approach proves the opportunity of alternation of the system parameters in order to make the system stable
- Links inductances are increased from 0.2 mH to 0.3 mH and the feeder inductances between nodes *2* and *3*, *3* and *4*, *4* and *5* are decreased from 4 mH to 2 mH
- Damped voltage oscillations together with the Nyquist plot where the point (-1; 0) is not enclosed any more confesses stable operation of the grid







Conclusions

- Power sources of different nature and loads of various power levels interlinked by cables introducing additional impedances and combined together into a grid may become a reason of voltage instabilities
- The paper introduced an approach of experimental impedance identification allowing for obtaining impedance information including internal control algorithms of a power converter in the frequency domain
- Results proved the possibility to forecast voltage instabilities in the aggregated system based on Nyquist and Bode plot analysis and time-domain simulations.