Modelling of Aggregated Operation of Power Modules in Low-Voltage DC-Grids

K. Rykov, L. Ott, J.L. Duarte, E.A. Lomonova

TU/e
Den Dolech 2
5612 AZ
Eindhoven, The Netherlands
k.rykov@tue.nl

Introduction

The paper focuses on small-signal analysis of aggregated operation of the low-voltage DC-grids comprising various power and load modules. Complex impedances, which can be identified experimentally, represent the internal structure of power converters and may become a reason for voltage instabilities while being gathered together in the DC-grid using cables. The paper proposes ideas to analyze and forecast possible resonance issues of parallel operation of power modules in the test model of the 380V DC-grid and make recommendations in order to avoid them.

Experimental Impedance Identification

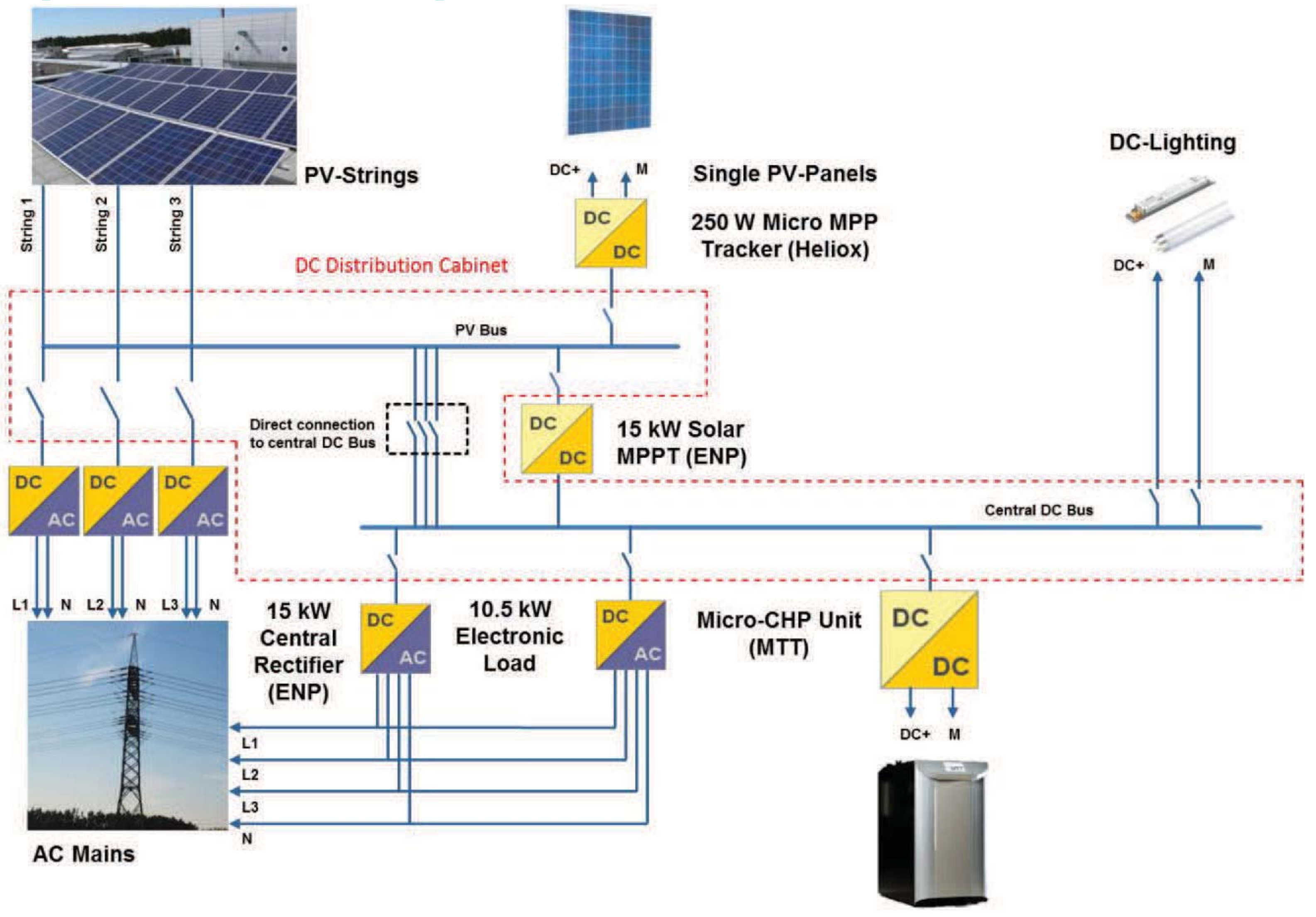


Figure 1: Aggregated DC test grid at Fraunhofer IISB.

Being complex systems, low-voltage DC-microgrids up to 1500 VDC include several modules (sources and loads), connected to the common bus with cables, with different power levels, control loops and EMC filters (Fig. 1).

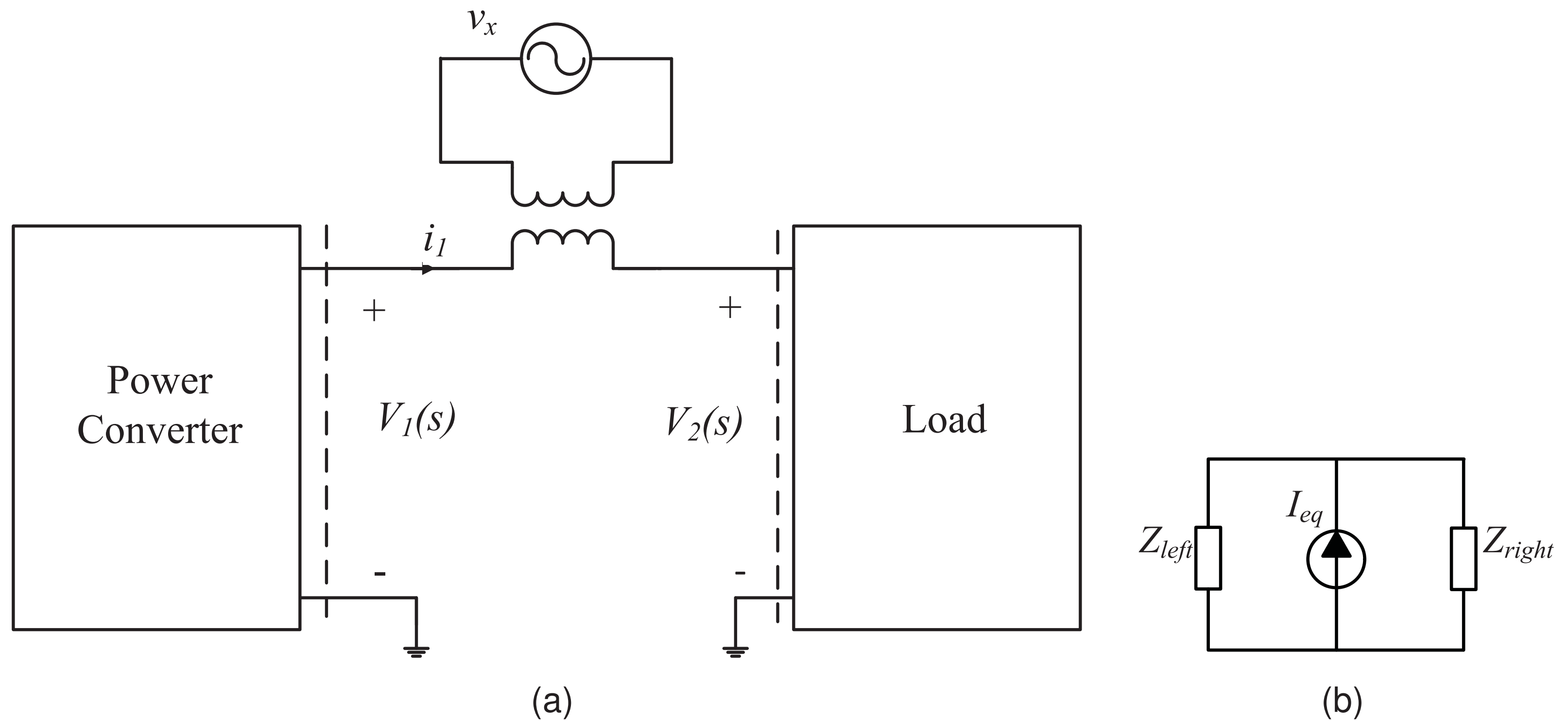


Figure 2: (a) Impedance identification method applied to a single converter (load) module; (b) Simplified impedance representation at one of the points of connection in the DC grid.

In order to apply voltage stability analysis, all power module impedances should be preliminarily assessed using experimental impedance identification approach (Fig. 2). Being measured according to the convention of being fed into the grid, the introduced AC current together with voltage allow for obtaining impedance expressions

$$Z_1(s) = \frac{\| V_1(s) \|}{\| I_1(s) \|}[\angle V_1(s) + \angle I_1(s)] \qquad \text{and}$$

$$Z_2(s) = \frac{\| V_2(s) \|}{\| I_1(s) \|}[\angle V_2(s) - \angle I_1(s)] \tag{1}$$

on the left and right side from excitation correspondingly. Frequency responses of five devices from the test DC grid are depicted in Fig. 3.

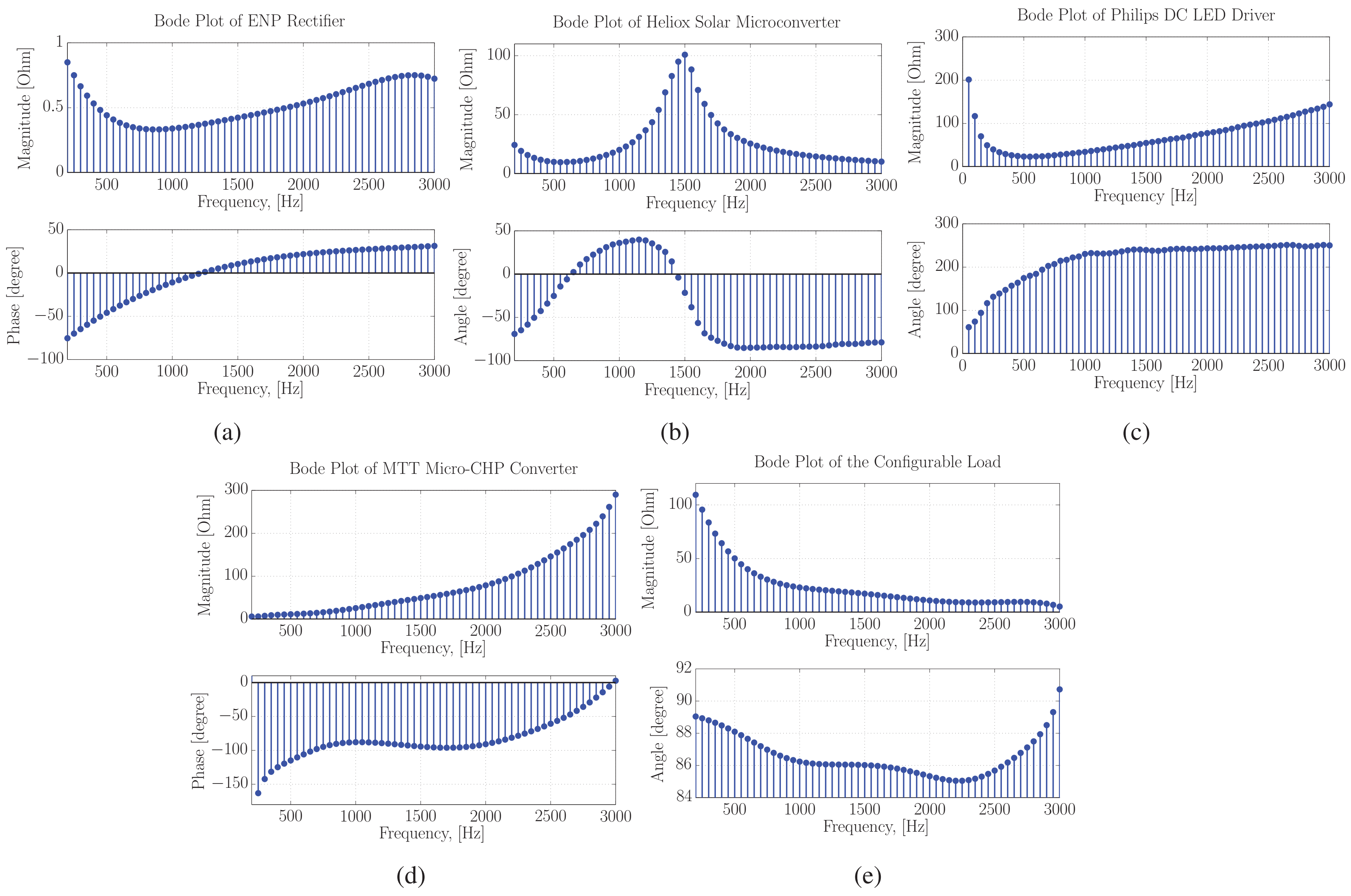


Figure 3: (a) Bode plot of the central rectifier; (b) Bode plot of the solar micro inverter; (c) Bode plot of the DC LED driver; (d) Bode plot of the Micro-CHP unit converter; (e) Bode plot of the configurable load.

System Aggregation

System aggregation is based on building the admittance matrix, where the values, opposite to all identified impedances and impedances of connecting cables, are included. The resulting admittance matrix for the DC-grid consisting of N-modules

$$Y_{N,N} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1N} \\ Y_{21} & Y_{22} & \cdots & Y_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{k1} & Y_{k2} & \cdots & Y_{kN} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{N1} & Y_{N2} & \cdots & Y_{NN} \end{bmatrix} \tag{2}$$

has the size of [N x N], where the elements of the main diagonal relate to admittances of the power modules themselves and adjacent elements correspond to admittances of cables interconnecting those modules. Considering any point of the grid (see Fig. 2) as a point of connection, for instance, at module *k*, the resulting matrix (2) should be divided into two parts – to the left and to the right from the point of connection with corresponding impedances $Z_{left} = 1/Y_{1,k(k,k)}$ and $Z_{right} = 1/Y_{k,N(1,1)}$. Resonance issues of two parallel impedances (Fig. 2(b)) occur when the denominator of the system transfer function $G(s) = 1/(1 + Z_{left}/Z_{right})$ equals to zero, in other words, the following condition $Z_{left}/Z_{right} = -1$, or $Z_{left} + Z_{right} = 0$ should be satisfied.

Modelling of Aggregated Operation of Power Modules in Low-Voltage DC-Grids

K. Rykov, L. Ott, J.L. Duarte, E.A. Lomonova

TU/e
Den Dolech 2
5612 AZ
Eindhoven, The Netherlands
k.rykov@tue.nl

Parallel Operation of Two Modules

Let us investigate possible voltage stability issues considering parallel operation of two modules – 15 kW central rectifier (left module), and one 28W DC LED driver (right module) interlinked by a short cable with negligible impedance value. Impedances of the left and right modules are expressed, as follows:

$$Z_{left,0} = 1/N_{\mathrm{REC}} \cdot [M_{\mathrm{REC},0} \cdot \cos\varphi_{\mathrm{REC},0} + \mathrm{j} \cdot M_{\mathrm{REC},0} \cdot \sin\varphi_{\mathrm{REC},0}] \quad (3)$$
$$Z_{right,0} = 1/N_{\mathrm{LED}} \cdot [M_{\mathrm{LED},0} \cdot \cos\varphi_{\mathrm{LED},0} + \mathrm{j} \cdot M_{\mathrm{LED},0} \cdot \sin\varphi_{\mathrm{LED},0}]\,, \quad (4)$$

where N_{REC} and N_{LED} are numbers of rectifier and LED modules respectively. Bode plots for one rectifier module as Z_{right} and three different numbers of LED modules are shown in Fig. 4.

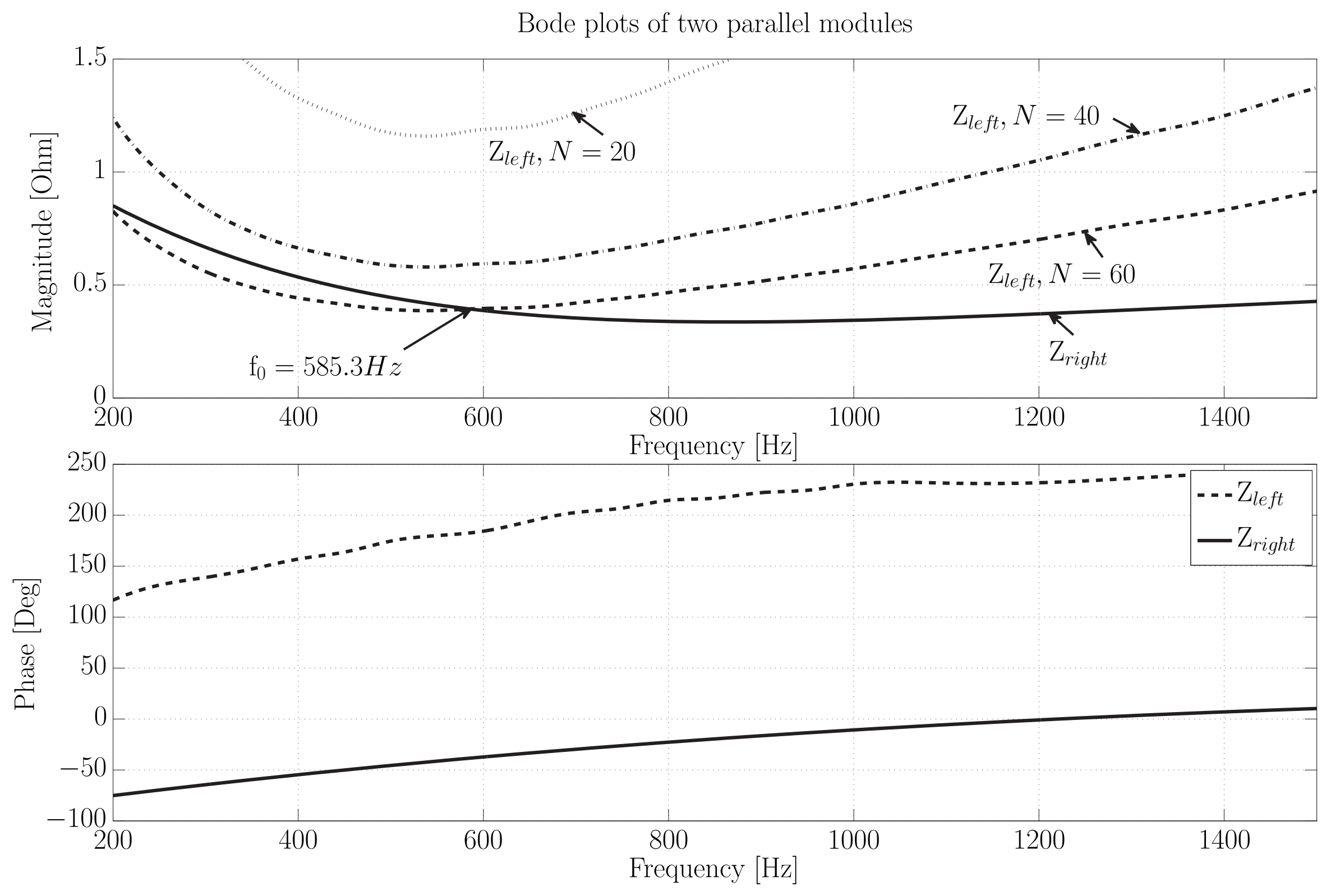


Figure 4: Bode plots of impedances Z_{right} and Z_{left} for $N_{\mathrm{LED}} = 20$, $N_{\mathrm{LED}} = 40$, and $N_{\mathrm{LED}} = 60$.

In scenarios when extra cable length between modules is introduced, the total impedance of one of the modules, for instance, the right one (rectifier module), is increased by the cable impedance $Z_c = R_c + \mathrm{j}\omega L_c$ ($\omega = 2\pi f_0$). This allows for calculating cable impedance components $R_c = 84.8\mathrm{m}\Omega$ and $L_c = 71.37\mu\mathrm{H}$, which will lead to resonance at the specified frequency $f_0 = 585.3\mathrm{Hz}$ (Fig. 5).

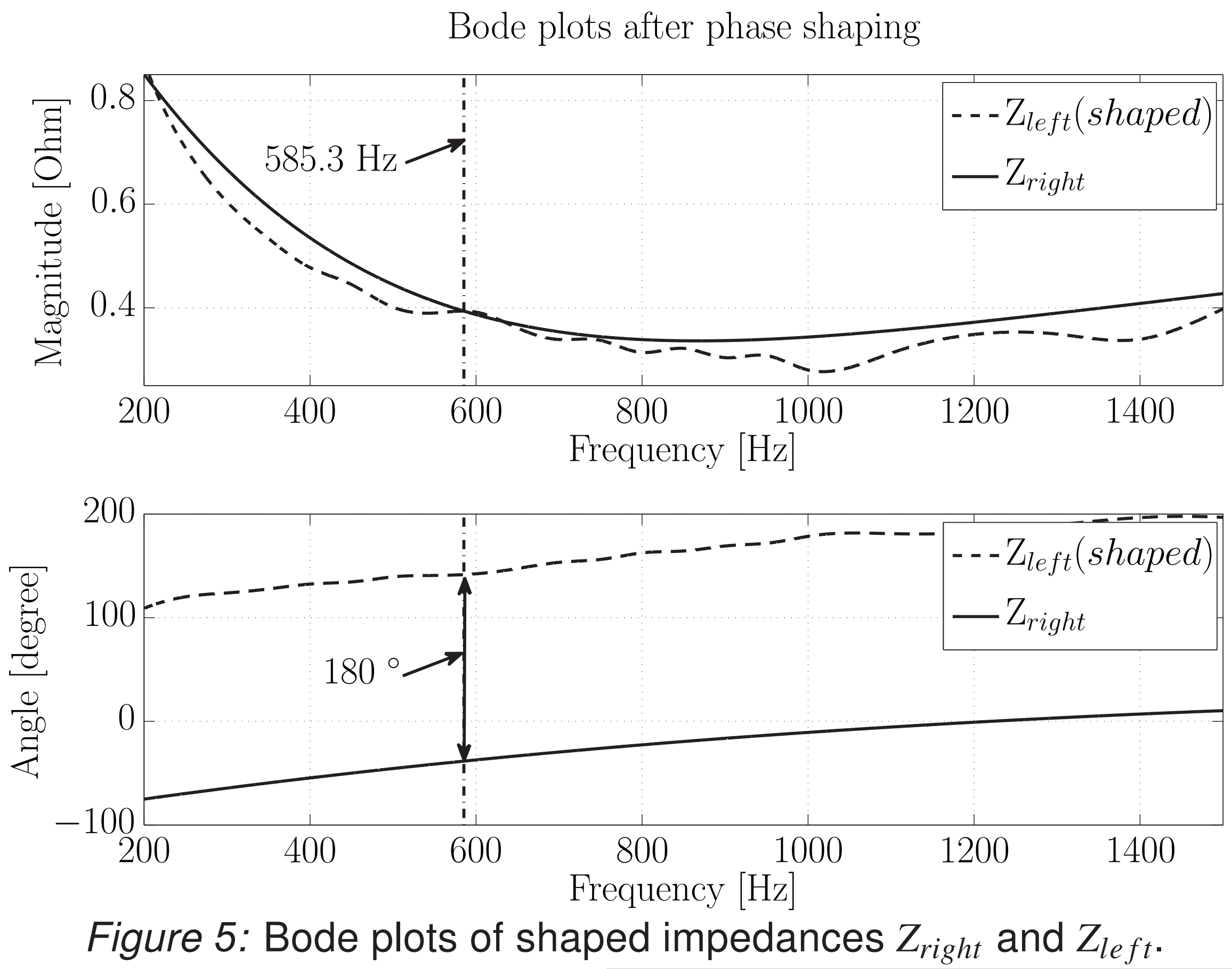
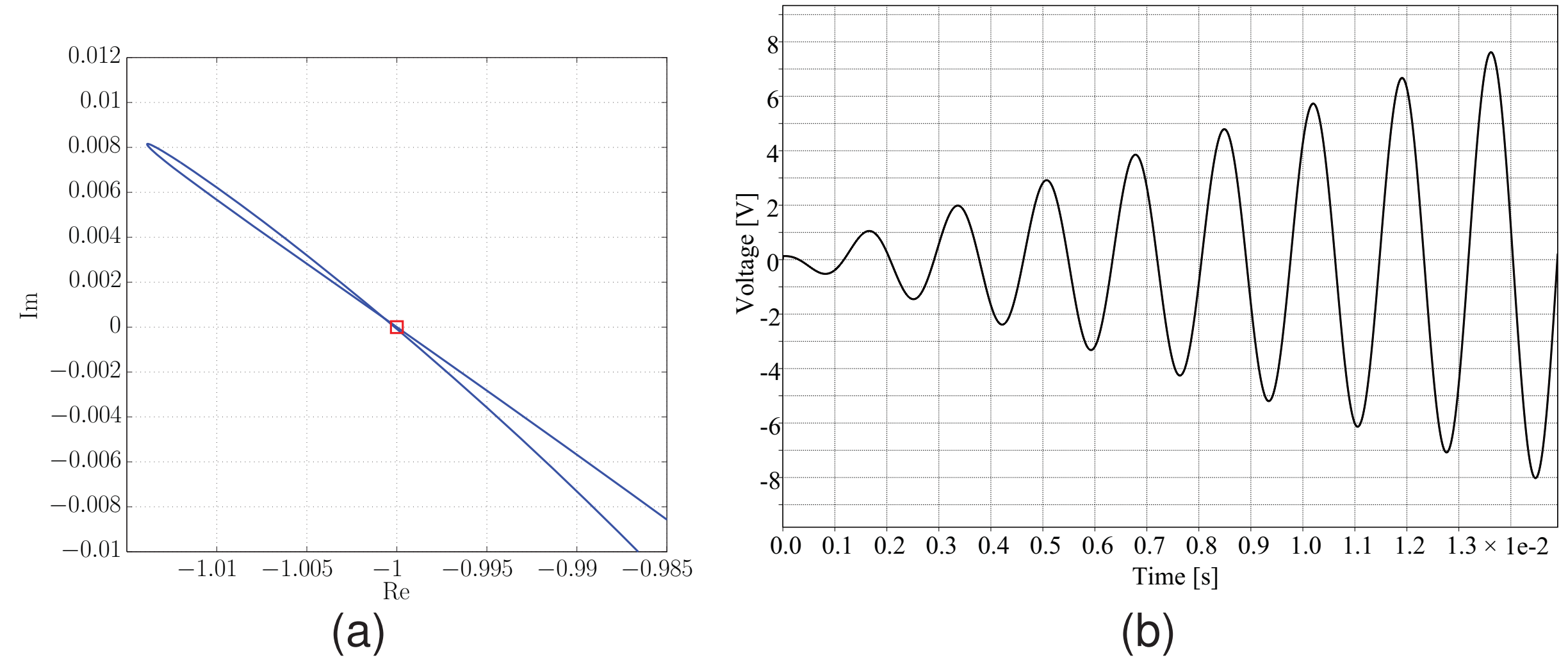


Figure 5: Bode plots of shaped impedances Z_{right} and Z_{left}.



(a) (b)

Figure 6: (a) Nyquist plot of the system transfer function; (b) Unstable time-domain simulation of the linear model with parallel impedances.

Nyquist plot and time-domain simulations of the unstable system are presented in Fig.6.

Analysis of a Complex Grid

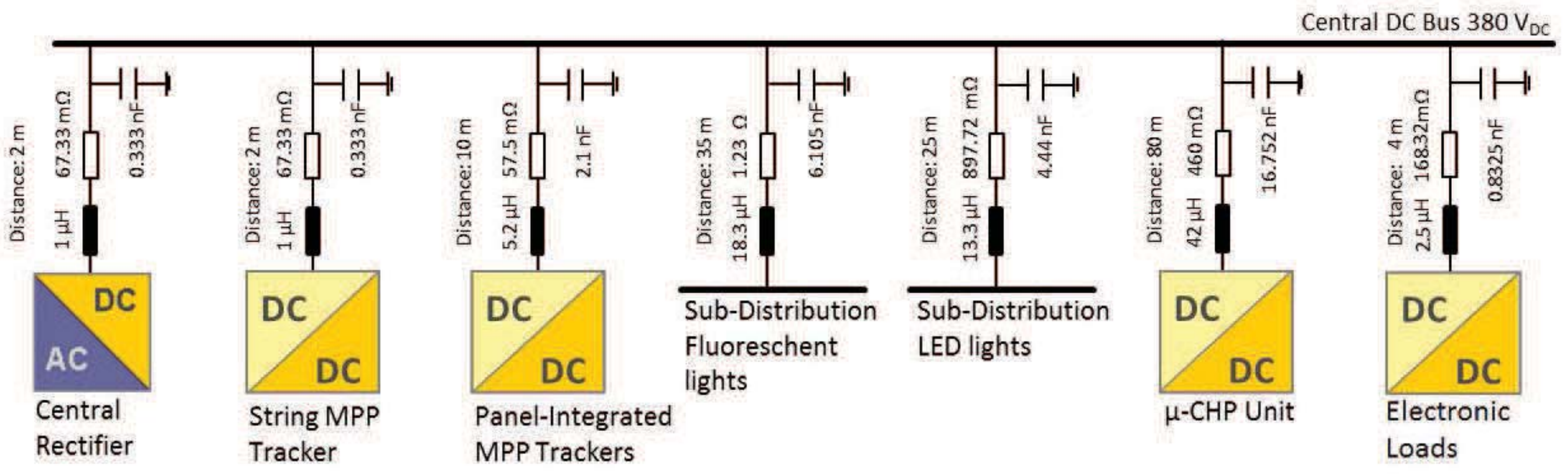


Figure 7: Main Power Modules of the DC Test Grid with specific connection impedance to the central DC bus.

Investigation of voltage instabilities based on parallel impedance interactions are also suitable for complex DC-grids (Fig. 3). The model of the grid at Fraunhofer IISB has six modules (Fig. 7), and the analysis is done at the point of connection at module 4. Corresponding bode plot, Nyquist diagram and time-domain simulation are presented in Fig. 8 and Fig. 9 correspondingly.

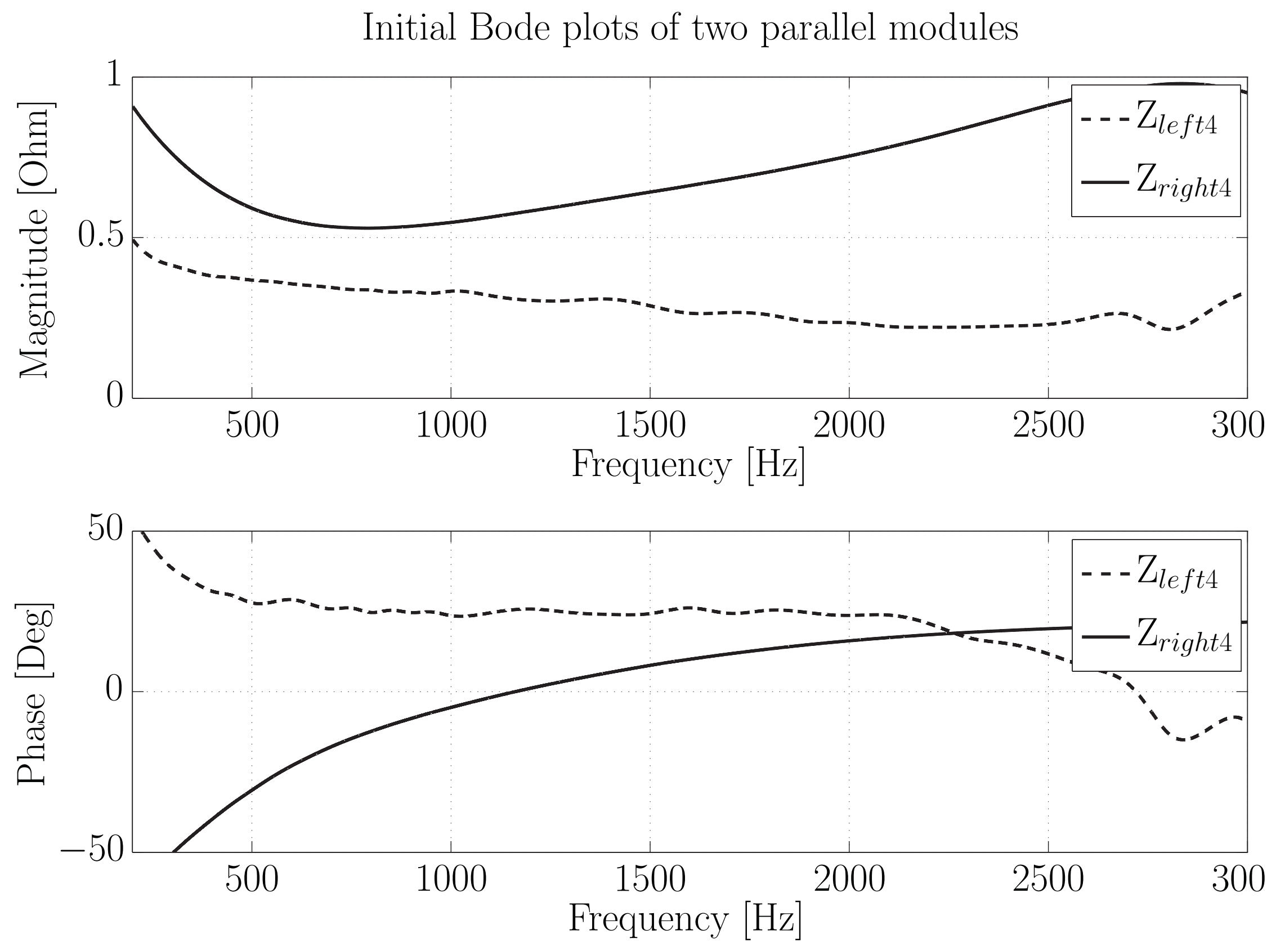
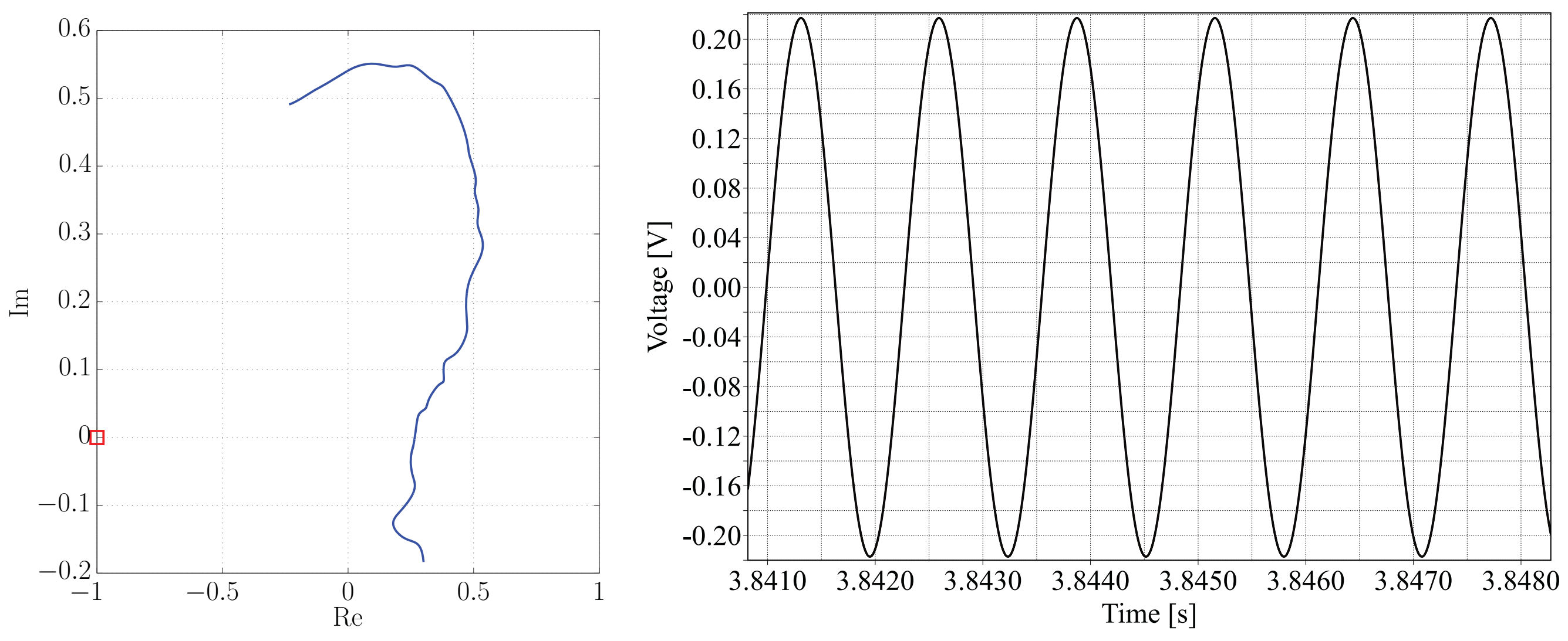


Figure 8: Combined view of parallel complex impedances Z_{left} and Z_{right}



(a) (b)

Figure 9: (a) Nyquist plot of the stable grid; (b) Stable time-domain simulation of the linear model with parallel impedances.

Conclusions

The reason for voltage instabilities in DC-grids is resonance issues caused by interaction of complex impedances, representing components of the grid. Different nature, structure, and power levels of grid modules, including sources and loads, interlinked with cables of various length and type make an impact on system behaviour. Presented approach gives the opportunity to analyse small-signal voltage stability at any point of the DC-grid and make conclusions with regard to different scenarios of operation.