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Influence of Dynamic Misorientation of PLL for Small-Signal Analysis of Converter Control in Weak Grids

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Introduction

Renewable energy sources are usually connected to the grid via converters, but control becomes challenging if the short-circuit ratio (SCR) at point of common coupling is low.

A good operating stability analysis is essential.

Voltage Oriented Control (VOC)

The control scheme consists of two cascaded control loops, the inner loop controls the current and the outer loop the DC-link voltage.

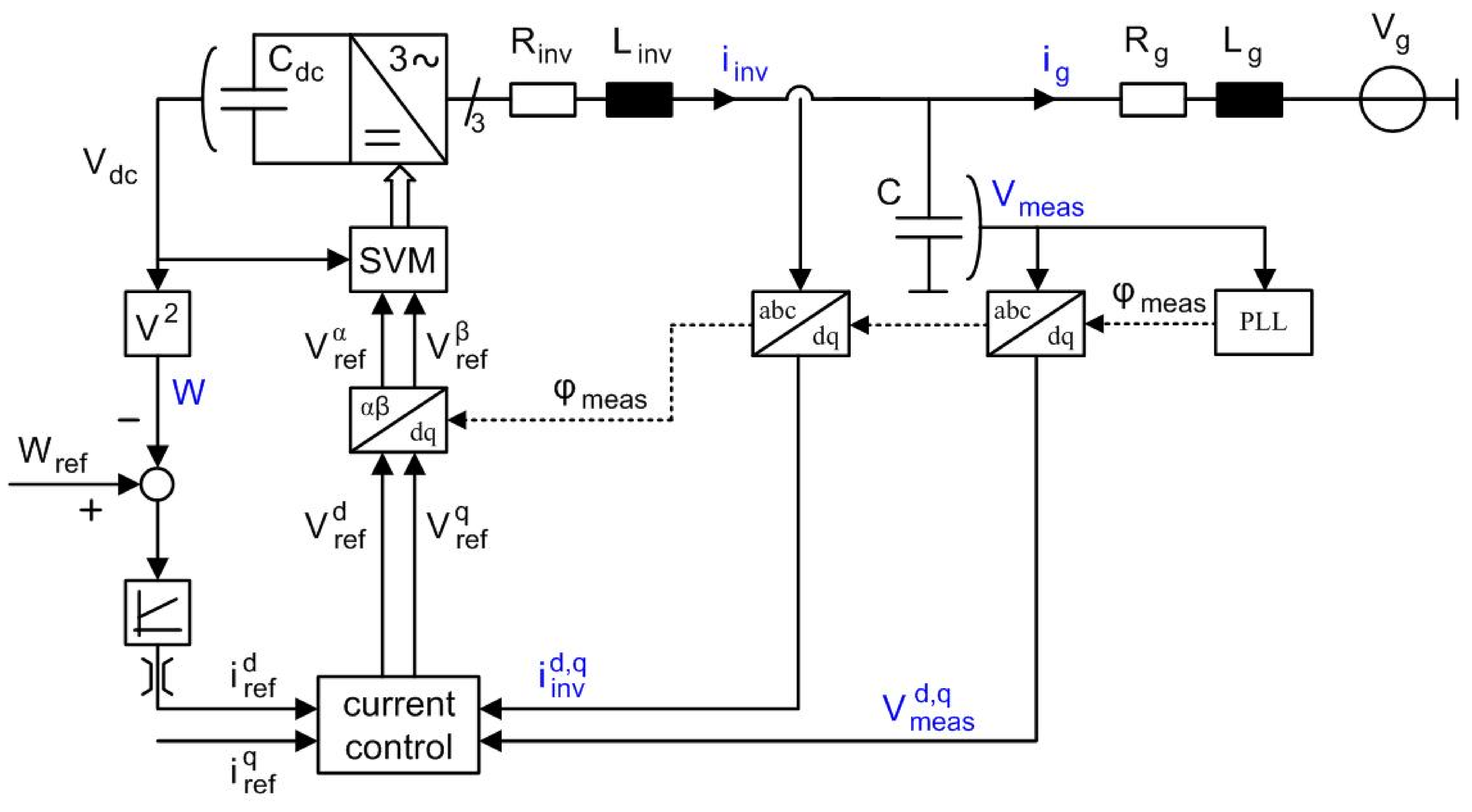


Figure 1: configuration of VOC

Modelling of State-Space Model

The complete state-space model for one grid-side converter with VOC connected via an LC-filter and a variable grid impedance to a voltage source consists of 14 states.

Variables x_1 to x_7 are the states of he control.

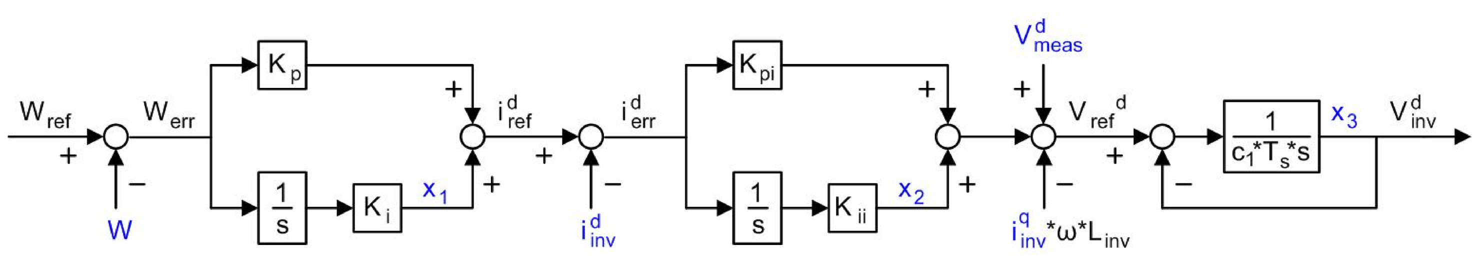


Figure 2: DC-link and i_{inv}^d control

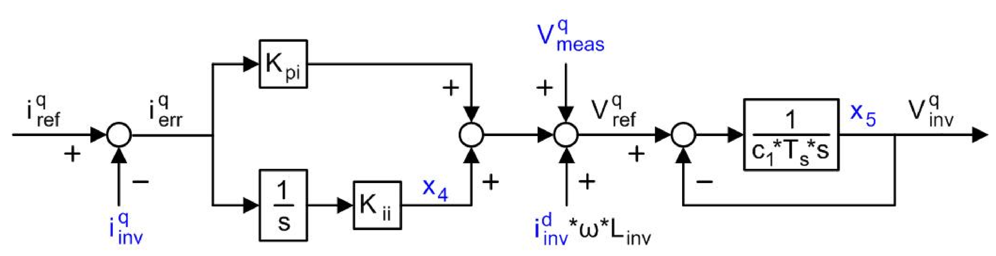


Figure 3: i_{inv}^q control

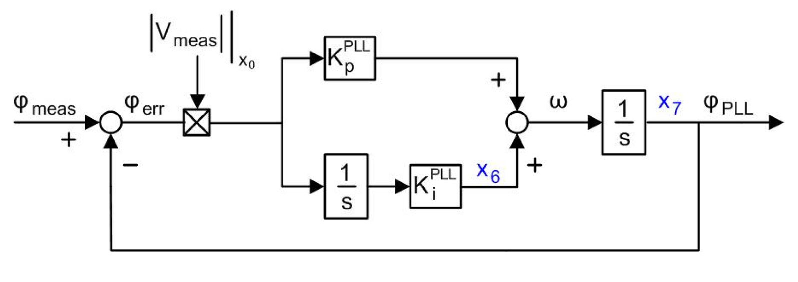


Figure 4: linearised synchronous reference-frame PLL

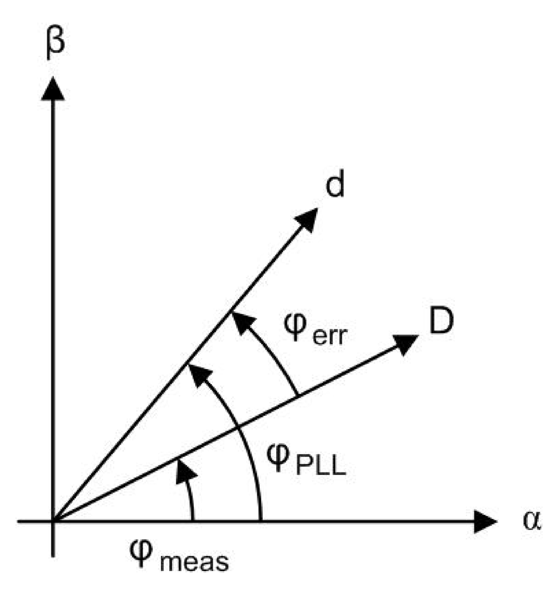
$$
\begin{aligned}
\dot{x}_1 &= K_i\cdot W_{ref} - K_i\cdot W\\
\dot{x}_2 &= K_{ii}\cdot(x_1 + K_p\cdot(W_{ref}-W)) - K_{ii}\cdot i^d_{inv}\\
\dot{x}_3 &= \frac{1}{T_{sw}}\cdot(V^d_{ref}-V^d_{inv})\\
&= \frac{1}{T_{sw}}\cdot(x_2 + K_{pi}(x_1+K_p(W_{ref}-W)) - i^d_{inv}) - i^q_{inv}\cdot\omega L_{inv} + V^d_{meas} - V^d_{inv})\\
\dot{x}_4 &= K_{ii}\cdot i^q_{ref} - K_{ii}\cdot i^q_{inv}\\
\dot{x}_5 &= \frac{1}{T_{sw}}\cdot(V^q_{ref}-V^q_{inv})\\
&= \frac{1}{T_{sw}}\cdot(x_4 + K_{pi}(i^q_{ref}-i^q_{inv}) + i^d_{inv}\cdot\omega L_{inv} + V^q_{meas} - V^q_{inv})\\
\dot{x}_6 &= K_i^{PLL}\cdot|V_{meas}|\big|_{x_0}\cdot\varphi_{meas} - K_i^{PLL}\cdot|V_{meas}|\big|_{x_0}\cdot x_7\\
\dot{x}_7 &= x_6 + K_p^{PLL}\cdot|V_{meas}|\big|_{x_0}\cdot\varphi_{meas} - K_p^{PLL}\cdot|V_{meas}|\big|_{x_0}\cdot x_7
\end{aligned}
$$

i_{inv}^d, i_{inv}^q, U_{inv}^d, U_{inv}^q, i_g^d and i_g^q are the states of the AC-side and W (= V^2_{DC}) is the state of the DC-side.

$$
\begin{aligned}
\dot{i}^D_{inv} &= \frac{V^D_{inv}}{L_{inv}} - \frac{R_{inv}}{L_{inv}}\cdot i^D_{inv} + \omega\cdot i^Q_{inv} - \frac{V^D_{meas}}{L_{inv}}\\
\dot{i}^Q_{inv} &= \frac{V^Q_{inv}}{L_{inv}} - \frac{R_{inv}}{L_{inv}}\cdot i^Q_{inv} - \omega\cdot i^D_{inv} - \frac{V^Q_{meas}}{L_{inv}}\\
\dot{V}^D_{meas} &= \frac{i^D_{inv}}{C} - \frac{i^D_g}{C} + \omega\cdot V^Q_{meas}\\
\dot{V}^Q_{meas} &= \frac{i^Q_{inv}}{C} - \frac{i^Q_g}{C} - \omega\cdot V^D_{meas}\\
\dot{i}^D_g &= \frac{V^D_{meas}}{L_g} - \frac{R_g}{L_g}\cdot i^D_g + \omega\cdot i^Q_g - \frac{V^D_g}{L_g}\\
\dot{i}^Q_g &= \frac{V^Q_{meas}}{L_g} - \frac{R_g}{L_g}\cdot i^Q_g - \omega\cdot i^D_g - \frac{V^Q_g}{L_g}
\end{aligned}
$$

$$
\dot{W} = \frac{2}{C_{DC}}\cdot P_{DC} - \frac{3}{C_{DC}}\cdot(V^D_{inv}\cdot i^D_{inv} + V^Q_{inv}\cdot i^Q_{inv})
$$

Besides, the dynamic misorientation of PLL has to be taken into account. For steady state, the D-axis of the grid and the d-axis of PLL are the same. If there is e.g. a change in the converter output current, the grid D-axis moves, and PLL has to track it.



$$
\begin{aligned}
x_d &= x_D + x_Q\cdot\varphi_{err}\\
x_q &= x_Q - x_D\cdot\varphi_{err}\\
x_D &= x_d - x_q\cdot\varphi_{err}\\
x_Q &= x_q + x_d\cdot\varphi_{err}
\end{aligned}
$$

Figure 5: dynamic misorientation of PLL

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Validation of Small-Signal Model

The state equations were linearised around an operating point and the eigenvalues $\lambda = \sigma + j\omega$ of the state space, the participation matrix, the frequency of oscillation f and the damping ratio ς are calculated for VOC at a stiff grid.

Table 1: eigenvalues of VOC with dynamic misorientation of PLL

	0.000	0.000	0.003	0.006	0.000	0.589	0.000	0.001	Δx_1
	0.000	0.000	0.007	0.012	0.000	0.016	0.000	0.504	Δx_2
	0.000	0.000	0.241	0.364	0.000	0.009	0.000	0.001	Δx_3
	0.000	0.000	0.008	0.008	0.002	0.000	0.000	0.515	Δx_4
	0.000	0.000	0.328	0.268	0.000	0.000	0.000	0.000	Δx_5
	0.000	0.000	0.000	0.000	0.143	0.000	1.143	0.000	Δx_6
	0.000	0.000	0.001	0.001	1.144	0.000	0.143	0.001	Δx_7
	0.008	0.000	0.262	0.328	0.000	0.027	0.000	0.001	Δi_{inv}^{D}
	0.000	0.000	0.361	0.246	0.000	0.000	0.000	0.012	Δi_{inv}^{Q}
	0.500	0.000	0.000	0.000	0.000	0.000	0.000	0.000	ΔU_{meas}^{D}
	0.000	0.500	0.000	0.000	0.000	0.000	0.000	0.000	ΔU_{meas}^{Q}
	0.492	0.000	0.005	0.005	0.000	0.001	0.000	0.000	Δi_{g}^{D}
	0.000	0.500	0.004	0.002	0.003	0.000	0.000	0.001	Δi_{g}^{Q}
	0.000	0.000	0.025	0.043	0.000	0.593	0.000	0.001	ΔW
λ	$-90.6 \pm 3.4e7i$	$-0.7 \pm 3.4e7i$	$-1{,}009.5 \pm 2{,}173.2i$	$-830.2 \pm 1{,}877.3i$	-160.4	$-131.7 \pm 222.9i$	-20.0	$-62.8 \pm 0.1i$	
f	5,530,965	5,483,841	346	299	0	35	0	0	
ς	+0.000	+0.000	0.421	0.404	1.000	0.509	1.000	1.000	

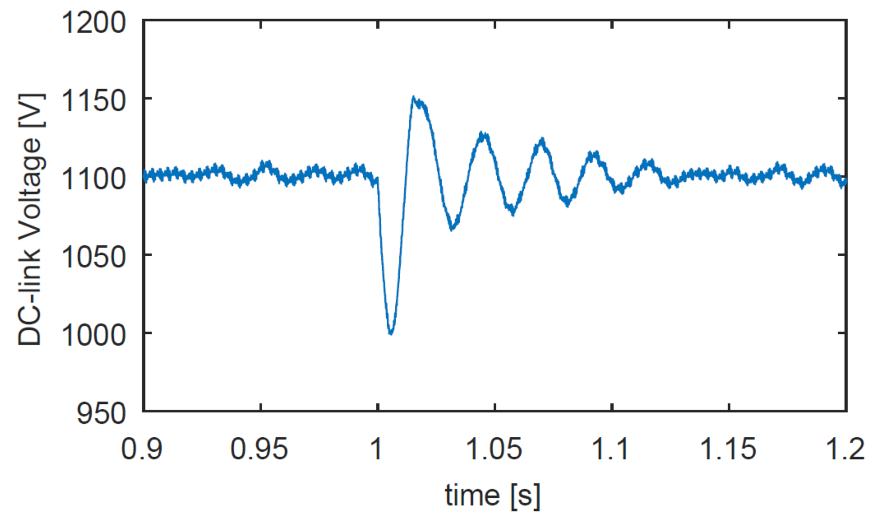
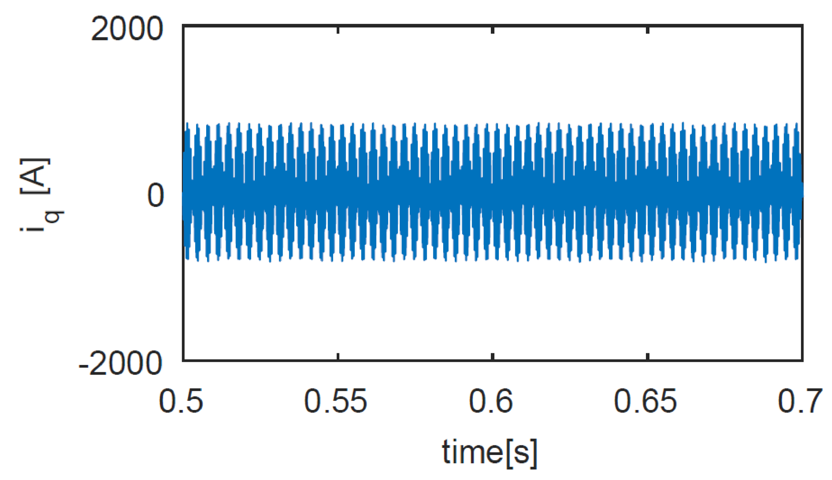


Figure 6: oscillation of DC-link voltage



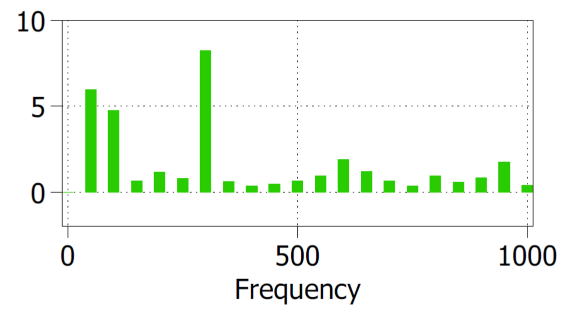


Figure 7: oscillation and frequency spectrum of i_{inv}^{Q}

Influence of Dynamic Misorientation

PLL behaviour at weak grids is not satisfying and the dynamic misorientation can lead to instabilities although the PLL is stable in steady state.
For investigation, the migration of the eigenvalues for the developed small-signal model of VOC and converter is plotted.

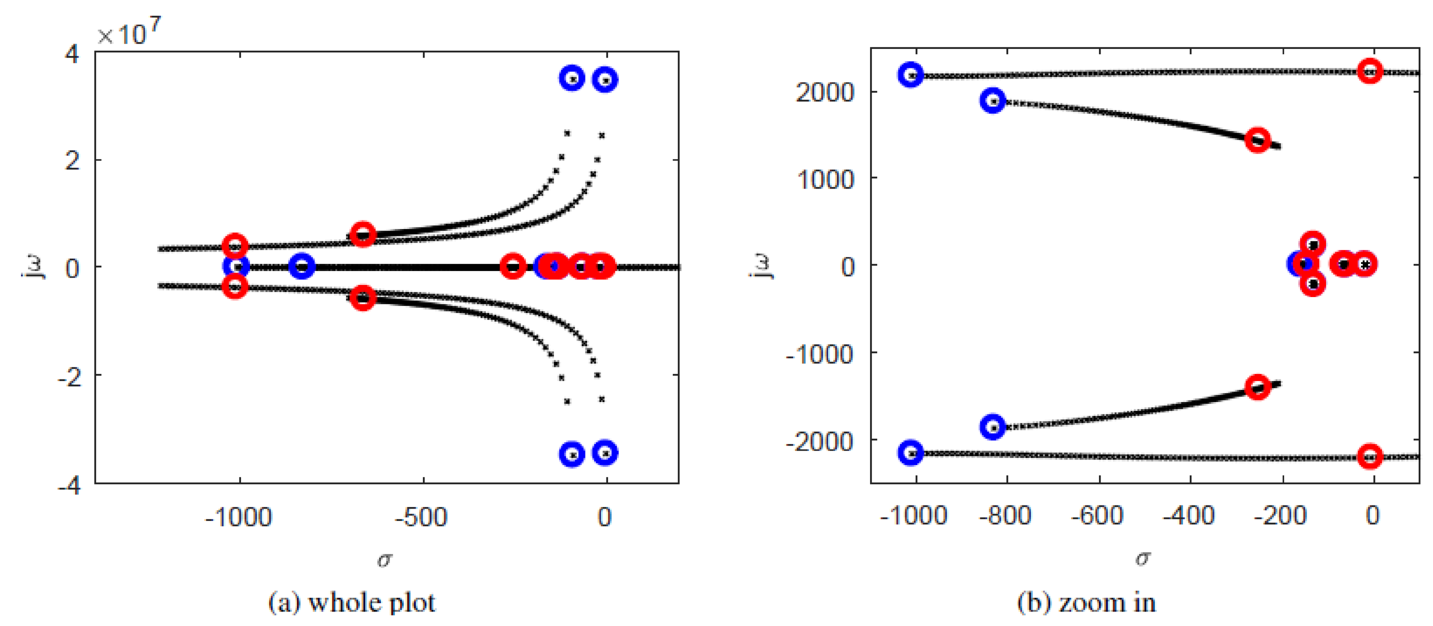


Figure 8: root locus for small-signal behaviour with consideration of dynamic misorientation, variation of SCR (blue: stiff grid, red: stability limit)

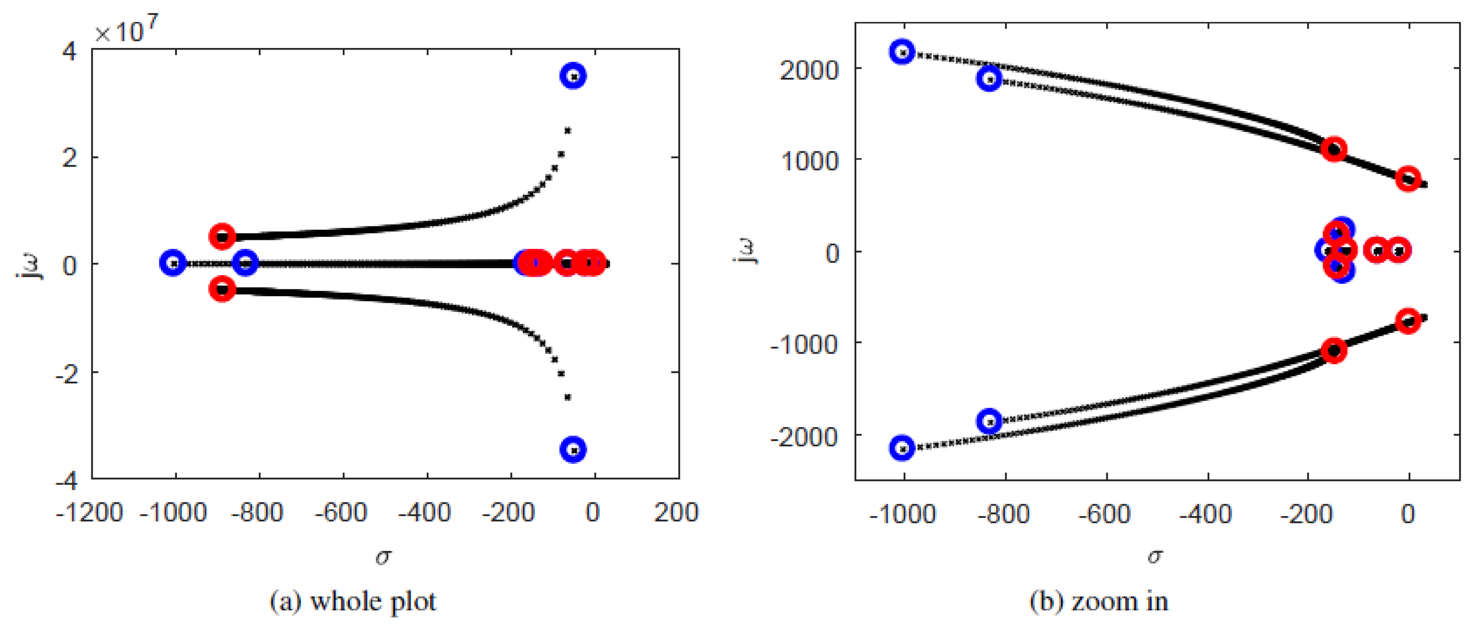


Figure 9: root locus for small-signal behaviour without consideration of dynamic misorientation, variation of SCR (blue: stiff grid, red: stability limit)

Comparison shows how important consideration of dynamic misorientation of PLL is for weak grids. Eigenvalue analysis leads to stable region for SCR $\geq$ 4.67 with consideration of dynamic misorientation and SCR $\geq$ 1.13 without (the physical transmission limit for a steady-state operating point of the configuration is SCR $\geq$ 1.07).

Conclusion

A systematic approach to develop the complete state-space representation is developed.

The developed small-signal model allows a fast investigation of the influence of single control parameters.

The dynamic misorientation of PLL is important for stability.

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