

Supplementary Information

Quantitative Analysis of the Synchronization Stability Region of Grid-Connected Converters During Fault Ride-Through Considering LVRT Characteristics

Fei Li^{1,2,*}, Huanhuan Chen^{1,2}, Longchao Guo³, Qiang Chen^{1,2}, Xing Zhang^{1,2}

¹School of Electrical Engineering and Automation, Hefei University of Technology, Hefei 230009, Anhui Province, China

²National-Local Joint Engineering Laboratory for Renewable Energy Grid Integration Technology, Hefei University of Technology, Hefei 230009, Anhui Province, China

³Sungrow Power Supply Co., Ltd., Hefei 230088, Anhui Province, China

Journal: Electrical Engineering

Corresponding author: Fei Li, lifei@hfut.edu.cn

Online Resource 1

S1. Jacobian Matrices During Voltage Sags

This supplementary material provides the detailed Jacobian matrices and associated partial derivatives referred to in Section 3.4 of the main manuscript.

When the grid voltage sags and the grid-connected current has not reached the current-limiting value, the Jacobian matrix $\mathbf{B}_1$ is partitioned as

$$\mathbf{B}_1 = \begin{bmatrix} \mathbf{B}_{11}^{7 \times 7} & \mathbf{B}_{12}^{7 \times 4} \\ \mathbf{B}_{21}^{4 \times 7} & \mathbf{B}_{22}^{4 \times 4} \end{bmatrix}. \quad (\text{S1})$$

The four submatrices in Eq. (S1) are given as follows.

$$\mathbf{B}_{11}^{7 \times 7} = \begin{bmatrix} 0 & \frac{\partial V_{tq}}{\partial \delta} & 0 & 0 & 0 & 0 & \frac{\partial V_{tq}}{\partial i_{1q}} \\ k_{ipll} & k_{ppll} \frac{\partial V_{tq}}{\partial \delta} & 0 & 0 & 0 & 0 & k_{ppll} \frac{\partial V_{tq}}{\partial i_{1q}} \\ 0 & \frac{\partial V'_{td}}{\partial \delta} & \frac{\partial V'_{td}}{\partial i_{td}^*} & 0 & 0 & \frac{\partial V'_{td}}{\partial i_{1d}} & 0 \\ 0 & 0 & \frac{\partial V'_{td}}{\partial i_{fd}^*} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{\partial V'_{td}}{\partial i_{fq}^*} & 0 & 0 & 0 & 0 \\ k_{ipll} i_{1q} & k_{ppll} i_{1q} \frac{\partial V_{tq}}{\partial \delta} & \frac{k_p}{L_1} \frac{\partial V'_{td}}{\partial i_{fd}^*} & \frac{k_i}{L_1} & 0 & -\frac{R_d}{L_1} & \omega_n + k_{ppll} i_{1q} \frac{\partial V_{tq}}{\partial i_{1q}} \\ -k_{ipll} i_{1d} & -k_{ppll} i_{1d} \frac{\partial V_{tq}}{\partial \delta} & \frac{k_p}{L_1} \frac{\partial V'_{td}}{\partial i_{fq}^*} & 0 & \frac{k_i}{L_1} & -\omega_n & -\frac{R_d}{L_1} - k_{ppll} i_{1d} \frac{\partial V_{tq}}{\partial i_{1q}} \end{bmatrix} \quad (\text{S2})$$

$$\mathbf{B}_{12}^{7 \times 4} = \begin{bmatrix} 0 & \frac{\partial V_{tq}}{\partial V_{cq}} & 0 & \frac{\partial V_{tq}}{\partial i_{2q}} \\ 0 & k_{ppll} \frac{\partial V_{tq}}{\partial V_{cq}} & 0 & k_{ppll} \frac{\partial V_{tq}}{\partial i_{2q}} \\ \frac{\partial V'_{td}}{\partial V_{cd}} & 0 & \frac{\partial V'_{td}}{\partial i_{2d}} & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ -\frac{1}{L_1} & k_{ppll} i_{1q} \frac{\partial V_{tq}}{\partial V_{cq}} & \frac{R_d - k_p}{L_1} & -\omega_n + k_{ppll} i_{1q} \frac{\partial V_{tq}}{\partial i_{2q}} \\ 0 & -\frac{1}{L_1} - k_{ppll} i_{1d} \frac{\partial V_{tq}}{\partial V_{cq}} & \omega_n & \frac{R_d - k_p}{L_1} - k_{ppll} i_{1d} \frac{\partial V_{tq}}{\partial i_{2q}} \end{bmatrix} \quad (\text{S3})$$

$$\mathbf{B}_{21}^{4 \times 7} = \begin{bmatrix} k_{ipll} V_{cq} & k_{ppll} V_{cq} \frac{\partial V_{tq}}{\partial \delta} & 0 & 0 & 0 & \frac{1}{C} & k_{ppll} V_{cq} \frac{\partial V_{tq}}{\partial i_{1q}} \\ -k_{ipll} V_{cd} & -k_{ppll} V_{cd} \frac{\partial V_{tq}}{\partial \delta} & 0 & 0 & 0 & 0 & \frac{1}{C} - k_{ppll} V_{cd} \frac{\partial V_{tq}}{\partial i_{1q}} \\ k_{ipll} i_{2q} & \frac{V_{gf} \sin \delta}{L_2 + L_g} + k_{ppll} i_{2q} \frac{\partial V_{tq}}{\partial \delta} & 0 & 0 & 0 & \frac{R_d}{L_2 + L_g} & k_{ppll} i_{2q} \frac{\partial V_{tq}}{\partial i_{1q}} \\ -k_{ipll} i_{2d} & \frac{V_{gf} \cos \delta}{L_2 + L_g} - k_{ppll} i_{2d} \frac{\partial V_{tq}}{\partial \delta} & 0 & 0 & 0 & 0 & \frac{R_d}{L_2 + L_g} - k_{ppll} i_{2d} \frac{\partial V_{tq}}{\partial i_{1q}} \end{bmatrix} \quad (\text{S4})$$

$$\mathbf{B}_{22}^{4 \times 4} = \begin{bmatrix} 0 & \omega_n + k_{ppll} V_{cq} \frac{\partial V_{tq}}{\partial V_{cq}} & -\frac{1}{C} & k_{ppll} V_{cq} \frac{\partial V_{tq}}{\partial i_{2q}} \\ -\omega_n & -k_{ppll} V_{cd} \frac{\partial V_{tq}}{\partial V_{cq}} & 0 & -\frac{1}{C} - k_{ppll} V_{cd} \frac{\partial V_{tq}}{\partial i_{2q}} \\ \frac{1}{L_2 + L_g} & k_{ppll} i_{2q} \frac{\partial V_{tq}}{\partial V_{cq}} & -\frac{R_d}{L_2 + L_g} & \omega_n + k_{ppll} i_{2q} \frac{\partial V_{tq}}{\partial i_{2q}} \\ 0 & \frac{1}{L_2 + L_g} - k_{ppll} i_{2d} \frac{\partial V_{tq}}{\partial V_{cq}} & -\omega_n & -\frac{R_d}{L_2 + L_g} - k_{ppll} i_{2d} \frac{\partial V_{tq}}{\partial i_{2q}} \end{bmatrix} \quad (\text{S5})$$

The partial derivatives and current-reference values involved in $\mathbf{B}_1$ are expressed as

$$\left\{ \begin{array}{l}
\frac{\partial V_{tq}}{\partial \delta} = -\frac{V_{gf} \cos \delta L_2}{L_2 + L_g}, \\
\frac{\partial V_{tq}}{\partial i_{1q}} = \frac{R_d L_g}{L_2 + L_g}, \\
\frac{\partial V_{tq}}{\partial i_{2q}} = -\frac{R_d L_g}{L_2 + L_g}, \\
\frac{\partial V_{tq}}{\partial V_{cq}} = \frac{L_g}{L_2 + L_g}, \\
\frac{\partial V'_{td}}{\partial \delta} = -\frac{V_{gf} \sin \delta L_2 2\pi f_c}{L_2 + L_g}, \\
\frac{\partial V'_{td}}{\partial i_{1d}} = \frac{R_d L_g 2\pi f_c}{L_2 + L_g}, \\
\frac{\partial V'_{td}}{\partial V_{cd}} = \frac{L_g 2\pi f_c}{L_2 + L_g}, \\
\frac{\partial V'_{td}}{\partial i_{2d}} = -\frac{R_d L_g 2\pi f_c}{L_2 + L_g}, \\
\frac{\partial V'_{td}}{\partial V'_{td}} = -2\pi f_c, \\
\frac{\partial i_{fd}^*}{\partial V'_{td}} = \frac{i_{fq}^* k I_n}{i_{fd}^* V_n}, \\
\frac{\partial i_{fq}^*}{\partial V'_{td}} = -\frac{k I_n}{V_n}, \\
i_{fq}^* = \frac{0.9 V_n k I_n - V'_{td} k I_n}{V_n}, \\
i_{fd}^* = \sqrt{I_{\max}^2 - (i_{fq}^*)^2}.
\end{array} \right. \quad (S6)$$

When the current reaches the limiting value, the Jacobian matrix $\mathbf{B}_2$ is basically identical to $\mathbf{B}_1$. However, the partial derivatives associated with the current references become

$$\left\{ \begin{array}{l}
\frac{\partial i_{fd}^*}{\partial V'_{td}} = 0, \\
\frac{\partial i_{fq}^*}{\partial V'_{td}} = 0.
\end{array} \right. \quad (S7)$$