Impedance-Based Accurate Stability Assessment of Inverter-Based Microgrids Using a Compact Perturbation Generator

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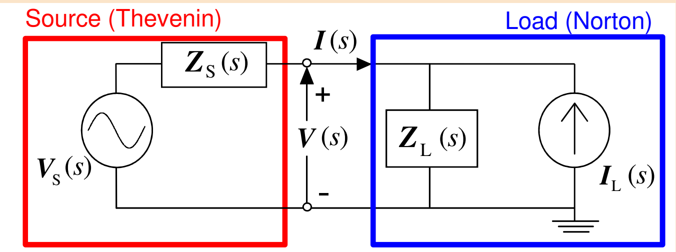
1 Purpose of this study

Sub-synchronous oscillations (SSOs) caused by inverter-based resources (IBRs) have been increasingly reported. Because IBRs exhibit fast dynamics and nonlinear behavior, impedance-based analysis has recently gained attention. To ensure safety and protect proprietary information, stability must be evaluated prior to grid connection.

This study examines the feasibility of assessing system stability in parallel IBR operation by integrating individually measured impedance data. A laboratory microgrid is constructed to deliberately induce SSOs, and analytical results are compared with experimental observations. Through this comparison, the validity and applicability of the proposed approach are confirmed.

2.A Methodology for evaluating system stability based on impedance

Fig. 1. Thevenin and Norton equivalent circuit.



The impedance-based stability assessment identifies the impedances, $Z_S(s)$ and $Z_L(s)$. In a DC system, the current at the split point can be expressed as the following equation, and if the ratio of of $Z_S(s)$ and $Z_L(s)$ (loop gain) equals to -1, the system collapses.

$$I(s) = \left(-I_L(s) + V_S(s)/Z_L(s)\right)\frac{1}{Z_S(s)/Z_L(s) + 1}.$$

Similarly, in AC systems, when any eigenvalue of the loop gain matrix $\boldsymbol{L} = \boldsymbol{Z}_S\boldsymbol{Z}_L^{-1}$ passes through $(-1, j0)$, the system may become unstable.

2.B Algorithm for generating rectangular perturbations

To calculate the dq impedance matrices, perturbation voltages are injected at the split point so that only the d- or q-axis is excited in the synchronous reference frame. This requires the perturbation generator to output a composite wave of positive and negative sequences in the stationary reference frame. Traditionally, sinusoidal perturbations were generated by linear amplifiers or PWM inverter. This study instead proposes a one-pulse switching generator without PWM control, enabling direct injection of rectangular-wave perturbations without the magnetic saturation caused by transformers required for system insertion, and without limitations from inverter LC filter bandwidth.

Fig. 2.1. Sinusoidal waveform.

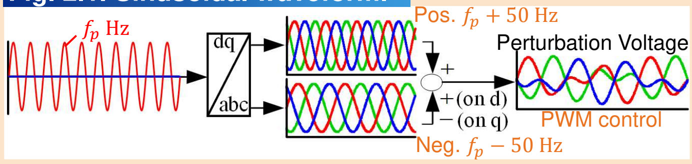
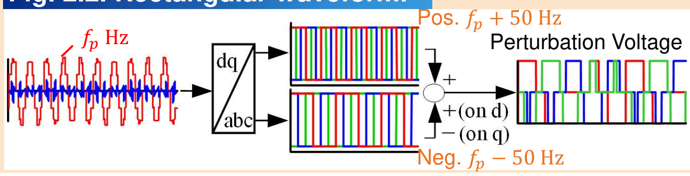
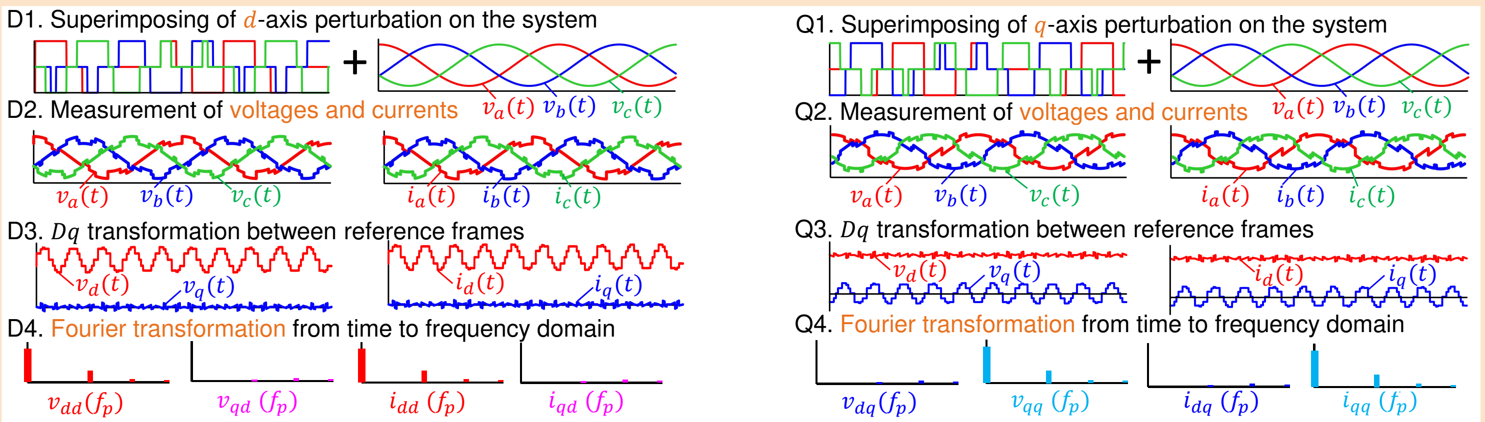


Fig. 2.2. Rectangular waveform.



2.C Calculation flow of the impedance matrix at a perturbation frequency (Fig. 2.3.)



5. Calculation of the impedance matrix $\boldsymbol{Z}$ at f_p Hz

$$\boldsymbol{Z} = \begin{bmatrix} Z_{dd}(f_p) & Z_{dq}(f_p) \\ Z_{qd}(f_p) & Z_{qq}(f_p) \end{bmatrix} = \begin{bmatrix} v_{dd}(f_p) & v_{dq}(f_p) \\ v_{qd}(f_p) & v_{qq}(f_p) \end{bmatrix} \begin{bmatrix} i_{dd}(f_p) & i_{dq}(f_p) \\ i_{qd}(f_p) & i_{qq}(f_p) \end{bmatrix}^{-1}$$

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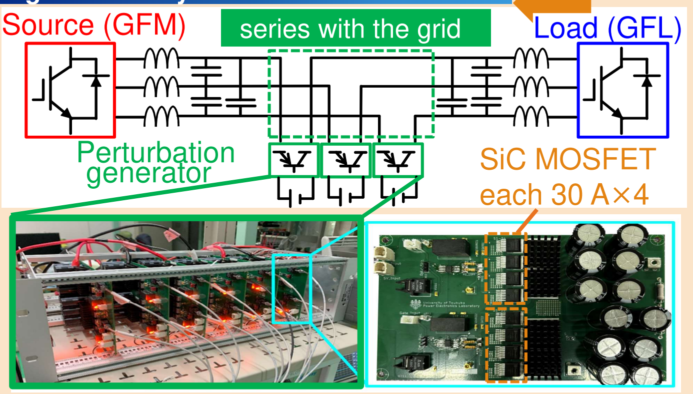
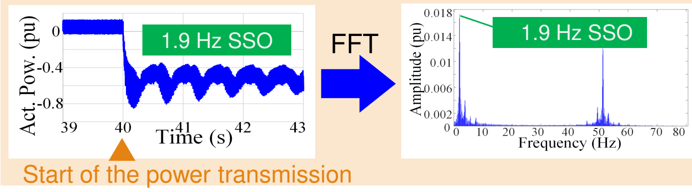
3 Impedance measurement in the MG with intentionally induced SSO

Fig. 3.1. MG System with GFM and GFL.



Three full-bridge converters with two half-bridges each

Fig. 3.2. Time response of the active power.



A microgrid (MG) with grid-forming (GFM) and grid-following (GFL) inverters was built in the laboratory. To intentionally induce SSOs, the active power command was stepwise varied from 0 to 0.5 pu, resulting in an oscillation at 1.9 Hz. A compact perturbation generator for impedance measurement was also developed and connected in series with the load system.

4 System stability evaluation combining individually measured impedances

When GFL and GFM inverters operate in parallel, simultaneous impedance measurement shows a gain crossover at 1.9 Hz (Fig. 4.1), indicating potential instability in the loop-gain eigenvalue loci (Fig. 4.2). In practice, however, parallel operation causes SSOs (Fig. 3.2), making impedance measurement difficult. To overcome this, each inverter is connected to an infinite bus (Fig. 4.3) and measured individually, with results analytically combined. The derived impedance characteristics (Fig. 4.4) and stability assessment (Fig. 4.5) closely match those from simultaneous measurement, demonstrating that instability can be safely predicted without actual parallel operation.

Fig. 4.3. Systems for individual measurements.

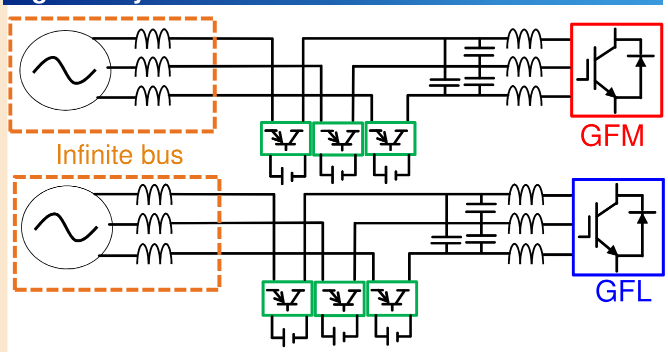


Fig. 4.1. Simultaneous measurement impedance.

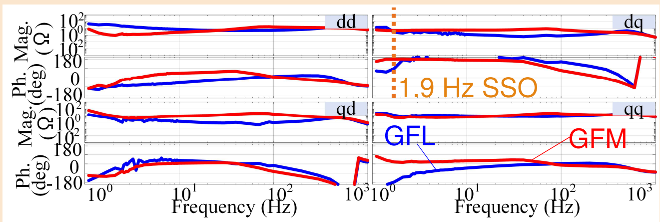


Fig. 4.4. Individual measurement impedance.

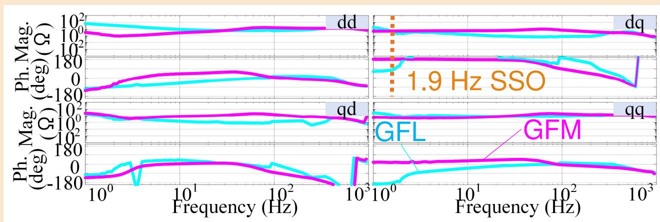


Fig. 4.2. Stabilities at simultaneous measurements.

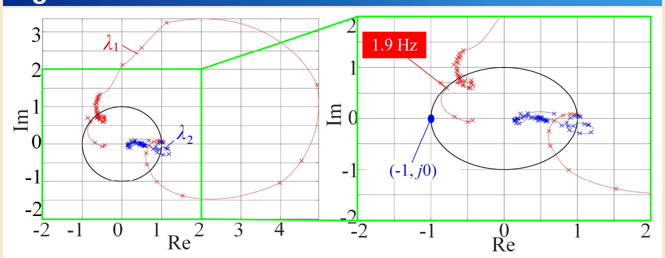
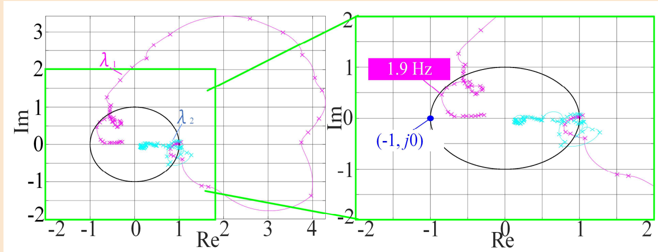


Fig. 4.5. Stabilities at individual measurements.



5 Conclusion

In this study, instability in microgrids composed of GFM and GFL inverters was identified using a compact perturbation generator based on a rectangular-wave algorithm. The stability derived from the impedance measured by individually connecting each inverter to the grid showed good agreement with that obtained from the impedance measured during parallel operation, confirming the applicability of impedance analysis even in unstable systems. This approach enables safe and simple prediction of future instabilities prior to actual operation, thereby supporting the maintenance of stable power systems.