Parallel Operation of Grid-Forming Power Inverters

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***Abstract*—The use of renewable energy sources has been increasing during the last decade. The inverters used for the connection to the grid can be controlled in two modes, grid-following (GFLI), and grid-forming (GFMI). This thesis investigates and validates control methods, without communication, for the operation of parallel GFMIs in standalone mode (SA). The thesis is divided into two main parts. The first part is related to single inverters working as GFLI and GFMI, whereas the second part is dedicated to the study and validation of parallel GFMIs. In this part, two main scenarios are addressed, the case of parallel operation with inductive lines and resistive lines. For each scenario, different types of droop control were simulated and tested in the laboratory.**

I. Introduction

With the use of renewable sources in GFMI mode, participation in the power-sharing among the generators can be realized thanks to their ability to set amplitude and phase of the output voltage. A well-established technique is the droop control, which is widely used thanks to automatic power sharing. In contrast with the mechanical inertia of the synchronous generators, which naturally slows down their response to disturbances on the grid, the GFMIs present a fast response. Therefore, the rate of change of frequency (RoCoF) should be limited by the control. Furthermore, the conventional droop control methods consider active and reactive power flows as decoupled. Nonetheless, this hypothesis is met if the grid impedance is predominately inductive, which is not always true, particularly for low-voltage transmission grids.

II. Research Question

The examined question was how different types of droop control behave for parallel GFMIs in SA mode. The quality of the control was assessed with laboratory validation, considering the active power-sharing between the inverters and the frequency response for a load step.

A. Method

Different tasks were completed before the study of parallel GFMIs. I implemented a GFLI whose current control was used as the inner loop of a GFMI. Once I obtained a GFMI, the parallel operation was analyzed and tested. Each control methods was simulated in Simulink, where the code was generated. The controller platform is developed by the company and called B-Box RCP.

III. System Under-Study

Two GFMIs are connected in parallel to a passive load, as shown in Fig. 1. GFMI1 forms the grid and it can be considered a reference for GFMI2, which is synchronized to it. Therefore, an additional voltage measurement is used for GFMI2. For the voltage synchronization, a proportional-integral controller is implemented, whose outputs are given as feed-forward to the droop control loop.

IV. Droop Control Methods for Inductive Lines

For an inductive line, the active and reactive power flows are decoupled. The active power flow depends on the phase difference, whereas the reactive power flow depends on the difference in voltage amplitude.
First, the proportional droop control was implemented,

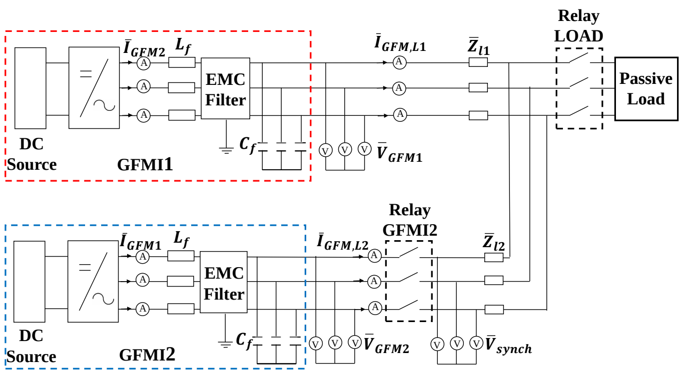

Figure 1: Electrical schematic of the system under-study

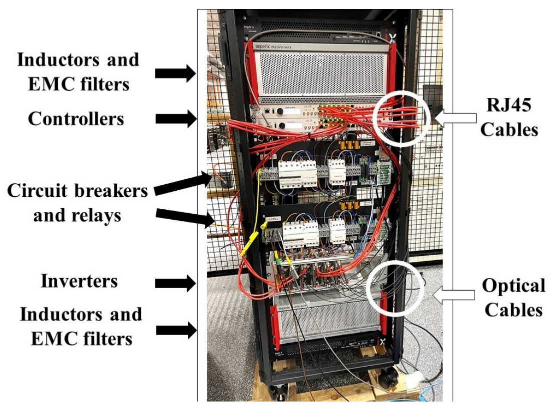

Figure 2: Electrical system implemented for the laboratory validation

which is based on two separate controls: $(P - \omega)$ and $(Q - V)$. The voltage reference, in terms of frequency and amplitude, is adjusted proportionally to active and reactive power, respectively. The droop proportional coefficients, m and n, are designed to ensure the steady state maximum variation for the voltage amplitude and the frequency. The RoCoF is limited by adding a low-pass filter in the control. First, the system was tested considering equal droop control coefficients for the two GFMIs. The results showed an equal distribution of active power and a RoCoF less than $1Hz/s$. Then the proportional droop control was tested considering $m_1 = 2m_2$. The system presented an undamped response for a load step. For this reason, a second method was studied. This method add a derivative term, which was designed to dampen the response by adjusting the pole placement of the transfer function. This resulted in a dampen transient, see Fig. 4. Moreover, the steady-state power-sharing was not affected and is proportional to m. However, the RoCoF was approximately 2.5 times larger than before.

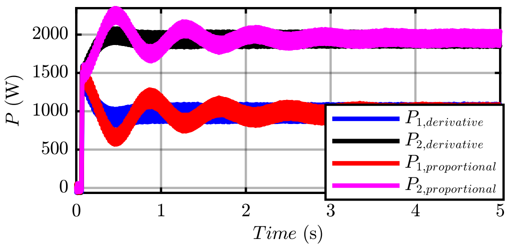

Figure 3: Comparison of active power flows for a load step: proportional droop and proportional droop with derivative term

Moreover, a first-order VSG generator was implemented for SA mode. The impact of the virtual inertia was tested in the laboratory. The virtual inertia, τ_J is chosen to limit the RoCoF.

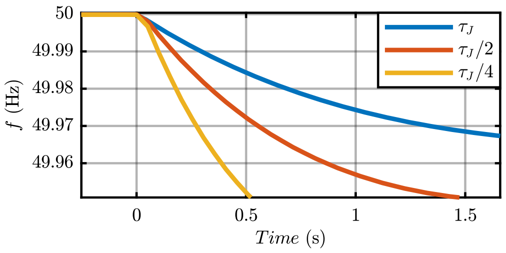

Figure 4: Comparison of frequency variation for a load step with different virtual inertia values

The control was tested with different virtual inertia values. The experimental results were consistent with the theory. The RoCoF is inversely proportional to the virtual inertia.

V. Droop Control Methods for Resistive Lines

For resistive lines, a conventional droop can cause oscillation in the system and possible instability. Therefore, two decoupling methods were studied and tested with a proportional droop. The first one is the virtual impedance, where a virtual voltage drop is added in the control to mimic the presence of an inductor, L_v. The system was tested for different values of L_v to observe the effect on the decoupling. For a low X/R, oscillation appeared after a load step, see Fig. 5. By increasing the virtual impedance value, the decoupling increased and the amplitude of the oscillations was reduced. Active power-sharing was marginally affected, whereas reactive power-sharing was negatively affected.

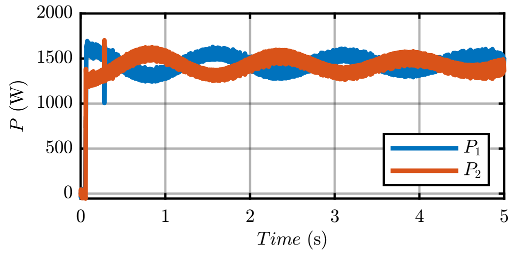

Figure 5: Active power flows for a load step: virtual impedance method with insufficient decoupling

The second method is based on a linear transformation method. Considering the active power flow for a resistive line, it depends on both phase and amplitude variation of the voltage. This dependence is proportional to the inductive and resistive parts of the line impedance, respectively. This method transforms active and reactive power accordingly to the line impedance, such that they depend only on angle variation and voltage amplitude variation. P' and Q' are given as input of the droop control.

$$P^{'} = \frac{X_l}{Z_l}P - \frac{R_l}{Z_l}Q \quad Q^{'} = \frac{R_l}{Z_l}P + \frac{X_l}{Z_l}Q \tag{1}$$

The experimental results showed that this method ensures sufficient decoupling but it causes active power-sharing inaccuracy in SA mode, see Fig. 6.

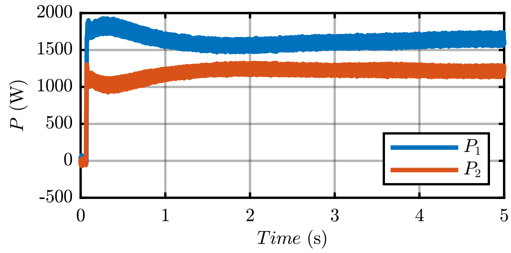

Figure 6: Active power-sharing inaccuracy for a load step: linear transformation method

VI. Conclusion

The experimental results were consistent with the theory and an evenly distributed power-sharing was obtained, except for the linear transformation method. A first-order droop control can result in an undamped transient. Therefore, proportional droop control is not suitable for GC mode. Moreover, a further investigation for the proportional droop with the derivative term is needed to reduce the RoCoF. A more advanced VSG model to dampen the system response can be investigated for the grid-connection mode.