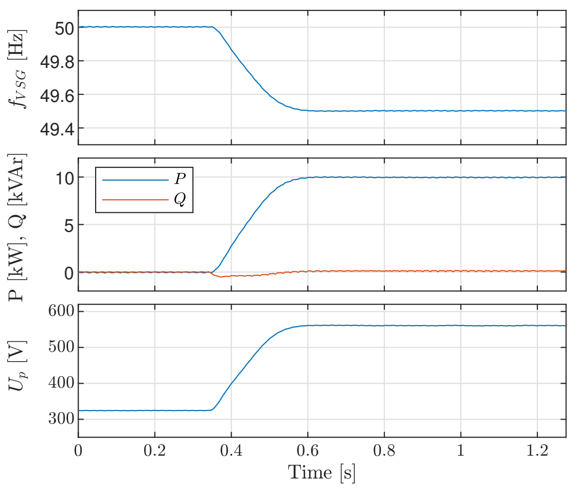

Fig. 11. Frequency droop response of VSG in the real-time HIL system.

The PI current control is designed for $\sim 60°$ phase margin with $T_s = 1/f_{sw}/2$. The proportional and integral gains are $K_P = 3.49$ and $K_I = 0.107$, respectively. The algorithm runs at both peaks of the PWM triangular carrier signal. Since the sampling is synchronized to the PWM, the current ripple in phase current i_a is eliminated in Fig. 10(b), only small ripples caused by noise in the measurement can be observed. The transient of i_d is about as expected. The overshoot reflects a bit smaller phase margin, the reason is that two consequent current samples are averaged, but this delay is not considered in the design of the PI gains. The small transient in the q direction current is due to that decoupling between the d and q channels was not applied during the test. In the transient of u_d a peak can be seen during the actuation, the steady-state of voltage u_d is the same. Since both the dead-time and the choke resistance are zero, no additional voltage drop in d direction, only the 325 V grid voltage. The transient change of u_d is around 75 V, which comes from the product of the change of the current and the proportional gain.

The response of the VSG system recorded at the DSP side is shown in Fig. 11. The frequency of the grid steps from 50 Hz to 49.5 Hz. It can be seen the frequency of the VSG follows this change. Most of the signals are similar to the off-line simulations shown in Fig. 5, the active power tends to 10 kW according to the frequency droop parameter while the reactive power stays at zero. However the virtual pole voltage U_p is much larger at this operating point, since for stability reason both the virtual resistance and inductance are increased. In order to reach these smooth transients, additional filters are used in the grid voltage measurement and the power calculations. These filters change the stability borders, and required to modify the virtual impedance.

6. Conclusions

A HIL simulation framework has been developed for real-time testing of the AFE rectifier control algorithms. The model-based system development is supported by automatized code-generation. Both the main circuit HIL model and the embedded control are generated from Simulink models. The operation and current control of the AFE model were demonstrated, the system exhibited realistic behaviors, e.g. the deadtime effects are presented that may help developing deadtime compensation algorithms, harmonic elimination techniques.

The dq-frame current control is extended by a virtual synchronous generator model to serve active and/or reactive power demand of the grid from energy storage and/or renewable sources. The frequency and voltage droop characteristics of the system is studied in off-line simulation and in the HIL system. The real-time VSG control required precise voltage calibration and needed to use additional filtering, which influenced the selection of virtual impedance parameters.

In future plans, the main circuit model needs to be extended with ac side capacitor and grid impedance to obtain more realistic system behaviors. Similarly the dc side ideal voltage source also need further development both in the HIL model and in the control.

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