A Smart Distribution Grid Laboratory

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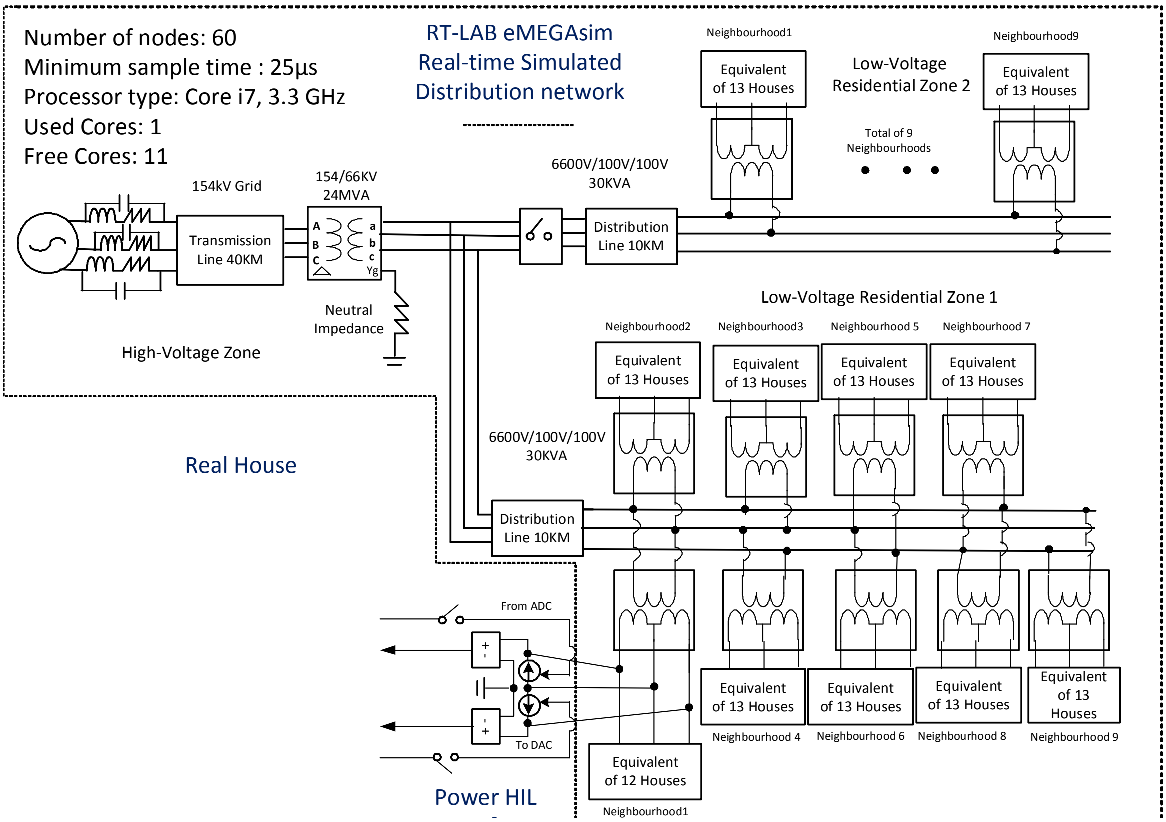
***Abstract*- This paper details a Smart Grid Laboratory for the study of modern house distribution systems with multiple energy sources and energy regeneration capability. The laboratory is designed to perform real-time simulation of a realistic distribution system connected to multiple houses. In addition, a real house with typical appliances and power sources is connected to the eMEGAsim real-time simulator with a Power-Hardware-In-the-Loop (PHIL) interface. Such PHIL interface enables the simulation of a simulated plant and real devices at a connection point where actual energy is exchanged between the two parts. Because of the coupling delays and the bandwidth of the plant and real devices, the stability of such a PHIL connection is not guaranteed. This paper will have a special emphasis on the stability of such power-HIL simulation.**

I. Introduction

The smart grid should be able to manage energy supply and demand by all users down to the distribution network.

It means more than simple improved energy efficiency. Smart distribution grids can include any energy-user actions to enhance reliability, reduce peak demand, shift usage to off-peak hours and lower total energy consumption. It can also manage very innovative ways to use customer-generated energy (solar, wind, and other renewables) and re-inject it into the grid. The increased use of electric vehicles can also have an impact on the grid, either for charging or for energy reserve in the car battery. Smart grid designers must also have a better understanding of how energy is used by each appliance or piece of equipment.



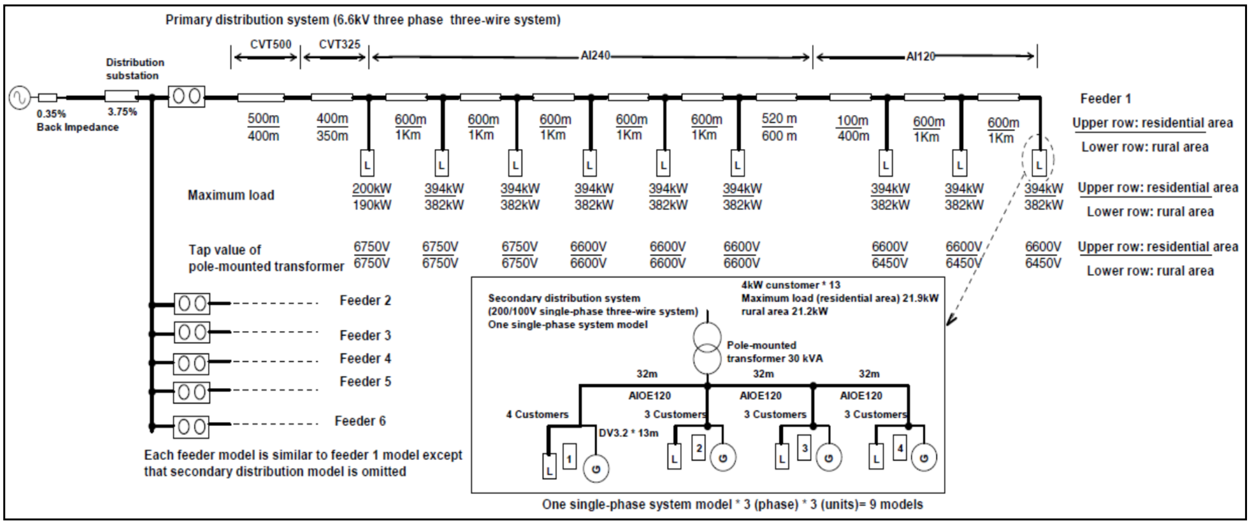


Fig. 2. A typical Japanese distribution network.

II. The Smart-Grid Laboratory

OPAL-RT has recently delivered a real-time simulator that will be used in a micro-grid laboratory. This laboratory includes a real house connected to a 10-kW power amplifier interfaced with the eMEGAsim power system simulator in a power-Hardware-In-the-Loop (power-HIL), as depicted in Fig. 1.

The house is equipped with appliances and other equipment, including fuel cell, photo-voltaic systems and other equipment that is being contemplated for future houses. These houses will be integrated into modern micro-grids where each house could also return energy to the grid.

Such distributed energy distribution and generation systems will become very complex due to possible interactions between intelligent equipment located in each house and with the power grid. For example, what will happen to the system if the feeder is disconnected from the power grid? Which generators, located in several houses, will control the voltage and frequency?

The Microgrid Laboratory will enable analyzing such interactions between the power grid and house equipment by injecting the house current to the feeder circuit simulated by the eMEGAsim real-time simulator, which in turn will return the feeder voltage to the house with a power-HIL connection, as described in Fig. 3.

The simulator, amplifier and house form a closed-loop system that may become unstable under certain operating conditions, like any other closed-loop systems. Such possibility of instability is studied in this paper, and has been studied in other works by different authors for HIL [3] and power-HIL[1][2][4][5].

A. Typical Japanese Distribution System

Figure 2 presents the schematic of a typical Japanese distribution system which could include several feeders and secondary distribution systems feeding about 13 houses each. The model in Fig. 1 is a simplified version of a typical Japanese distribution system presented in Fig. 2. It is composed of a simulated power system, implemented in the eMEGAsim real-time simulator, the amplifier and the real house.

The simulated power system includes a 154-kV equivalent source, a 154-kV transmission line and a 154-kV to 6.6-kV transformer feeding the distribution system. The distribution system include two feeders with several 6.6-kV to 200-V transformers connected to 13 houses each. The lower feeder contains 12 house loads simulated in the eMEGAsim simulator while one real house is connected to the simulator through the NF 10-kW power amplifier.

III. Power-HIL Interface

The main challenge of the power-HIL set-up is to increase the simulator bandwidth and load power without reaching unstable operation.

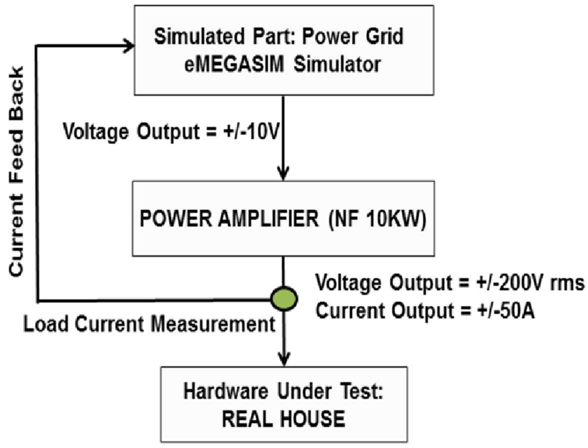


Fig. 3. Real-time Simulator, power amplifier and real house connection

A key component of the power-HIL set-up is, of course, the power amplifier. Typically, power amplifiers have higher bandwidth and power ratings when in voltage mode. This is good considering that typical loads will be inductive and/or resistive. The NF amplifier characteristics are listed in Table 1. The parameters are given for the controlled voltage mode.

In the first phase of this project, the simulator was used with a time step of 50 µs and the objective was to optimize all other PHIL simulator parameters to reach good accuracy up to about 1 to 2 kHz.

Table 1: NF Power Amplifier characteristics

Manufacturer	NF Corporation
Maximum voltage	200V rms
Maximum output current	50A
Maximum absorbing current	18A
Frequency response	0-1kHz (error <0.2%) 1-20 kHz (error <2%)

IV. POWER-HIL STABILITY ISSUES

Instability is caused by the delays introduced by the simulator sampling (analog input and output converters, model time steps, …) and the power amplifier. They must be eliminated to prevent damage to the equipment and to obtain the maximum precision of the simulation. This type of instability can depend on various factors:

1- The choice of amplifier output type: current controlled or voltage controlled.
2- The ratio of the load power to the short-circuit power of the feeder circuit – the risk of instability increases with the power of the load.
3- The type of loads – the risk of instability increases for capacitive load and decrease for inductive loads (with voltage amplifiers).
4- The damping of the source impedance – the risk of instability increases when the damping is low, which is the case when the total load connected to the feeder is small.
5- The power amplifier bandwidth – the risk of instability increases when the amplifier bandwidth is high; but the simulation precision decreases when the amplifier bandwidth is low; therefore one challenge is to make the best compromise between the amplifier bandwidth, amplifier cost and simulation accuracy.
6- The sampling frequency of the simulator – the risk of instability increase when the sampling frequency is low; typical sampling frequency for high-end real-time simulators used for HIL and PHIL vary between 20 kHz and 50 kHz.

The PHIL systems must therefore be designed to prevent instability and, at the same time, to increase the overall simulation precision in order to accurately simulate the complex interactions between power electronic systems including their control and protection installed in the real house and other power electronic systems installed in simulated houses. The simulator accuracy must also be good enough to simulate real instability that could arise in real-life due to interactions between power electronic systems and motor loads installed in houses and on the feeders.

V. STUDY OF THE POWER-HIL STABILITY LOOP

The circuits of Fig. 1 and Fig. 2 can easily be simulated in real-time with eMEGAsim at time step below 50 µs. However, such a circuit is still too complex to study the instability phenomenon and find the relation between circuit parameters and the risk of instability. In order to simplify the analysis, an equivalent circuit was developed and depicted in Fig. 4. Careful design and analysis of the circuit can help increase the stability of this circuit.

A. Model source impedance adjustment

The impedance of the feeder was evaluated to be equal to 0.127mH (0.04 Ω at 50 Hz, corresponding to a short-circuit current of 5000A). As the house module is driven by a voltage driven power amplifier and the feedback is a current, a direct current injection into an inductive feeder circuit would cause stability issues under certain circumstances [1]. A parallel resistance of 4 Ω was therefore added to the feeder inductance to limit its high frequency impedance above 5 kHz. It is important to understand that this parallel resistance is not part of a real feeder circuit and is added to stabilize the PHIL connection by limiting the high-frequency impedance of the feeder.

B. Power amplifier bandwidth

We assume that the power amplifier bandwidth is 20 kHz approximated by a first order filter in our analysis.

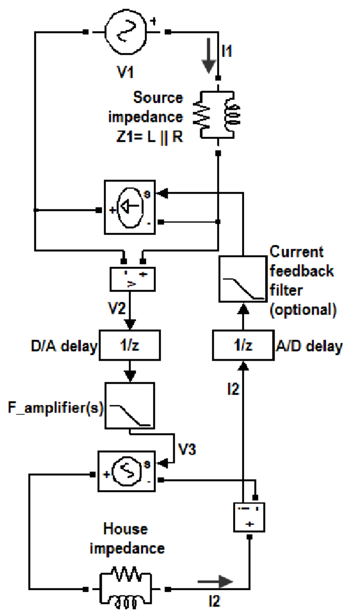


Fig. 4. Circuit equivalent to study power-HIL stability

C. Current filter

We added, optionally, a first order current filter to the circuit to increase the stability of the system, tuned at 1 kHz.

D. Stability analysis

The complete power-HIL loop can now be analyzed using Bode diagrams. The stability condition is that the open loop gain be less than one, at all frequencies where phase shift is less than -180 degrees

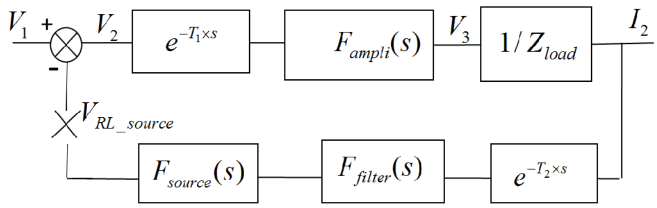


Fig. 5. Power-HIL open-loop transfer function

F_{source}: network equivalent impedance seen at the secondary side of the 200/30KVA transformer
Z_{load} : real house impedance.
F_{ampli}: amplifier frequency response.
F_{filter}: optional current feedback filter.

e^{-Ts} : delays of the analog output and input analog to digital converters (T_1 and T_2 are equal to T, the model time step).

The complete open-loop equation is therefore equal to:

$$F(s) = \frac{1}{Z_{load}} e^{-2Ts} F(s)_{ampli} F(s)_{filter} F(s)_{source} \quad (1)$$

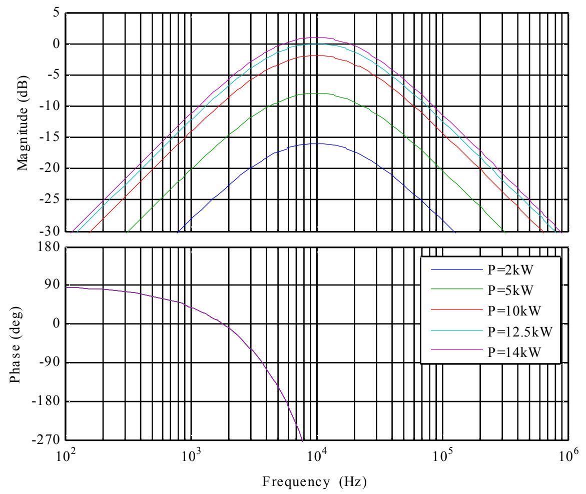


Fig. 6. Open-loop power-HIL frequency (resistive load, no filter)

The stability of the loop then depends on many factors such as the type of load, typically inductive and or resistive, the sample time of the simulator (1/z delays), the amplifier bandwidth and optionally the current feedback filter. In these tests we used a time step of 50µs.

E. Analysis without current feedback filter with resistive load

In this case, it can be observed that stability is guaranteed for load powers below 12 kW because open-loop gain is below 1 at this power for all frequencies as shown in Fig. 6.

F. Analysis with current feedback filter and resistive load

The addition of current feedback filter, tuned with -3dB corner frequency of 1 kHz, increases the maximum load power to about 70 kW as shown in Fig. 7.

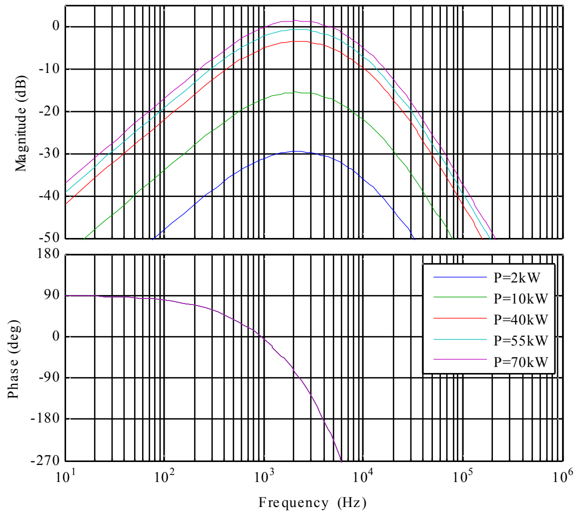


Fig. 7. Open-loop power-HIL frequency response with 1 kHz current feedback filter, resistive load

Time domain step response also validates this conclusion. Fig. 8 shows the step response for various load and shown that we approach the stability limit when reaching 55 kW load.

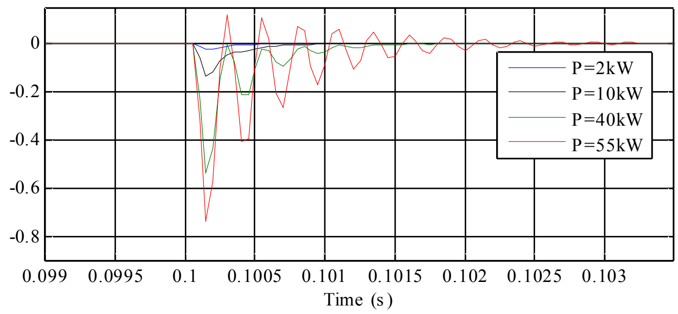


Fig. 8. Step-response of the power-HIL set-up for resistive load with current feedback filter.

These results were obtained by the increased damping of the source impedance by adding a resistor R in parallel with the source inductance. In this case, *Zload* will be equaled to R for high frequency. This is reasonable for the actual project considering that the damping of the other 12 houses connected to the same feeder should have an equivalent resistive load larger than the resistive load of one house.

G. Cases with inductive loads.

For a pure inductive load, the PHIL will be stable as long as the load inductor is larger than the source inductor, as determined in [1].

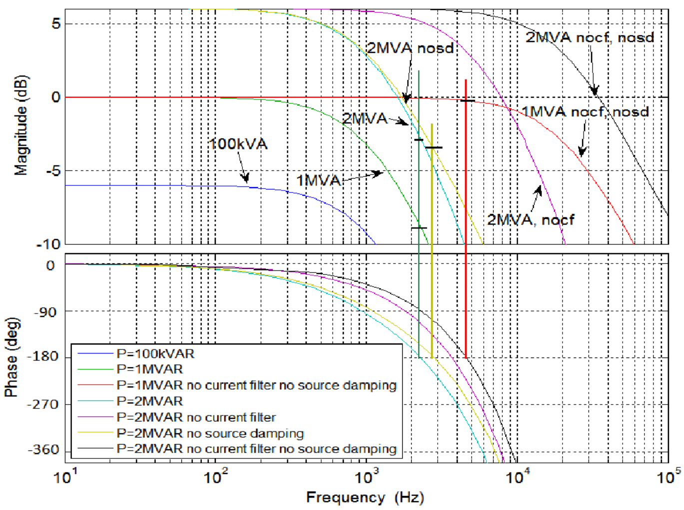


Fig. 9. Open-loop frequency response for purely inductive load and different power-HIL configurations

In the actual project, the short circuit current of the source is about 5000A, which corresponds to a short-circuit power of 1MVA at 200V. This short-circuit power of 1 MVA corresponds to a very small inductance as compared to the equivalent inductor of one house. Therefore in our case, at 1 MVA, the load inductance is equal to the source impedance. In Fig. 9, these curves correspond to 1 MVA. The stability margin is found by inspection: it's the magnitude of the open-loop function when its phase crosses -180 degrees. The '1MVA nocf, nosd' (case without current filter nor 4Ω source damping) is interesting because the stability margin is less than 0.2 dB, so it confirms the limit predicted in [1]. In the figure, 'nocf' stands here of 'no current filter' and 'nosd' for 'no source damping'. The same case with a time step of 25 µs sees its stability margin increase to 0.8 dB which is still marginal but confirms the stabilization effect of a lower sample time. But with filter and damping ('1MVA' curve), the stability margin is increased to 9dB. It is also interesting to see than cases with load inductance small than source inductance, prefixed '2MVA' are stable only with the current filter in place ('2MVA nosd'), the case with only the source damping ('2MVA nocf') is unstable.

The reason that the current filter seems more stabilizing than the source damping method is only because the cut-off frequency of the current filter (1 kHz) is lower than the source damping method tuned at 5 kHz. If we adjust the source damping resistor to 4/5 Ω instead of 4Ω (i.e. tune it to 1 kHz), the current filter and damping resistor have been found to have the exact same effect on stability. This was to be expected since the two frequency functions are products in the open-loop equation (1).

CONCLUSION

The paper presented a Smart Distribution Grid Laboratory and the power-HIL simulator used to simulate a real-house inside a simulated distribution grid. The power-HIL set-up was studied in terms of stability.

The stability analysis done in this work leads us to the following conclusions:

- The stability of the PHIL system is strongly dependent on the ratio of the load impedance to the source impedance and on the load type.
- A purely resistive load will be stable if a first-order current filter and/or source damping resistor is present in the circuit with a cut-off frequency between 1 and 10 kHz.
- A purely inductive load should always be stable with typical distribution circuits.
- A current feedback filter or source damping resistor increases the stability margin for resistive and inductive loads.
- Lower sampling time increase the simulation stability along with its accuracy.

In any case, the actual load is much more complex than a pure resistive, inductive or even capacitive load. Typical modern house loads will include several power electronic loads and generation systems. Considering that a precise load model is not yet available, designing a PHIL system that will be stable for all possible load conditions is very difficult. This difficulty increases if good simulation accuracy is also required for the high frequency.

At the time of publication of this paper, the actual PHIL laboratory was not yet completed. Future work will report on the results of the actual Smart Distribution Grid Laboratory and verify its stability and accuracy under various test scenarios.

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