EXPERIMENTAL INVESTIGATIONS OF ELECTRICAL INFLUENCES ON POWER LINE COMMUNICATION PERFORMANCE IN DISTRIBUTION GRID APPLICATIONS

Benedikt MÖLDERS
RWTH Aachen University – Germany
moelders@ifht.rwth-aachen.de

Tobias Markus PLETZER, Markus WÄCHTER, Michael KOCH
devolo AG – Germany
{tobias.pletzer, markus.waechter, michael.koch}@devolo.de

ABSTRACT

Powerline communication (PLC) offers the chance for distribution grid operators to use the existing energy cable grid simultaneously as an infrastructure for communication purpose. In this paper practical examinations under realistic conditions are performed in the distribution grid laboratory of the Center for Grid Integration and Storage Technologies of RWTH Aachen University. Measurements with different photovoltaic (PV) inverters demonstrate the robustness of state of the art G3-PLC modems against additional attenuation and emission of noise of PV inverters in operation. Furthermore the adaptive reconnection ability of these modems is pointed out for smart grid application.

INTRODUCTION

The successful implementation of future smart grids relies on the availability of a reliable and cost efficient communication infrastructure. Powerline communication (PLC) offers the chance to use the existing low voltage (LV) cable grid for data transmission instead of using external networks or building an extra infrastructure. PLC as a possible backbone for future information and communication (ICT) infrastructure has to guarantee a reliable and sufficient performance even in the occurrence of electrical disturbances or in combination with increased decentralized power generation. But due to the fact that the operation of PLC leads to cable networks used as a shared medium of power supply and communication, the communication channel underlies continuous changes [1].

Todays and future distribution grids are characterised by a potential partial high density of decentral power generation units, for instance solar power systems. For the transformation of the direct current (DC) at the output of the solar panels into alternating current (AC) for power grid connection, power inverters are needed. These power inverters use e.g. pulse-width modulation PWM as a control algorithm and semiconductor devices for switching actions. As a consequence of switching, harmonics above 50 Hz can be produced and emitted into the power grid. Therefore photovoltaic (PV) inverters can act as an additional noise source leading to further disturbances on the powerline channel [2]. To comply with grid integration standards [3], output filters with inductances (L) and capacitances (C) in the form of L, LC or LCL filters are used to damp the outgoing frequencies [4]. In contrast to the risk of additional channel noise, PV inverters could have a damping effect on high frequency signal distribution because of its output filters connected to the power grid. For this reason, practical examinations on PV inverters under load conditions in a realistic testbed are performed in this paper.

A further issue relating to distribution grid applications is a change of the energy cable grid topology in operation. In case of electrical faults or due to operational needs, for instance maintenance works, the cable topology can vary and thus the powerline network has to be flexible and adaptive to build up new communication routes to ensure a reliable reconstruction of the communication line. Powerline networks consist of a central personal area network (PAN) coordinator modem acting as a point of data concentration and PAN end devices installed e.g. in households for smart metering applications, acting as clients.
The central PAN coordinator modem for PLC can be installed at the LV side of the substation transformer. After a disconnection of the transformer at the LV side by an open circuit breaker or tripped LV fuse, the communication path to the underlying PAN clients are also disconnected and the implemented reconnection ability of the PAN clients has to take place. Depending on the switching cause and fault scenario, another substation with a PAN coordinator is able to supply the underlying distribution grid. In this case, all PAN clients have to set up a new robust connection to the PAN coordinator in the other substation. The reconnection ability of state of the art PLC modems is investigated and results are presented and discussed in this paper.

TESTBED FOR PLC INVESTIGATIONS

To investigate the applicability of PLC in various scenarios, experimental tests are carried out in the distribution grid laboratory of the Center for Grid Integration and Storage Technologies of RWTH Aachen University [5]. The laboratory grid for PLC testing consists of a LV-cable grid (35 to 240 mm² type NAYY) of more than 3.000 m length in total. The individual cable lines range from 20 to 500 m in length and can be interconnected flexibly by inserting LV fuses of type NH2 into fuse-switch-disconnectors in distribution cabinets (1-6, A and B in Figure 1). Furthermore the LV cable grid can be connected to different medium voltage substations with power ratings from 400 to 1250 kVA.
To each of the distribution cabinets 1-6, a G3-PLC modem is installed as a PAN client. The G3-PLC standard is part

of the narrow band PLC technology (NB-PLC) and uses frequencies below 500 kHz for signal modulation. The PLC modems used in this examinations operate in the frequency band of 150 kHz to 500 kHz, which is not part of the CENELEC band (3 kHz to 148.5 kHz) and allowing data rates up to 240 kBit/s on the physical layer [6][7]. G3-PLC PAN coordinators (in figures only 'PAN'), running on the same hardware platform as the PAN clients (in figures only 'PLC'), are installed in two medium voltage substations and acting due to its configuration as a server for incoming data from the six clients.

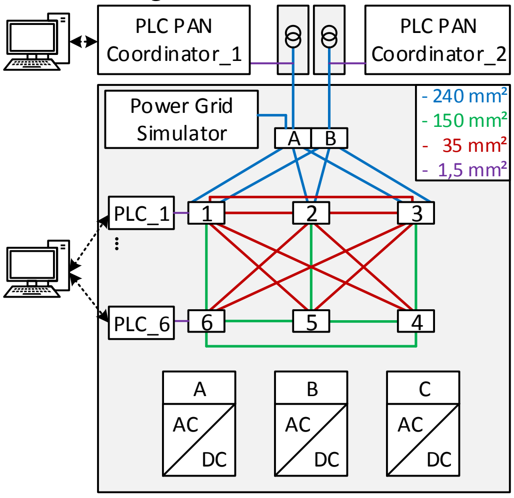

Figure 1 Topology of the LV-distribution grid laboratory of the Center for Grid Integration and Storage Technologies.

By the use of a power grid simulator voltage dips, a change of grid frequency or unsymmetrical phase-voltages can be supplied to the network. Installed PV inverters of different vendors and power classes allow an experimental study on the robustness of PLC technology. Specifications of the inverters, used for the following examinations are listed in Table 1.

Table 1 Specifications of the photovoltaic inverter.

Inverter	**A**	**B**	**C**
Manufacturer	**A**	**B**	**B**
Quantity	**1**	**1**	**3**
AC Phases [#]	**3**	**3**	**1**
AC Power [kVA]	**36**	**33,3**	**4,4**

DESCRIPTION OF THE METHODOLOGY

Measurements on the physical as well as on application layer are performed.

The measurements with focus on PV inverters are done with the testing setup in Figure 2. Different PV inverters (see Table 1 for specification) are connected by short cable lines, fuses and current transducer with two distribution cabinets in series to a medium voltage substation in the Testing Center. A PAN client is installed right behind the AC/DC inverter, to verify the robustness even in electrically close installation. On the LV side of the substation, behind the voltage fuses, the corresponding PAN coordinator for the communication link is installed.

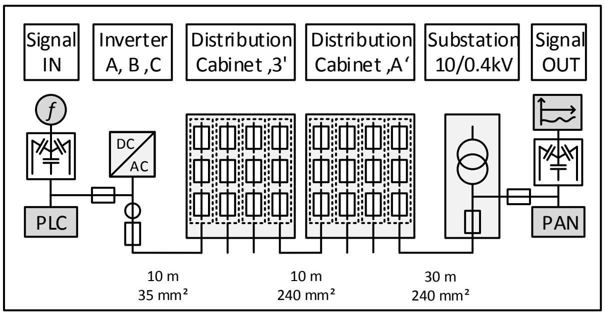

Figure 2 Experimental setup for inverter tests on PLC.

In this test setup the channel qualification is done by a signal attenuation and noise measurement. For this purpose a frequency generator is placed close to the PAN client. The feed in power of the frequency generator is set to P_{in} = +13 dBm, similar to the output power of the PLC modems for the modulation of the signal on the 50 Hz grid frequency. A spectrum analyser of the type Tektronix RSA306 is installed close to the PAN coordinator to measure the power level P_{out} of the signal reaching the PAN coordinator. The difference between P_{in} [dBm] and P_{out} [dBm] is defined as the signal attenuation ΔP [dB] of the channel, which is also frequency dependent. Noise measurements with the spectrum analyser detect the mean power level P_{noise} [dBm] of emitted noise signals in a time span of 2 minutes. Both, the frequency generator and the spectrum analyser, are connected by a capacitive coupling unit with the LV grid to uncouple the grid voltage from the measurement devices.

In order to demonstrate the adaptive reconnection ability of PLC technology a test setup in Figure 3 is used.

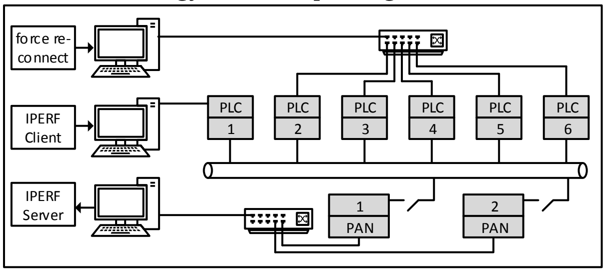

Figure 3 Topology for PLC reconnection tests.

This setup can also be used to examine, if there is an appreciable influence of nearby PAN clients on reconnecting in one network. The open source tool iPerf in Version 3.0.11 is executed on two different computers to generate and measure a time resolved transmission control protocol (TCP) data stream between a PAN coordinator and the PAN client. To simulate the change in network topology a circuit breaker on both PAN coordinators (PAN1 and PAN2) is used. Both PAN coordinators are connected on the network side to the iPerf server by a common switch. In the initial state, both circuit breakers are closed, but all PAN clients (PLC1-6) have a defined and stable network connection only with PAN1 coordinator. When the switch of PAN1coordinator opens, for instance due to a fault scenario, the PAN client PLC1 is forced by the enduring TCP data stream to seek for another PAN coordinator. The other PAN clients (PLC2 to PLC6) are not used for data transmission. In this test setup a third computer is used to force a spontaneous and simultaneous reconnection of these end devices to rebuild a connection to the new PAN coordinator right after the disconnection. Thus the influence of concurrent connecting PAN clients on the reconnection sequence can be observed.

ROBUSTNESS OF G3-PLC MODEMS IN INTERACTION WITH PV INVERTERS

Results of damping measurements with different PV inverters and disconnected PLC devices are given in Figure 4.

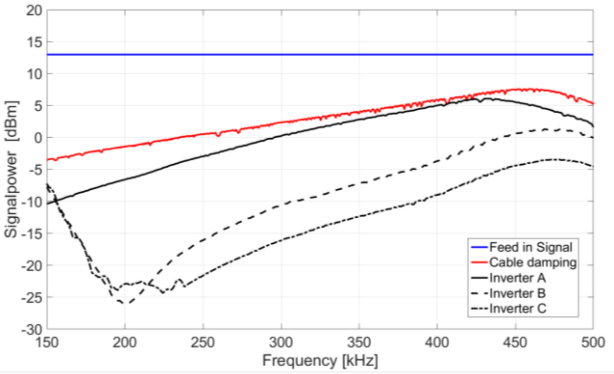

Figure 4 Damping measurements on test grid.

The chain of damping elements, consisting of cables, distribution cabinets and installation equipment leads to a damping of the signal to a minimum of P_{out}^{min} = -4 dBm at a frequency of f = 150 kHz. Additional installation of a parallel inverter increases the damping effect of the power signal in total. The subtraction of the cable damping characteristic from the inverter attenuation measurement leads to the net inverter attenuation in Figure 5.

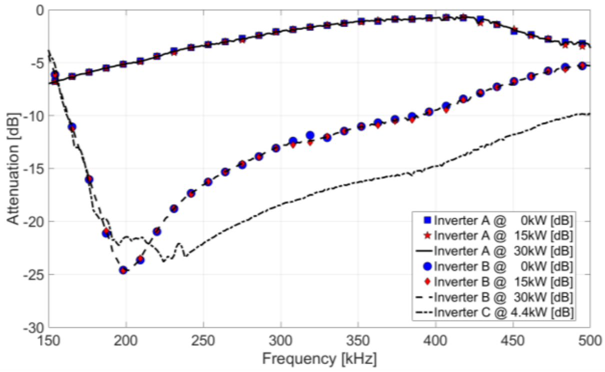

Figure 5 Attenuation of PV inverter in operation.

The graph shows, that there is no dependence of the operation state and output power on the attenuation characteristic, because of the static output filters. Furthermore it is observable that the filter design differs between manufacturer A and B significantly in damping characteristic. The power inverters B and C of manufacturer B effect a maximum attenuation of ΔP = -25 dB at f = 200 kHz. Maximum attenuation of inverter A is measured at f = 150 kHz of ΔP = -7 dB.
Beside the attenuation characteristic, the noise emission of these inverters under load is measured with disconnected PLC devices and plotted in Figure 6.

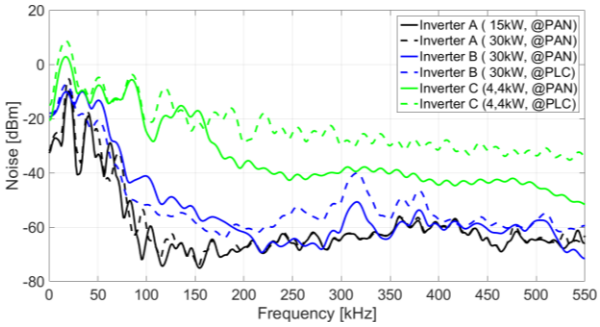

Figure 6 Noise emission of PV inverter in operation.

The measurement graphs of inverter A at P_{load} = 15 kW and P_{load} = 30 kW show, that there is no significant difference in noise power in dependence of the output power for this PV inverter. The noise emission of inverter A is limited to a low level of noise of P_{noise}^{max} < -55 dBm for frequencies above f > 150 kHz, where G3-PLC starts an CENELEC bandwidth ends. The noise level of the grid without connected devices is measured as below P_{noise}^{max} < -55 dBm, too. Tests with inverter B and C are performed under high output power load of the inverters, but with a varying placement of the spectrum analyser. Because of the cable and installation damping, the maximum noise emission from the PV inverter under operation is measured directly at installation clamps of the inverter. The noise emission graph of inverter C shows with increasing frequency a falling characteristic of noise level amplitude. For frequencies of f > 200 kHz the noise amplitude stays below P_{noise}^{max} < -35 dBm at the connection point of the PAN coordinator. Noise emission in CENELEC band (f < 148.5 kHz) is even above P_{noise}^{max} > 0 dBm, thus leading to a reduced signal to noise ratio (SNR) in a critical region of SNR < 10 dB, where in dependence of the implemented OFDM (orthogonal frequency-division multiplexing) modulation scheme, a noticeable increase in bit error loss rate (BER) and thus a decrease in transmission rate can be expected [8].
Additional iPerf measurements with G3-PLC modems as PAN clients and PAN coordinators showed no decrease of transmission rate in TCP and UDP connection for any test setup, because of the sufficient SNR in this frequency range.

AVAILABILITY AFTER GRID TOPOLOGY CHANGES

Exemplary results of the reconnection ability tests for PLC modems are plotted in Figure 7.

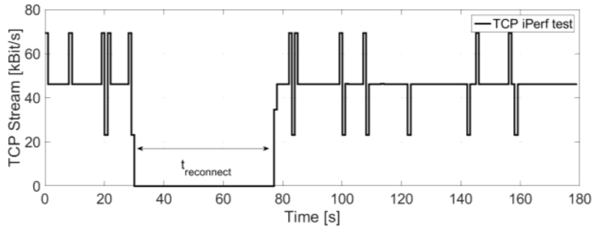

Figure 7 Exemplary result of a PLC reconnection tests.

The graph of Figure 7 shows the time resolved TCP data rate in kBit/s, when PLC1 as PAN client is connected to a PAN coordinator and an interruption process to the PAN coordinator is started at $t = 30$ s. After a mean time of approximately 45 s, the reboot of the PLC system is done and a successful commutation of the communication path to the other PAN coordinator leads to a robust return of the data rate.

The same test procedure is done with 6 concurrent PAN clients. However Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism is typically used for medium access control on the shared medium by the PLC modems [9], no significant increase in connection time compared to single modem tests is measured. Thus, reconnection ability could be successfully demonstrated.

CONCLUSION

Practical examinations on different PV inverters show, that an additive signal attenuation of the output filter and noise emission in operation are strongly dependent on the design of the inverter by the manufacturer. Noise emission of the PV inverters is measured above $P_{noise}^{max} > 0$ dBm in CENELEC frequency range, which may lead due to a noticeably reduced SNR to a decrease of PLC performance. An influence on the transmission rate of the tested G3-PLC modems by parallel PV inverter operation was not observable in any test setup. Further tests should be performed with multiple power inverters in common operation to examine the possibility of additive noise or damping effects.

The reconnection ability after an interruption of the communication link in case of e.g. switching actions in the grid is demonstrated by a test in this paper. By a time-resolved data rate measurement, mean reconnection times of 45 s through man made interruptions in the test setup can be observed and after that a stable communication link is established again.

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