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Experimental set-up to study power quality in single-phase split-phase distribution systems

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Abstract. Power Quality (PQ) has been an important topic since the creation of distribution systems. The deployment of the Advanced Metering Infrastructure (AMI) provided an important tool to measure the PQ of the electric power in the consumption points. One of the smallest secondary distribution systems in terms of power consumption is the single-phase split-phase system (120 V/240 V) that countries such as the United States, Canada, and some countries of central and south America have. Due to its size, this secondary distribution system is more prone to PQ issues. To that end, an experimental set-up was built by the authors so the distribution system from the Low Voltage (LV) transformer to the final appliances of the different houses was emulated. The aim is to capture the currents and voltages observed by the smart meter located at the entrance of the house and look for the different responses. A combination of real and dummy loads was installed in the set-up, so real noise could also be simulated. The set-up was totally automated by an industrial controller and relays, and it produced a very detailed dataset that could be used for multiple purposes.

Key words. Power Quality (PQ), Advanced Metering Infrastructure (AMI), single-phase split-phase system, distribution system, experimental analysis.

1. Introduction

In the split-phase distribution system, the conventional residential electrical power is often supplied via overhead service wire, as shown in Fig. 1. This distribution system is present all across the American continent and supplies three wires to the residential customer. The wires consist of two hot wires (L1 and L2) and a neutral [1] [2]. The neutral in this kind of power grids is tied to the earth ground every few electric poles or at underground connections. Each house has its own grounding system with a connection between the neutral wire and the ground via a rod in the soil. Most of the AMI used in this type of distribution system consist of form 2S electric meters, which are non-Blondel compliant [3] [4]. They only measure the line-to-line voltage, V_{LL}, and the two-line currents (I_1 and I_2). The meters have no access to the neutral conductor as shown in Fig. 2. The metering calculations for billing purposes assume that the voltage between leg 1 and neutral and the voltage between leg 2 and neutral are equal in magnitude and with a phase-shift of 180º.

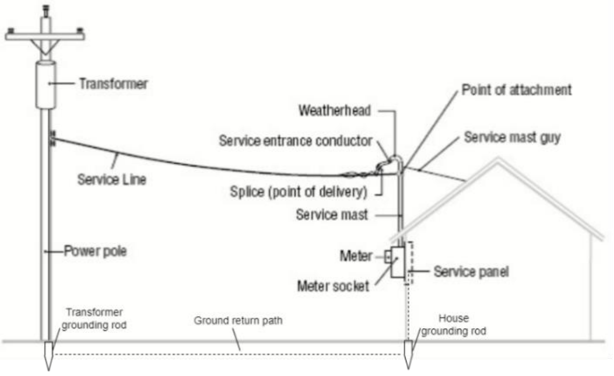


Figure 1: Elements in the typical OH distribution system in US and Canada (short line/single house configuration)

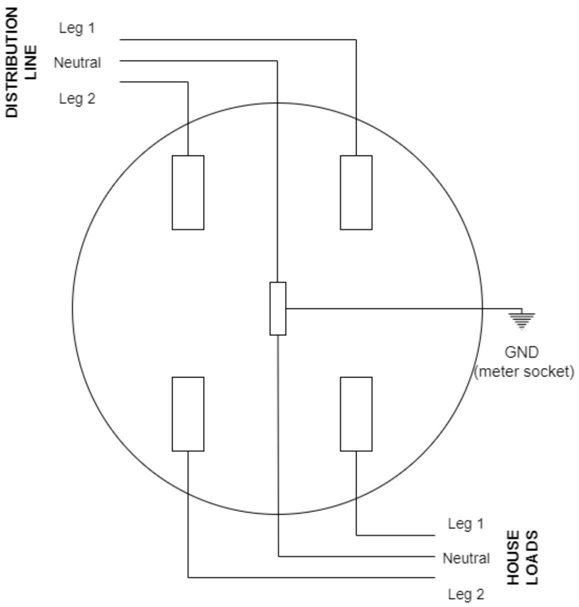


Figure 2: Form 2S meter electric diagram

It is notorious that non-Blondel compliant meters make some assumptions that could lead to different inaccuracies. The error made may be larger depending on the consumption pattern downstream the meter, mainly load imbalance, but also depending on the voltage dips, disconnection of the neutral conductor and others.

One of the most interesting PQ issues happens when the neutral wire gets disconnected or damaged. Since the impedance of the neutral wire is usually in the order of magnitude of tenths of Ohms (which is the ideal situation and the design condition), the loop is closed via the neutral wire. The alternative path is the one closed through the earth ground and typically has a higher impedance. Both are electrically in parallel. This problem is known as the Floating Neutral (FN) problem.

The FN fault has been approached solely from the perspective of the three-phase four-wire distribution system [5] [6]. Even so, very low quantity of data is available to study this problem. As it is a novel problem, must record what the existing AMI measures.

The paper is divided into the following sections: In Section 2 The methodology is presented and the justification of it, in Section 3 the hardware set-up is described with the details, in Section 4 the control strategy is described, in Section 5 the obtained database is described and in section 6 the applicability and the conclusions are described.

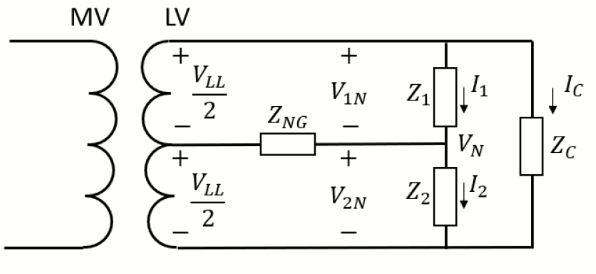


Figure 3: Simplified schematic of distribution system

2. Methodology

Fig 3 shows a simplified circuit of the split-phase distribution system. The low voltage (LV) transformer converts the medium voltage to a 240 V LV level, which is divided into two 120 V circuits, as described in the previous section. In that diagram, it is assumed that the LV transformer only feeds one single house. Inside the house, Z_1 represents the parallel combination of all the appliances connected between leg 1 and neutral, Z_2 represents the parallel combination of all the appliances connected between leg 2 and neutral, and the Z_C represents the parallel combination of the 240 V appliances, which are connected between both hot legs.
Z_{NG} represents the parallel combination of the ground path impedance and the neutral wire impedance explained in the previous section. For a normal operation of the house, the return current of the split-phase system flows through the neutral wire, so the value of the Z_{NG} is the same as the impedance of the neutral wire. However, if the connection of the wire is not done properly or gets damaged, that impedance will be higher, affecting the PQ of the house [7]. The higher the impedance, the greater the voltage swing between both legs and the neutral, causing the voltage to go out of the boundaries set by the National Electric Code (NEC) [8]. Furthermore, this voltage swing will be time dependent due to its dependency on the load unbalance inside the house.

Breaking the neutral wire intentionally in a real house with the purpose of obtaining real faulted data is not feasible from a safety point of view. To study this pattern, an experimental set-up was built in a laboratory environment, for emulating the circuit explained in Figure 3 [7].

3. Hardware set-up

The set-up was built in the microgrid laboratory of the center of applied research 'Tecnalia Research and Innovation', which is in Derio, Spain. As shown in Fig 6, Tecnalia set up a space of approximately 24 m^2 (8 m x 3 m) in which a power source, two cabinets containing all the purely resistive loads (also known as dummy loads), the relays and the controller device, some tables to place the real appliances and another extra table for a laptop and the Data Acquisition System (DAqS) were placed.

For the feeding of the emulated house, a ***Cinergia GE+50 vAC/DC*** [9] was used. This power source allows to create any voltage system that the user wants, in this case, the 240/120 V split-phase system was simulated, and the three wires were extracted. The primary side of the power source was connected to a single-phase European type of grid. The 60 Hz frequency was also configured in the output wires.

The whole setup is floating from the neutral of the actual laboratory, so the modification of the return path impedance of the emulated distribution system could be done properly, without affecting the safety of the whole laboratory. Overcurrent protections were installed in addition to a safety grounding of the cabinets, in case of a short-circuit arises. It is important to differentiate the ground of the set up and the return path of the emulated grid, which was emulated by the impedances described above, so the return path is floating through the real ground of the laboratory environment.

For the control system, an industrial controller hardware was used, the ***BECKHOFF BK9100*** [10] with an ethernet Transmission Control Protocol/Internet Protocol (TCP/IP) communication system. The module allows to control individual relays for each appliance, so their connection to Leg 1, Leg 2 and Neutral wire (connection done in each appliance socket) could be opened and closed as required by the user. The control commands were sent from a laptop with a small python script, which constantly communicates with the *BK9100* device. The industrial controller device also has the control over the Z_{NG} impedance being emulated at each moment, so all the control was centralized.

Figure 4: Beckhoff BK9100 controller with some of the relays

The values of Z_{NG} selected for the setup were 0 ohm (just the neutral wire impedance, so the normal operation could also be simulated), 1 ohm, 2-ohm, 3-ohm, 4-ohm, 5-ohm and 10-ohm. All the $Z_{NG} > 0$ impedances will simulate the different cases in which the impedance returns through the ground (for the different faulted scenarios). These values were selected based on [8] requirements.

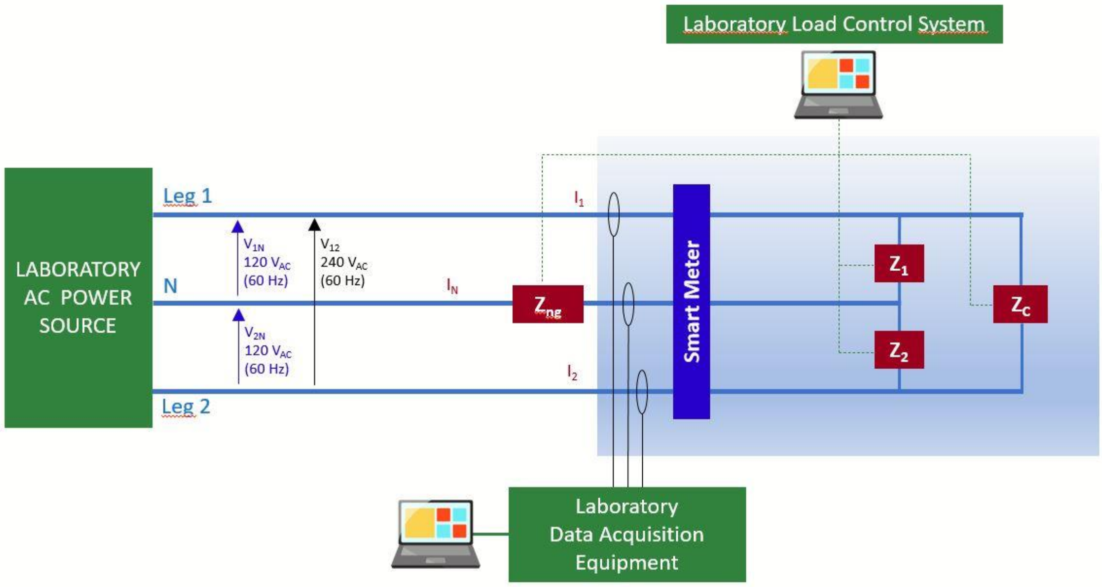


Figure 5: Emulation of the single-phase split-phase transformer. Lab set-up scheme.

For the consumption side, as already explained, 13 of the most typical real American appliances, in combination with some dummy resistive loads were installed. The list of loads and its resistance in ohms is detailed in Annex I (Table I). One relay was attached to each appliance socket, so the control loop could be implemented as described in section 4.

To emulate the smart meter and collect the data so it could be post-processed, a DAqS was used, the ***DEWESoft SIRIUSi-HS 4xHV 4xLV*** [11]. It has four high voltage channels and four low voltage channels, which were used for current and voltage measurements through the proper transductors/probes. As described in section I, the real form 2S smart meter has access to V_{LL}, I_1 and I_2, but no to V_{1N} and V_{2N}. For research and system understanding purposes these last 2 measurements were also collected.

The complete hardware scheme can be seen in Annex II in Figure 11.

Figure 6: Overall lab set-up at Tecnalia microgrid laboratory

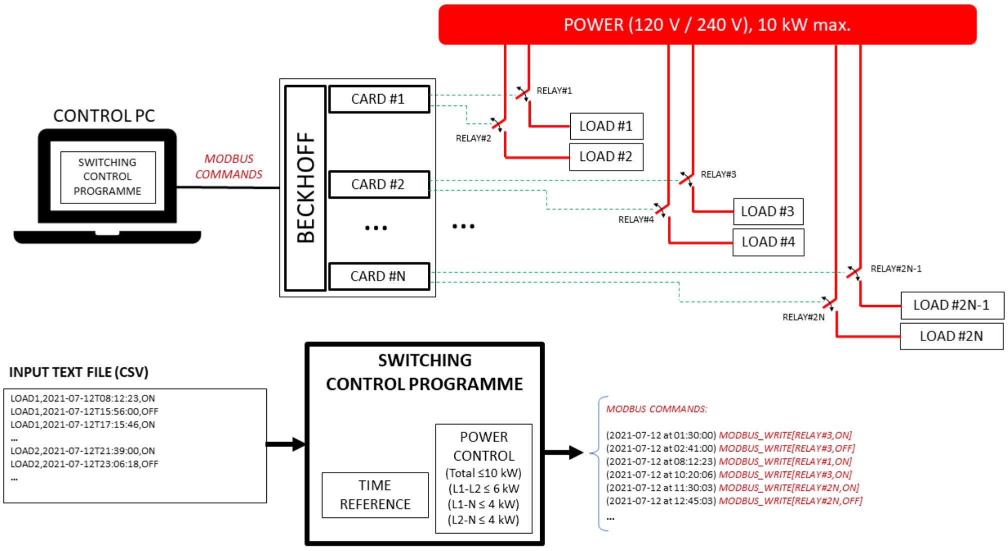
4. Control and Monitoring

From the software perspective, the control was done using a laptop with a small python script. The input for the set-up is a load schedule type of file (a csv file), in which the desired switching schedules of the loads were defined with the on and off switching orders. The python script translated these files into the proper MODBUS commands with the real timestamps and sent them to the *BK9100* controller. The control loop scheme can be seen in Figure 8.

For the DAqS, the *DEWESoft* device uses its own software, which allows to control the device, start the storage, plot real-time waveforms and so on. The data was exported to a data file, usually a .csv/.txt file, so its post-process could be done in the desired environment.

The *Cinergia* power source was controlled manually in the display. Once the power level is set, no further action is required.

Figure 7: The control PC, the DAqS and the control devices in the cabinet



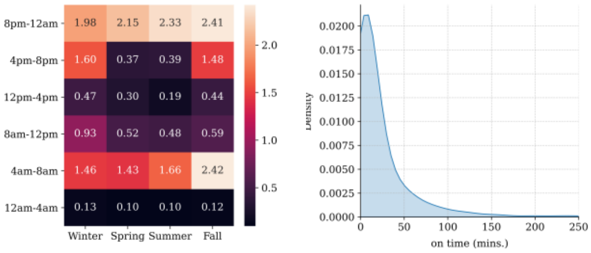
```
LOAD1,2021-07-12T08:12:23,ON
LOAD1,2021-07-12T15:56:00,OFF
LOAD1,2021-07-12T17:15:46,ON
...
LOAD2,2021-07-12T21:39:00,ON
LOAD2,2021-07-12T23:06:18,OFF
...
```

```
(2021-07-12 at 01:30:00) MODBUS_WRITE[RELAY#3,ON]
(2021-07-12 at 02:41:00) MODBUS_WRITE[RELAY#3,OFF]
(2021-07-12 at 08:12:23) MODBUS_WRITE[RELAY#1,ON]
(2021-07-12 at 10:20:06) MODBUS_WRITE[RELAY#3,ON]
(2021-07-12 at 11:30:03) MODBUS_WRITE[RELAY#2N,ON]
(2021-07-12 at 12:45:03) MODBUS_WRITE[RELAY#2N,OFF]
...
```

Figure 8: Scheme of the control loop

A. *Appliance switching pattern design*

The load schedules were planned before running the different test cases. Each test case had a fixed time length in which a load schedule of the same time length was run. Load schedules were set up according to the typical statistical values that each appliance type have. The design parameters are how often an individual appliance would switch on for a given time (generally 1h) and how long an appliance would be online when switched on.



	Winter	Spring	Summer	Fall
8pm-12am	1.98	2.15	2.33	2.41
4pm-8pm	1.60	0.37	0.39	1.48
12pm-4pm	0.47	0.30	0.19	0.44
8am-12pm	0.93	0.52	0.48	0.59
4am-8am	1.46	1.43	1.66	2.42
12am-4am	0.13	0.10	0.10	0.12

Figure 9: Incandescent lamp switching parameters

A statistical model was built for each load type based on a public database [12]. The switching events were designed as a Poisson random process, using the two statistical variables defined before. Figure 9 details the values selected for a particular appliance, and this was done for each appliance of the set-up. The full load schedules for the simulated single house were constructed using statistical models for individual appliances.

As explained before, the control PC, which was running the main Python script, was responsible for sending switching on and off commands to the BK9100 so the relays of the different sockets could follow the patterns defined in the load schedules for the different test cases.

5. Output database

The experiments were conducted over almost a year, collecting more than 180 days of experiments with several different load schedules, neutral impedance values and conditions were simulated in Tecnalia laboratory. The DAqS gathered the real waveforms of the different test cases, as the form 2S meter does. With the idea of optimizing the quantity of data being stored, only certain load schedules were saved with the waveforms sampled at 10 kHz. The majority of the test cases were collected using 1-sec Root Mean Square (RMS) calculations.

A. Data analysis

In order to check that the set-up was working well and to evaluate the error done, a comparison was done against the simulated currents obtained using the mathematical model of Fig 3. As shown in Fig 10, the error done in the currents is really small in terms of RMS.

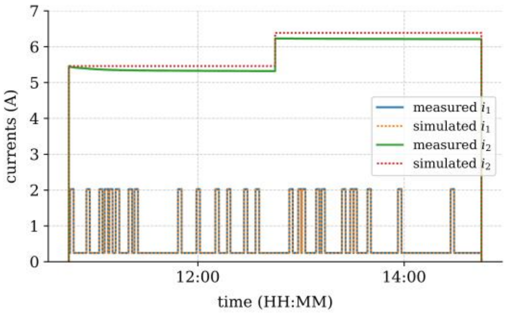


Figure 10:model predicted currents vs measured currents simulating dummy loads

Also, the differences between the simulated data and the realistic data wanted to highlight for example, different inrush current profiles of the real appliances were captured by the AMI, which were not present in the simulated data.

6. Applicability

The database obtained from this set-up has been mainly used to study the FN condition and testing a detection algorithm in a controlled laboratory environment [7]. The problem described in the previous sections is a PQ issue that is considered important and hazardous in the split-phase distribution system.
Since approximately half of the test cases were run with $Z_{NG} = 0$ (also defined as healthy scenarios), it is notorious that the FN problem is not the only application that this database can be used for. These particular test cases contain information about the normal operation of a house that was automated based on real human behaviour. Load disaggregation in a split-phase system is another interesting topic in which this database can be used for, since the switching on and off of the different appliance types and timestamps are also available in the dataset. The intellectual and industrial property of the dataset belongs to Hubbell Inc.

7. Conclusion

The experiment helped to detail the detection algorithm performance of the FN problem [7], yielding results closers to the real world than using a simple model simulated but a computer and a model full of simplifications.

The database generated from these tests is unique: it is the first database with a sampling frequency (FS) of 1 sec that contains data from faulted neutral houses in different conditions. Noise effect introduced by the real appliances that have an electronic part in them such as a laptop, a computer monitor, microwave and so on gives the set-up a good realistic that a simple PSCAD/Simulink model could not simulate.

The set-up considered up to 13 different real appliances, considered the most common ones in a house. The authors caution against assuming that the behaviour of the specific house is representative of the houses in any location on the American continent, because new special appliances could introduce new features that weren't seen while conducting this experiment. A more detailed analysis must be done, including different types of appliances that are not so common. Also, at Tecnalia lab only 240V dummy loads were simulated, not considering the noise, phase shift or inrush current pattern that these appliances can generate. Concerning the power source, the *Cinergia* has the ability to introduce some PQ issues, such as voltage dips and a level of Total Harmonic Distortion (THD) in the voltage waveform. Some of these anomalies were introduced in the analysis in some test cases, such as introducing a THD of 5%-8%, but a more extent analysis should be conducted.

As explained in the previous sections, the return path impedance was simplified by a purely resistive and fixed value of impedance. This may not be totally accurate for a faulted case, since the resistivity of the soil is dependant of a lot of factors [13].

Acknowledgement

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Annex I: list of loads

Table 1: list of dummy loads

Appliance label	R [ohms]	Connection options
Range emulator	22	Leg-Leg
Oven emulator	15	Leg-Leg
Water heater emulator	10	Leg-Leg
Furnace emulator	15, 100	Leg-Leg
Coffee maker emulator	22	L1
R_1	22	L1, L2
R_2	68	L1, L2
R_3	130	L1, L2
R_4	270	L1, L2
R_5	500	L1, L2
R_6	1k	L1, L2
R_7	2k	L1, L2
R_8	4k	L1, L2
R_9	8k2	L1, L2

Table 2: list of real appliances

Appliance label	Nº	Connection options
Incandescent lamp	3 (per leg)	L1, L2
Vertical sanding fan	1	L2
Toaster	1	L1
Floor fan	1	L2
Room air conditioner	1	L1
Refrigerator	1	L2
TV	1	L1
Fluorescent lamp	1 (per leg)	L1, L2
Vacuum cleaner	1	L2
Furnace fan	1	L1
Computer monitor	1	L2
Laptop	1	L1
LED lamp	2 (per leg)	L1, L2
Handheld hair dryer	1	L2
Microwave	1	L1

Annex II: hardware set-up complete scheme

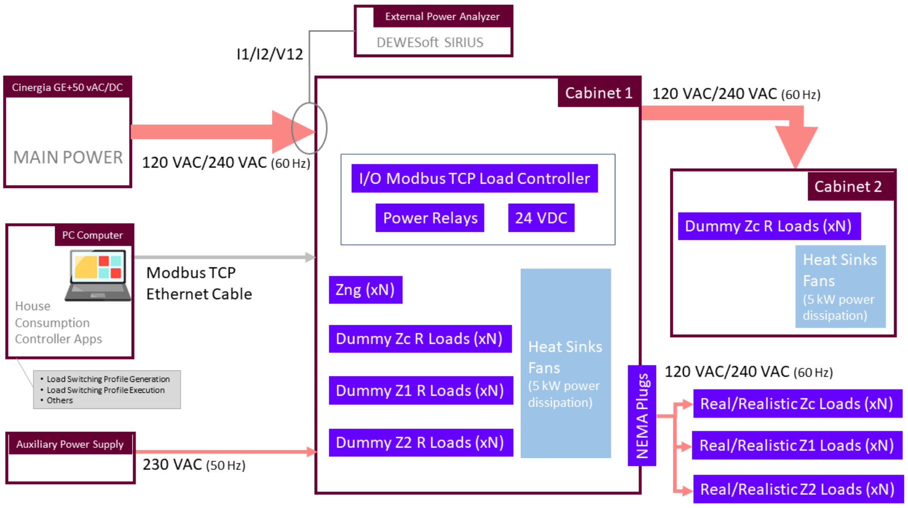

Figure 11: Hardware complete scheme