HARMONIC INTERACTIONS AND RESONANCE PROBLEMS IN LARGE SCALE LV NETWORKS

M. C. Benhabib, P. R. Wilczek, J. M. A. Myrzik, J. L. Duarte
Department of electrical engineering, Eindhoven University of Technology
Den Dolech 2, CR 2.12, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
Tel.: 0031 40 247 3712, Fax: 0031 40 245 0735
m.c.benhabib@tue.nl

Abstract – The complexity of low-voltage (LV) networks increases with the increasing number of connected dispersed generation, such as photovoltaic systems, and nonlinear loads, like energy saving lamps and personal computers. Due to the huge number of connected equipments, an accurate analysis of LV networks is difficult to be realized, in particular for studying problems related to resonance or to harmonic interactions generated by the nonlinear loads and/or dispersed generation.

The main difficulty is the necessity of carrying out a detailed model of each nonlinear load and/or dispersed generation in order to introduce all harmonics as present in the real case. This is not straightforward because excessive computer memory and calculation time are required in view of the large number of equipments in a LV network. On the other hand, if the model of each nonlinear load is too simplified, loss of information concerning the harmonic spectrum is unavoidable.

So, this paper presents a method which makes it possible to solve memory problems in order to be able to study power quality issues (resonance effects and harmonic interactions) in LV networks. The approach leads to similar results of a nonlinear modeling description, since it is based on data from detailed models. Simulation and experimental results are given to demonstrate resonance problems and harmonic interactions in a network that contains 6 houses. Furthermore, an example of simulation study is also presented for a complex network that contains more than 50 houses.

Keywords: resonance, harmonic interaction, equivalent reduced model.

1 INTRODUCTION

In general, when trying to study the impact of nonlinear loads and dispersed generation (DG) such as photovoltaic (PV) systems in LV distribution networks, it is difficult to obtain representative simulation results that allow analyzing, for example, the influence of harmonic currents and their interaction with harmonic voltages and network impedances. The reason is that it is necessary to take in consideration a detailed model for each piece of nonlinear equipment connected to the network. However, the major difficulty when trying to simulate a large quantity of detailed models is mainly computer memory limitations.

To cope with memory problems the nonlinear models might be simplified by using techniques like average modelling, load flow techniques and state space theory. But, the fundamental limitation of these methods is that they can not describe the essential information related to the harmonics in the current and/or voltage generated by the nonlinear equipment.

An alternative modelling approach is proposed in this paper, which allows the introduction of enough detail in the simulations without requiring excessive computer memory. The resulting models are validated by comparison of simulation and experimental results. It is demonstrated that the proposed modelling technique can be used to simulate quite accurately the interaction between harmonic currents generated by a large number of nonlinear loads and dispersed generation.

Simulation and experimental results are given to validate the approach. Also a simulation study is presented for a complex network which contains more than 50 houses with nonlinear loads.

2 PRESENTATION OF THE MODEL

In this section the rationale that leads to the construction of simplified equivalent models of nonlinear equipment (nonlinear loads or dispersed generation) connected to the network is presented by means of two examples. The models are validated by measured results from experiments.

2.1 Nonlinear load (three-phase diode rectifier example)

A detailed Simulink model of a three-phase rectifier is shown in Fig. 1. The simulation results with this model description for the current and voltage on the grid terminals are shown in Fig. 2.
In Fig. 3 the detailed rectifier model shown in Fig. 1 is replaced by current sources with output data in tabular format, whose values at each simulation step are the same as the ones that have been obtained from the previous detailed simulation.

Simulation results with the simplified rectifier model in Fig. 3 are shown in Fig. 4.

By comparing Fig. 2 to Fig. 4 it can be clearly seen that the results are in perfect match. It can be concluded, that once a detailed simulation of the rectifier has been performed and its results stored in tabular format, an equivalent current source using that tabular can represent the rectifier in other simulation studies, which requires much less computation time.

2.2 Dispersed generation (PV system example)

A residential grid-connected PV system [1] is illustrated in Fig. 5. A detailed Simulink model for this system is shown in Fig. 6, which includes the equivalent circuit model of a photovoltaic cell (in our case the models for the solar cell is based on the well-known single-diode equivalent circuit taken form [2, 3, 4 and 5]) connected to a DC/DC converter, together with a DC/AC converter that are connected between a PV array and the electrical power system.
The DC/DC converter shown in Fig. 6 is a boost type including the maximum power point tracker (MPPT) of the PV array. The used basic control is given in [6]. The DC/AC converter consists of a single-phase inverter operating with a unity power factor. The instantaneous current command for the inverter can be commutated by multiplying $I_{\text{peak}}$ which is the output of the regulator (in our case a PI regulator) for the DC-voltage control system, with the AC system line voltage with unity sine wave amplitude obtained by using a robust Phase Locked Loop (PLL) [7].

Simulation results are shown in Figs. 7 to 10, based on a variation of the temperature $T$ and the irradiation $G$ from $T=25^\circ C$ and $G=1000 \text{ W/m}^2$ at $t=0$ to $t=0.15$, and from $T=15^\circ C$ and $G=300 \text{ W/m}^2$ from $t=0.15$ until $t=0.2$. 

![Figure 6](image1.png)

**Figure 6:** Detailed model of a PV system

![Figure 7](image2.png)

**Figure 7:** Simulated current on the terminals of the single-phase inverter in Fig. 6.

![Figure 8](image3.png)

**Figure 8:** Simulated terminal voltage of the single-phase inverter in Fig. 6.

![Figure 9](image4.png)

**Figure 9:** Simulated load current of the system in Fig. 6.

![Figure 10](image5.png)

**Figure 10:** Simulated supply current for the system in Fig. 6.
Again, the simulation results obtained with the detailed model in Fig. 6 for the current injected into the grid by the PV system are stored in tabular format; and a new simulation is run with a current source replacing the PV system, as shown in Fig. 11. The results are given in Figs. 12 to 15.

Figure 11: Simplified equivalent model of the PV system in Fig. 6.

Figure 12: Simulated terminal current of the single-phase inverter based on the simplified model in Fig. 11.

Figure 13: Simulated terminal voltage of the single-phase inverter based on the simplified model in Fig. 11.

Figure 14: Simulated load current with the simplified model of Fig. 11.

Figure 15: Simulated supply current with the simplified model in Fig. 11.

A perfect match is found comparing the results in Figs. 7 to 10 with the results in Figs. 12 to 15.

2.3 Experimental validation

In order to confirm the validity of the simplified equivalent models, two experiments performed on a laboratory set-up are presented. The first test is related to resonance issues, and the second one demonstrates current superposition effects in a feeder.

2.3.1 Resonance effects

The resonance phenomenon will become an important problem in LV networks by an increased number of nonlinear loads and dispersed generation. To study this problem the resonant frequency is measured with and without PV system connected to the grid.

The laboratory set-up representing a LV network is presented in Fig. 16. It consists of a grid emulator which feeds 6 houses. At first only a capacitor is connected and resonant frequency $f_1$ is measured. Next a PV system is connected to this LV network (house No 6) as on Fig. 16 and resonant frequency $f_2$ is measured again. The difference in $f_1$ and $f_2$ frequency let’s calculate capacitance insertion to the grid of the PV system.

As the result, resonant frequency decreases. That means that many PV systems connected to the grid decrease the resonant frequency. That’s why it’s important to study this problem.

Figure 16: Experimental LV network, set-up #1.
Experimental results are given in Figs. 17 to 20. On figure 17 we see the inverter current and voltage. On figure 18 the supply current and feeder voltage is given. The grid current is the sum of the inverter and capacitor currents, in resonance condition. The resonance frequency is seeing in fig. 20 which is equal to 1750Hz.

**Figure 17:** Measured feeder voltage and injected PV inverter current as a result of resonance in the set-up of Fig. 16.

**Figure 18:** Measured supply current and feeder voltage as a result of resonance in the set-up of Fig. 16.

**Figure 19:** Measured capacitor current when resonance occurs in set-up of Fig. 16.

**Figure 20:** FFT of the measured supply current when resonance occurs in the set-up of Fig. 16.

Concerning now simulation part, two data sets are necessary to be included as sources in the reduced simulation scheme: the polluted grid voltage (Fig. 22) and the PV inverter current under clean voltage grid condition (Fig. 23). Again, the simplified equivalent PV inverter model consists of a current source in parallel with a capacitor as shown in Fig. 21. The reason of adding this parallel capacitor is that it corresponds to the realistic situation of the tested PV inverters.

**Figure 21:** PV inverter simplified equivalent model.

The basic measured data are shown in Figs. 22 and 23, while the simulation results are given in Figs. 24 to 27.

**Figure 22:** Measured (and stored) polluted grid voltage (0.5% of harmonics for the 50 first harmonics).

**Figure 23:** Measured (and stored) current injected by the PV system when the grid voltage is free from distortion.

**Figure 24:** Simulated injected current and feeder voltage (to be compared with Fig. 17)

**Figure 25:** Simulated supply current and feeder voltage (to be compared with Fig. 18).
2.3.2 Superposition of currents

The second experiment will show the validation of the assumption that the implementation of current sources in the simulations with data in tabular format as taken from the individual operation of non-linear loads, will result in a correct superposition of effects in a complex LV network.

For this purpose, the measured data in the test set-up shown in Fig. 28 were taken for each PV system connected alone to the network (PV1, PV3 and PV6 at places 1, 3 and 6, respectively, in the experimental branch); and the stored results were implemented as current sources in the global simulation by respecting the original places of connection of the PV systems.

The intention is to show that it is possible to simulate each house alone, which contains dispersed generation and nonlinear loads and then to take the individual currents and implement them together in the global simulation. This will enable to simulate complex LV networks by taking into account the real currents and voltages of each nonlinear load and/or dispersed generation.

The measured currents for each PV connected alone are given Figs. 29 to 31.

Figure 29: Measured current and voltage of PV6 alone.

Figure 30: Measured current and voltage of PV3 alone.

Figure 31: Measured current and voltage of PV1 alone.

The stored current values are injected in the simulation scheme presented in Fig. 32. The simulation results are shown in Fig. 33.

Figure 28: Experimental LV network, set-up #2

Figure 26: Simulated capacitor current (to be compared with Fig. 19).

Figure 27: FFT of the simulated supply current (to be compared with Fig. 20).

Figure 32: Simulation scheme of the LV network with equivalent current sources of three PV systems together.
The resulting current in Fig. 33 can be compared with the experimental data in Fig. 34, where the three PVs are connected simultaneously in the laboratory set-up. It is clear that the experiment and simulation are in good match.

Remark1: In the experiment (Fig. 34) a high frequency current was measured (more then 30kHz). This current is flowing between two inverters. The frequency is not relevant for this investigation.

Remark2: The grid current measuring probe is clamped to measure the positive current flowing from the source to the houses. Since in the houses only PV systems are connected the current is flowing in the opposite direction and negative current shown in Fig.33 and Fig.34.

3 LV NETWORK SIMULATION

As an example of application of the proposed modelling approach by means of equivalent current sources, a complete LV network having 96 houses is simulated in such way that each house is represented by simplified equivalent models of a PV system in parallel with one nonlinear load comprising a single-phase diode rectifier. Each single-phase rectifier is connected to a RL load and produces individually a current THD equal to 6.6%, while the PV current has a THD = 0.86%.

A typical Dutch LV network is taken from [8], and comprises two feeders as shown in Fig. 35, being connected to a MV network via a 10kV/400V transformer. Each feeder is divided in five sections. The distance between each section is shown in Fig. 35 (section 1:100m, section 2: 100m, section 3: 180m, section 4: 50m, section 5: 50m). Each section contains houses, which are located at every 10m from each other. So, the total number of houses in one feeder is 48.
As shown in Table 1, the current THD of the network is higher than the allowed 5%, which requires the introduction of (active) filters in the distribution grid.

4 CONCLUSION

This paper proposes a way for studying complex LV networks which contain a large amount of nonlinear loads and dispersed generation. The main idea is to use stored real data (experimentation) or data from detailed models to construct simplified equivalent current sources, and to introduce these sources in tabular form in the complex LV network. By this way, problems related to computer memory limitations are avoided. Simulation and experimental results show that the approach is valid. The proposed model give good result when compared to experiment, and let’s to study problem concerning resonance effect and harmonic interaction between dispersed generation and nonlinear loads observed in LV network.

REFERENCES