CAPACITIVE COMPENSATION IN DISTRIBUTION GRID WITH NON-LINEAR VOLTAGE TYPE LOADS

S.M.Deckmann[1], J.A.Pomilio[1], E.A.Mertens[2], L.F.S.Dias[2], A.R.Aoki[3], M.D.Teixeira[3] and F.R.Garcia[4]

[1]DSCE/FEEC/UNICAMP C.P. 6101, 13081-970 Campinas - Brazil sigmar@dsce.fee.unicamp.br

[2]Elektro Eletricidade e Serviços Ltda. Campinas - Brazil

[3]LACTEC – Instituto de Tecnologia para o Desenvolvimento Curitiba, Brazil

[4]IESA Projetos, Equipamentos e Montagens S.A. Araraquara, Brazil

***Abstract* – Capacitive and LC passive filter structures are discussed for compensation of low voltage secondary networks distorting currents and/or voltages. Filters components dimensioning aspects as well as installation sites and efficiency are also considered. Problems arising due to primary voltage distortion are focused if the non-linear loads are of current or voltage source types. The need for more knowledge about the specific network and the connected loads is evidenced, in order to achieve the desired objectives with the passive filters installation.**

Keywords - Passive filters, power quality, non-linear loads, distribution systems.

I. INTRODUCTION

Electric Power companies are interested in applying passive filters or capacitive compensation in low-voltage distribution grids in order to postpone higher cost modifications to comply with the standardized voltage levels [1].

A LC passive shunt filter could, in principle, correct the displacement factor, improve the voltage profile and limit the harmonic circulation through the transformer, reducing its losses [2-4]. Despite of using tuned shunt filters, the results presented in the references do not eliminate the undesired harmonic current component, and the causes of the poor efficiency have not been adequately explained. As discussed in this paper, the main reason is the inherent inefficacy of shunt filters if the non-linear loads are of harmonic voltage type [5,6]. Additionally, the high cost of the filter inductor makes such alternative less competitive.

Another solution could be the use of a simple capacitor bank, concentrated at specific points or distributed along the feeder, for compensating the displacement factor. However, such alternative must be carefully analysed, in order to avoid resonances and harmonic amplification due to voltage distortion already present in the main (primary) system or imposed by non-linear loads.

II. PASSIVE COMPENSATION OF NON-LINEAR LOADS

The classical solution for reducing current harmonic distortion is to connect a shunt LC-series filter nearby the harmonic source in order to drain the current harmonics generated by the load, trying to keep the main source current sinusoidal. This approach considers that the non-linear load is a harmonic current source. In such situation the voltage at the PCC (point of common coupling) is determined almost only by the supply voltage source. This situation is typical of industrial loads.

In this case the filter design can follow different methods [7-10] and its efficiency depends on the main voltage source impedance. Note that if such impedance is null, the shunt filter is absolutely innocuous since all the load current will flow through the source.

The parallel resonance between the filter components and the source impedance, can be excited by non-characteristic harmonics [11] and must be carefully considered.

The relationship between the voltage source harmonic current (*Ii*) and the load harmonic current (*Ic*), shown in Fig.1, is given by:

$$\frac{I_i}{I_c} = \frac{Z_f}{Z_f + Z_i} \tag{1}$$

However, many power converters can't be well modeled as a harmonic current source. This is especially true for rectifiers with capacitive filter at the DC side. Such converter is widely used in low-cost, low-power applications. This is the typical case of domestic and commercial electronic loads, like TVs, PCs, ballast for fluorescent compact lamps, etc. For this situation, the traditional current model, analysis and filter design method is not far useful. In fact, a rectifier with capacitive filter imposes the voltage at the PCC during the diodes conduction [12,13]. The resulting current depends on the difference between the source and the load voltage, divided by the branch impedance. Fig. 1 shows a typical circuit and a possible model.

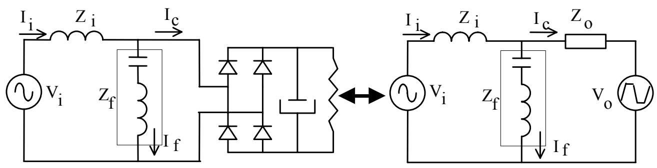

Fig. 1 Shunt passive filter applied for non-linear load of the voltage source type: circuit (left) and model (right).

For a voltage-type load, the source current (*Ii*) ratio to a specific harmonic voltage (V_o), generated by the load is given by [14]:

$$\frac{I_i}{V_o} = \frac{Z_f}{Z_o Z_i + Z_o Z_f + Z_i Z_f} \tag{2}$$

According to (2), the shunt filter effectiveness now depends on both, source and load model series impedance. If the source (Z_i) or the load (Z_o) impedance is zero, a shunt filter has no effect at all. As typically Z_i and Z_o are very low, a shunt filter efficacy is negligible. A better result is obtained with the use of series filter. However this solution is interesting if one considers, for example, as a goal, to reduce the THDV or increase the power factor for each particular equipment, as recommended by IEC [15]. Active solutions could also be considered [12,16].

However, it doesn't seem reasonable to connect a series filter for each consumer in a residential area secondary network. Maybe in a commercial building it could be feasible.

III. A CASE STUDY OF CAPACITIVE COMPENSATION IN A DISTRIBUTION SECONDARY

The distribution secondary analyzed next is a three-phase four-wire (220/127V), 60Hz system fed by a 13,8kV, 75kVA Δ/Y grounded transformer. The loads correspond to a Brazilian typical middle-class residential area consumer. As shown in Fig. 11 (last page), the Matlab SimPower System Toolbox was used for modeling the four wires system with the feeder impedances, including the neutral, with linear loads (parallel RL), and meters. Non-linear loads were implemented as single-phase rectifiers with capacitive filters, avoiding explicit current and voltage harmonic source representation.

It is quite difficult to model such converter in the frequency domain due to its non-linear nature. The equivalent impedance Z_o varies not only with frequency but depends on the output parameters, as capacitance and power delivered. Some models were described in the literature [17], but only for the rectifier operating in continuous conduction mode, which is not the real situation of home and commercial electronic appliances.

It was observed from one-week measurements at the transformer secondary, shown in Fig. 2, that the fundamental reactive power reaches a minimum value, during the night.

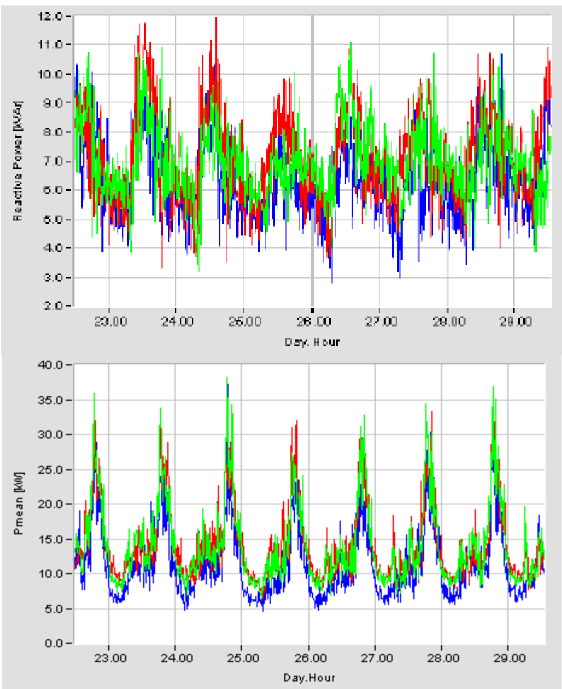

Fig. 2 – Reactive power (top) and active power (bottom), measured at the transformer secondary.

This value can be attributed to the connected refrigerators [6]. The reactive power increases during the morning, presumably due to the entrance of other electric machine driven appliances, like washing machines.

The active power varies along the day, reaching the highest values at evening, mainly due to showers and lightning, thus increasing the power factor. Also the harmonic voltage distortion increases during the evening, evidencing the influence of TV sets and fluorescent compact lamps, as shown in Fig. 3.

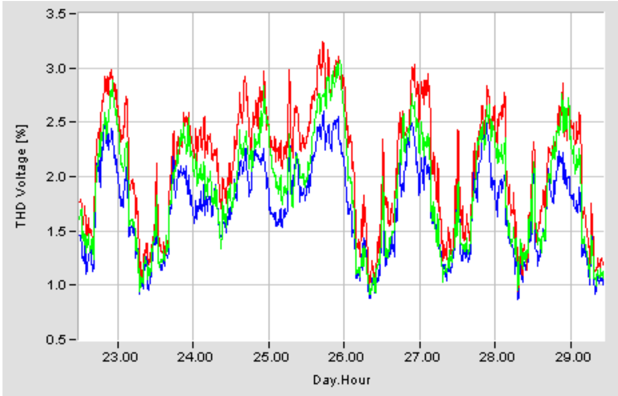

Fig. 3 – Secondary voltage total distortion along a week at the transformer secondary.

Based on these measurements, the network model was initially adjusted to reproduce the measured data in terms of power demand, voltage profile, and harmonic distortion. Non-linear (electronic) loads were connected along the feeder to represent 15% of the total demand. The system was loaded near the peak demand.

Measured and simulated voltage and current spectra at the secondary side of the transformer are shown in Figs. 4 and 5, and show a good agreement.

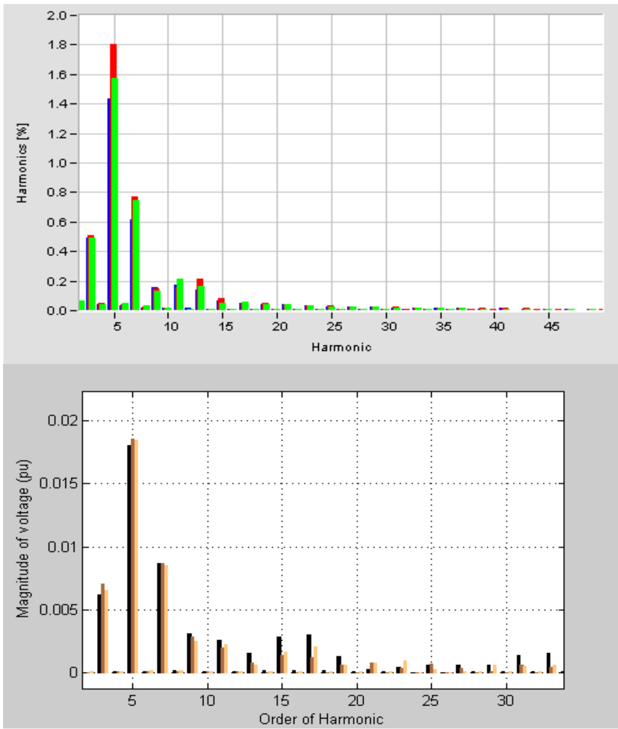

Fig 4. Measured (top) and simulated (bottom) voltage spectra at the transformer secondary.

Because there is a residual harmonic voltage component even when the secondary load is minimum, we presumed that the high-voltage side imposes such background distortion. Based on the measurements taken at the substation, 1.5% of the 5th harmonic and 0.3% of the 7th component were added to the input voltage.

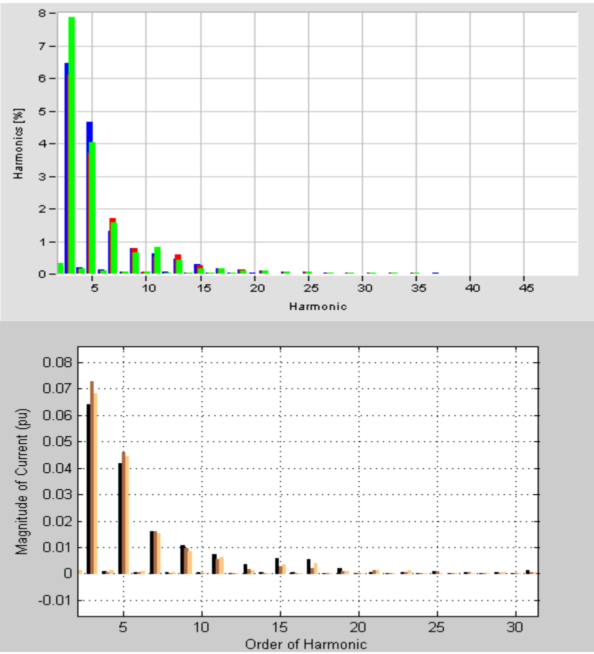

Fig 5. Measured (top) and simulated (bottom) current spectra at the transformer secondary.

3.1 Capacitive compensation at the secondary

The measurements indicate that the total reactive power varies from a minimum of 16 kVAr to a maximum of 28 kVAr. A capacitive compensator bank of 17,5 kVAr was designed and installed near the transformer (node 21, stressed in Fig. 11).

Such capacitance, together with the transformer leakage inductance, will produce the frequency response shown in Fig. 6. The minimum impedance seen by the primary occurs near 700 Hz. Thus the harmonics from the 5th to the 17th, if present in the high-voltage side, will find a low impedance path, and one could expect some harmonic current amplification in this frequency range.

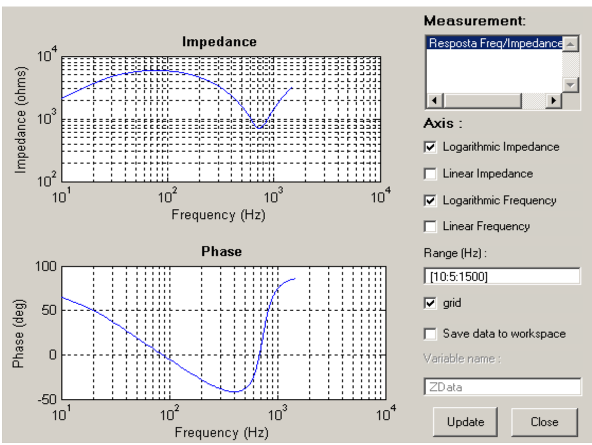

Fig. 6 – System impedance as seen by the transformer primary, with capacitive compensation.

Figures 7 and 8 show the measured and simulated spectra with capacitive compensation. The good agreement indicates again that the model is representative of the real system.

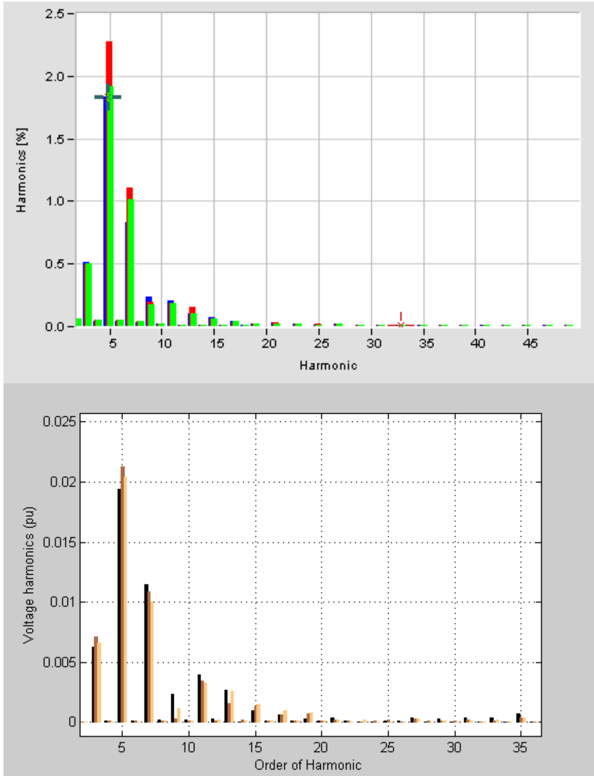

Fig. 7 – Voltage spectra at the transformer secondary: measured (top) and simulated (bottom), with capacitor installed.

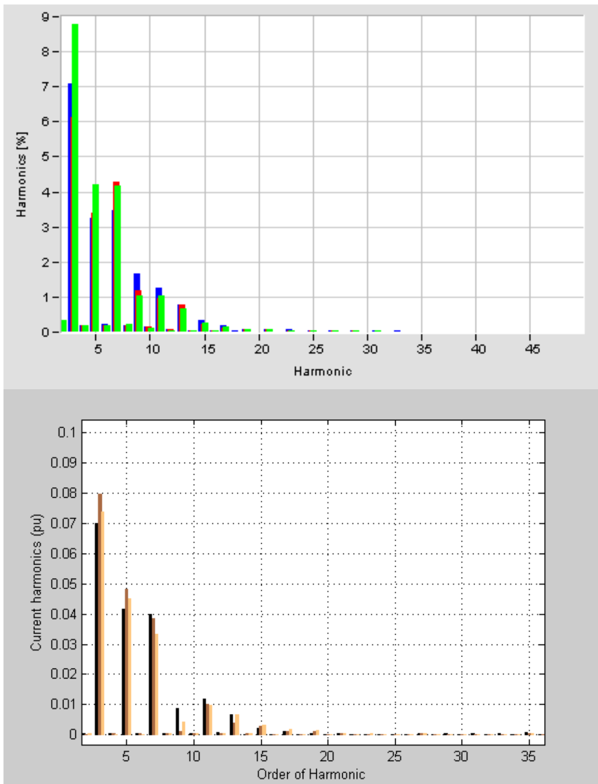

Fig. 8 – Current spectra at the transformer secondary: measured (top) and simulated (bottom), with capacitor installed.

As predicted, the voltage distortion increases from 2.5% to 3% (average values), and the current THD increases from 8% to 11%, in this case mainly due to the 5th component. Nevertheless, the resulting voltage THD (Fig. 9) is below the limit (5%), indicating that this reactive compensation strategy could be used, since complying with the harmonic limits of [18].

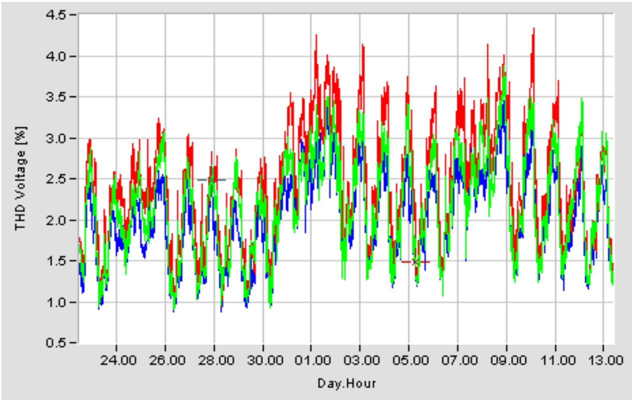

Figure 9. Voltage THD before (1st week) and after the capacitive compensation.

The main goal of the capacitive compensation is the improvement of the voltage profile along the feeder. Fig. 10 indicates the voltage level at some nodes for different compensation strategies.

The best result is obtained dividing the total 17.5kVAr capacitive bank for connection at two points: 30% at node 12 and 70% at node 34, according to the power demand distribution. It is indifferent, for the voltage profile if delta or star connection is used. While concentrating the capacitor bank at node 21 does not render the same voltage profile, it also allows an improvement in all voltage levels.

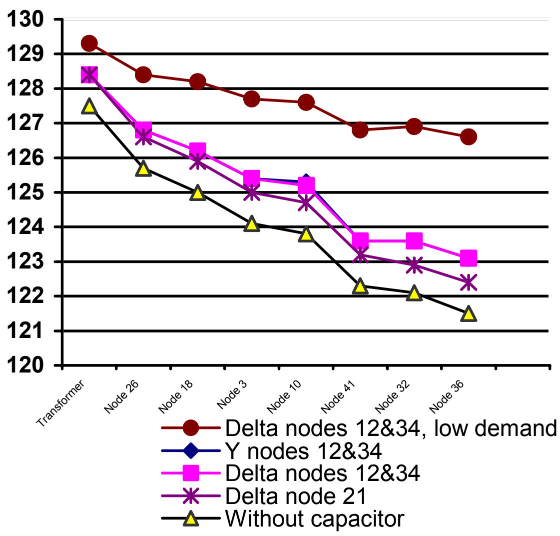

Fig. 10 – Node voltages for different compensation strategies.

It was also verified that under light load, the upper voltage limits are not violated.

The resulting voltage rise due to reactive compensation increases the power consumption. From simulations, the expected demand increase is about 1 to 2% at peak load. Considering only this consumption increase, the payback time for the capacitive compensation solution resulted to be 1.5 years.

IV. CONCLUSIONS

In some cases, it can be necessary to improve the voltage level at the consumers in order to comply with the standards. A possible solution is to use capacitive compensation for this purpose. However, due to the voltage and current distortion, it is necessary to verify, for each case, if the capacitors do not degrade in excess the waveforms.

Simulation can be used since the non-linear loads are well modeled. Residential and commercial power networks present non-linear voltage harmonic source type loads. The typical example is the single-phase rectifier with capacitive filter. Such converter does not determine the network current; otherwise, it imposes the voltage at the PCC. Shunt filters cannot filter out the resulting current harmonics, related to this kind of non-linearity. Such load imposes the PCC voltage, and not the respective current. More than this, shunt connected reactive compensators may increase the current harmonics circulations through the circuit, mainly if the high-voltage is already distorted.

The presented simulation results are based on a model that represents the real non-linear loads and adequately reproduces experimental measurements, allowing the usage for additional studies.

ACKNOWLEDGMENT

The authors would like to acknowledge the R&D working group of the project on this subject, supported by Elektro Energy and Services and developed during 2004 by Unicamp and Lactec.

REFERENCES

[1] ANEEL (2001) RESOLUÇÃO NORMATIVA Nº 505 de 26/11/2001

[2] A.M. de Oliveira, W.J de Medeiros Jr., A.M.M. Medeiros, A.C.M. do Valle, F.B.de Mendonça, "Energy Quality x Capacitor Bank", *Proc. of the 7th Brazilian Power Electronics Conference* COBEP 2003, Fortaleza, Ceará.

[3] J.R Macedo Jr., J. W. Resende, M.I Samesima,. e D. B. Gomes. "Aplicação de Filtros Harmônicos Passivos em Circuitos Secundários", *Proc. of II CITENEL*, Salvador, Nov. 2003, pp.845-852.

[4] C. Penna, e J. W. Resende, "Análise da Instalação de Filtros Harmônicos Passivos em Circuitos Secundários de Distribuição", *Proc. of II CITENEL*, Salvador, Nov. 2003, pp.839-844.

[5] S. M.Deckmann, J. A.Pomilio, E.A.Mertens, L.F.S.Dias: "Uso de filtros passivos em redes de distribuição com cargas não-lineares", Proceedings of the Brazilian Automatic Control Conference, CBA 2004, Gramado, September 21-24, 2004.

[6] J. A. Pomilio and S. M. Deckmann, "Characterization and compensation for harmonics and reactive power of residential and commercial loads", Proc. of COBEP 2005, Recife, Brazil, June 2005.

[7] R.L. Almonte, and A.W. Ashley, "Harmonics at the utility industrial interface: a real world example", *IEEE Trans. on Industry Applications,* Vol. 31, No. 6, Nov. Dec. 1995, pp. 1419-1426.

[8] J.A. Bonner, W.M. Hurst, R.G. Rocamora, R.F. Dudley, M.R. Sharp, J.A. Twiss, "Selecting ratings for capacitors and reactors in applications involving multiple single-tuned filters", IEEE Trans. on Power Delivery, Vol.10, No.1, 1995, pp.547-555.

[9] S.M. Peeran, W.P. Cascadden, "Application, design and specification of harmonic filters for variable frequency drives", *IEEE Trans. on Industry Applications,* Vol. 31, No. 4, 1995, pp. 841-847.

[10] D.E Steeper, R.P. Stratford, "Reactive compensation and harmonic suppression for industrial power systems using thyristor converters", IEEE Trans. on Industry Applications, vol. 12, no. 3, 1976, pp.232-254.

[11] L.S. Czarnecki, "Effect of minor harmonics on the performance of resonant harmonic filters in distribution systems", *IEE Proc. of Electric Power Applications,* vol 144, no.5, Sept. 1997, pp. 349-356.

[12] T. Key, and J-S Lai, "Costs and benefits of Harmonic Current Reduction for Switch-Mode Power Supplies in a Commercial Building*", Proc of IEEE Industry Applications Annual Meeting*, USA, 1995, pp.1101-1108.

[13] J. K Phipps, J. P Nelson, P. K. Sen, "Power Quality and Harmonic Distortion on Distribution Systems", *IEEE Trans. on Industry Applications,* vol. 30, no. 2, March/April 1994, pp. 476-484.

[14] F. Z. Peng, G-J Su, and G. Farquharson, "A series LC filter for harmonic compensation of AC Drives*". Proc. of the IEEE Power Electronics Specialists Conference - PESC'99*, Charleston, USA, June 1999.

[15] IEC - International Electro-technical Commission (1998). *IEC 61000-3-2: Electromagnetic Compatibility (EMC) – Part 3: Limits. Section 2: Limits for Harmonic Current Emissions (Equipment input current < 16 A per phase),* and Amendment A14, 2001.

[16] T. Tanaka. Y. Nishida and S. Funabiki, "A Method of Compensating Harmonic Currents Generated by Consumer Electronic Equipment Using the Correlation Function", *IEEE Transactions on Power Delivery*, Vol. 19, No.1, Jan. 2004, pp. 266- 271.

[17] A. Emadi, "Modeling of Power Electronics Loads in AC Distribution System Using the Generalized State-Space Averaging Method", *IEEE Trans. on Industrial Electronics*, vol. 51, no. 5, oct. 2004, pp. 992-1000.

[18] "IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems." Project IEEE-519. October 1991.

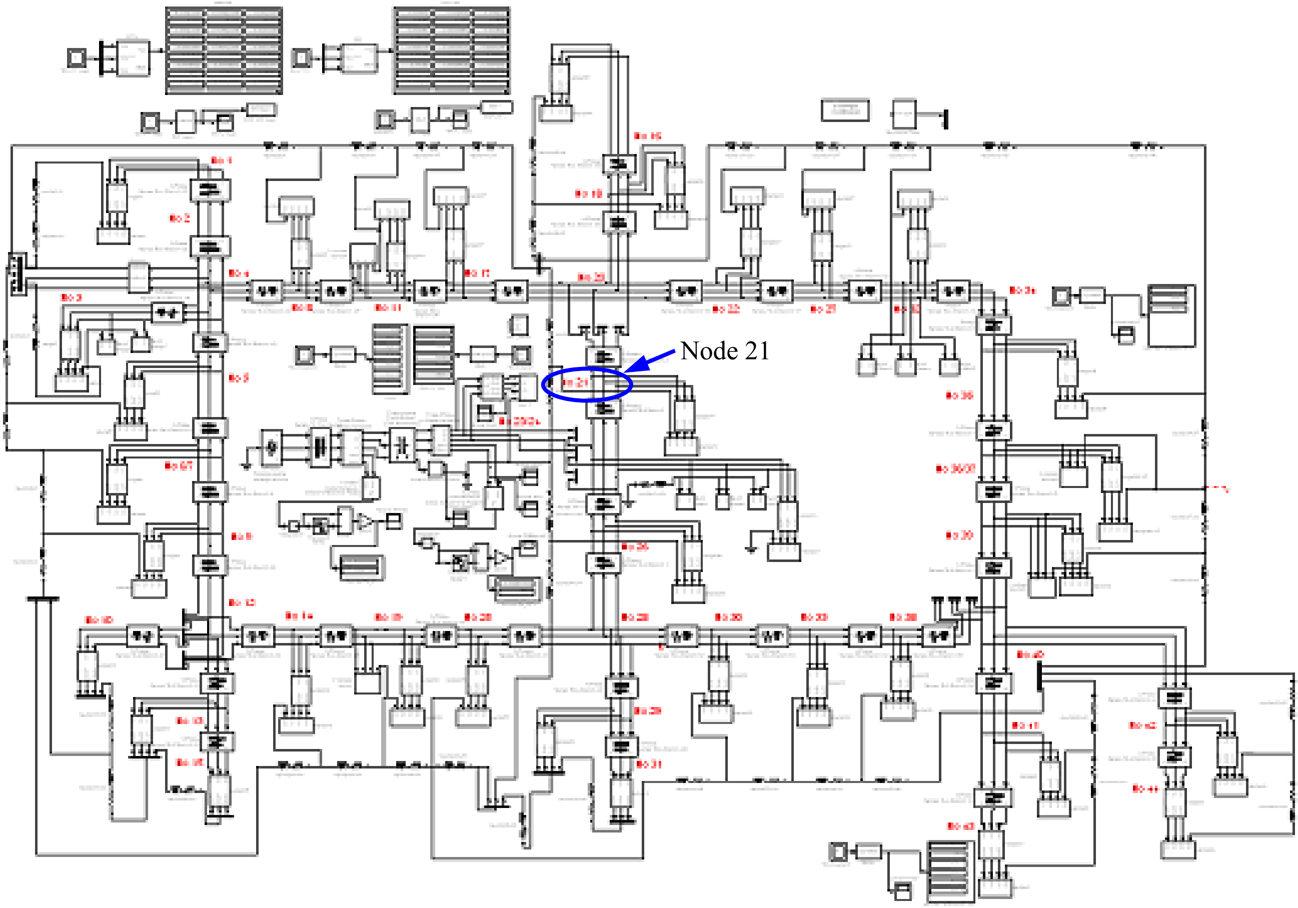

Fig. 11 - Complete 44 nodes, three-phase, four-wire secondary distribution grid, modeled with Matlab SimPower System Toolbox.