

**FEDERAL UNIVERSITY OF ITAJUBA - UNIFEI
GRADUATE PROGRAM IN ELECTRICAL ENGINEERING**

Francinei Lucas Vieira

**Impacts of Linear and Nonlinear Load
Modelling on Power Harmonic Metrics in
Smart Grid Context Using OpenDSS**

Itajuba, MG – Brazil
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Dissertation submitted to the Graduate Program in
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the title of **Master of Science in Electrical Engineering**.

Concentration Area: Electric Power Systems
Supervisor: Paulo Fernando Ribeiro, PhD.
Co-Supervisor: Benedito Donizeti Bonatto, PhD.

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*“The master is not the one who teaches;
it is the one who suddenly learns.”*

— **João Guimarães Rosa** (Brazilian novelist)

RESUMO

Os sistemas de potência estão passando por grandes mudanças à medida que a geração distribuída, os dispositivos eletrônicos de potência e as aplicações que tornam as redes elétricas mais inteligentes são inseridos nos sistemas. Embora as mudanças sejam benéficas para satisfazer as necessidades de cargas locais, problemas podem surgir nos parâmetros de desempenho elétrico devido ao impacto das alterações na rede. E para realizar estudos e verificar o impacto de novos elementos nos sistemas de distribuição, as ferramentas de simulação são recursos importantes para o planejamento de pesquisadores e engenheiros. Esta dissertação é um estudo de modelagem harmônica que abrange, por exemplo, os efeitos de cargas lineares agregadas em estudos harmônicos, a modelagem e composição de dispositivos lineares e não-lineares e o uso de sistemas equivalentes de potência para simulação. As simulações são realizadas usando diferentes modelos de carga para verificar o impacto e a sensibilidade da impedância do sistema e das tensões harmônicas resultantes. Fontes harmônicas representando cargas não-lineares típicas são conectadas ao sistema para analisar a distorção de tensão e a impedância do sistema em diferentes barramentos das redes simuladas. Os sistemas foram modelados e simulados no software OpenDSS. Os resultados mostraram que tanto o modelo quanto a composição de cargas possuem um impacto significativo na impedância do sistema e no amortecimento de ressonâncias paralelas. Porém, uma avaliação abrangente de cargas e geradores distribuídos através de medições é necessária para melhor entender seus comportamentos nas métricas de desempenho elétrico.

Palavras-chave: distorção de tensão; geração distribuída; harmônicos no sistema de potência; modelagem de cargas harmônicas; OpenDSS; varredura de frequência.

ABSTRACT

The electrical power systems are undergoing major changes as distributed generation, power electronic devices and smarter grids applications are inserted in the networks. Although the changes are beneficial for satisfying the needs of local loads, issues on the electrical performance parameters may arise due to the impact of the changes in the network. In order to perform studies and verify the impact of new elements in distribution systems, simulation tools are important resources for planning by researchers and engineers. This dissertation is a harmonic modelling study that covers, for instance, the effects of aggregate linear loads on harmonic studies, the modelling and composition of linear and nonlinear devices, and the use of equivalent power systems for simulations. Simulations are performed using different load models to verify the impact and sensitivity of the system impedance and resultant harmonic voltages. Harmonic sources representing typical nonlinear loads are connected into the system to analyse the harmonic voltage distortion and the system impedance at different buses of the simulated networks. The systems were modelled and simulated in the software OpenDSS. Results have shown that both load model types and composition have a significant impact on the system impedance and parallel resonance damping, but a comprehensive evaluation of loads and distributed generators through measurements are necessary for better understanding their behaviours on the electric performance metrics.

Keywords: distributed generation; frequency scan; harmonic load modelling; OpenDSS; power system harmonics; voltage distortion.

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LIST OF ABBREVIATIONS

AC	Alternate current
ACSR	Aluminium conductor steel reinforced
AMI	Advanced metering infrastructure
ANN	Artificial neural networks
ASD	Adjustable speed drive
BESS	Battery energy storage systems
COM	Component object model
CIGRÉ	The International Council on Large Electric Systems
CSI	Current source inverters
DC	Direct current
DERs	Distributed energy resources
DG	Distributed generation
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
EV	Electric vehicle
FACTS	Flexible AC transmission systems
HVDC	High-voltage direct current
IEC	International Electrotechnical Commission
IEEE	The Institute of Electrical and Electronics Engineers
IHD	Individual harmonic distortion
LV	Low voltage
MATLAB	MATrix LABoratory
MV	Medium voltage

OpenDSS	The open distribution system simulator
p.u.	Per unit
PCC	Point of Common Coupling
PFC	Power factor correction
PV	Photovoltaic panel
PQ	Power quality
RMS	Root mean square
THD	Total harmonic distortion
UNIFEI	Federal University of Itajuba
VBA	Visual Basic for Applications
VSC	Voltage-source converters

1. INTRODUCTION

1.1 Motivation

Renewable power generation had a capacity increase estimated in 178 GW worldwide only in 2017, led by solar photovoltaic (PV) power with 55% (REN21, 2018). In Brazil, there were about 545 MWp of grid-connected solar capacity until 2018, as seen in Fig. 1.1, distributed over 52,000 installations. Also, Brazil has over 5,500 municipalities and 55% of them had at least one grid-tied PV system in 2018, compared with 35% in 2017. Despite this incredible growth, the share of electricity consumption that has been produced by grid-connected solar PV systems is less than 0.3% (ENOVA SOLAR ENERGIA LTDA, 2019).

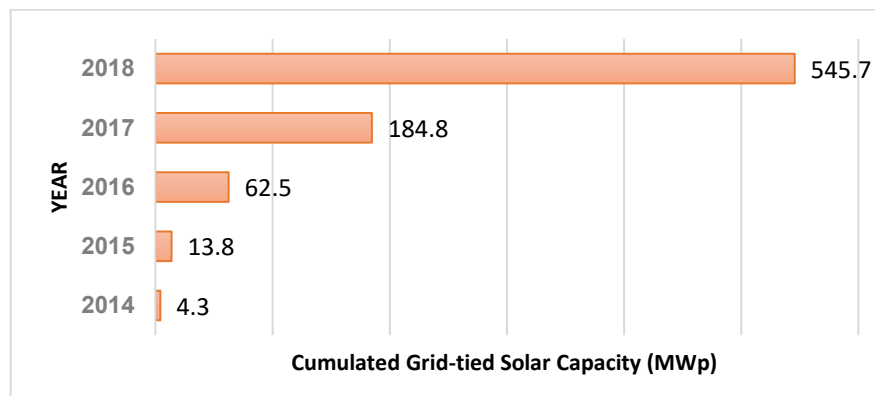


Fig. 1.1: Cumulative grid-tied solar capacity in Brazil, from 2014 to 2018 (ENOVA SOLAR ENERGIA LTDA, 2019).

Society faces an increasing demand for energy followed by low-carbon emission targets, incorporation of renewable energy resources, higher operational flexibility, and technological update on power systems with automation and communication devices. There is a need to integrate large amounts of energy-efficient equipment and renewable generation. However, production and consumption may change faster than the network can be adapted, increasing the demands on power quality and continuity of supply (BOLLEN, 2011).

Distributed renewable electricity production is one of the major concerns for energy systems integration. However, penetration of distributed energy resources (DER), also called distributed generation (DG), has been changing the operational and planning requirements of

power grids, for instance, the system balancing, equipment reliability, overvoltage and harmonic control (REN21, 2018).

Reducing energy consumption is an effective option for decreasing greenhouse gas emission, by either using appliances less often or using more energy-efficient appliances instead. More efficiency of electrical-motor drives and electronic lamps is a consequence of cheap and effective power-electronic converters. However, those converters may consume higher non-sinusoidal (*i.e.* harmonics) currents than conventional loads, posing a potential challenge for power grids.

Power quality (PQ) is still an important topic for modern grids mainly due to the proliferation of nonlinear and single-phase loads, as well the increasing application of sensitive loads (GUERRERO, 2017) and emerging technologies, for instance, electric vehicle (EV) chargers, battery energy storage systems (BESS), demand-response, and smart metering. All these aspects may impact the way PQ analysis, measurements, and problems are currently addressed.

If not managed correctly, the proliferation of electronic-based modern loads, DG and emerging technologies may cause a significant increase in unbalances, harmonic emissions, and voltage variations. They might bring non-intentional operative issues on the voltage performance, reducing the life span of grid equipment, or even challenges to keep the electromagnetic compatibility (EMC) in a high standard (BOLLEN et al., 2017b).

Moreover, harmonic source detection and assessment of the customer's emission in power grids are yet challenging problems (PAPIC et al., 2019), especially for determination of the correct harmonic responsibilities and the fairness promotion on the grid access among different stakeholders.

1.2 Research objectives

This dissertation proposes a technical analysis of integrated power performance metrics in scenarios of low and high penetrations of electronic-based loads in electrical power networks. The focus would be the analysis of different scenarios of load and generation – simulation models, composition, aggregation, topology – and analyse how they impact the system impedance and voltage distortion levels in the power grid. Studies will be performed using the

software OpenDSS (DUGAN; MCDERMOTT, 2011). This work aims to discuss the following questions:

- i. *What are the potential power quality impacts of distributed linear and nonlinear loads on primary power distribution systems?*

This first question leads to an effort for reviewing the state-of-the-art regarding impacts on power systems performance because of linear and nonlinear load connections, increasing penetration of DGs and emerging technologies. Some examples of impacts on the electric performance include voltage distortion, zero-sequence harmonics, limits on hosting capacity, metering error, increased losses, and overloading of distribution transformers.

- ii. *How serious the impacts will become when more and more energy-efficient appliances and consumer electronics penetrates residential and industrial loads?*

To answer this question, case studies are performed considering the robustness of loads and DG components in computational simulations, for scenarios of load aggregation, composition, equivalent load modelling, and increasing insertion of electronic-based components.

- iii. *How the changes in power system topology impact the harmonic emission?*

This question is answered by testing the current modelling practices for harmonic studies, its limitations, challenges, and trends for analyses of future power systems. The focus is given to analyses on how changes of the system topology could impact the harmonic emission in medium-voltage (MV) power systems.

1.3 Research relevance

Load modelling has significant importance in the harmonic analysis since that different model representation may show a variety of results. Also, linear loads may cause large damping on harmonics, thus, their interaction with nonlinear loads should be analysed. An increasing insertion of electronic-based generation and energy-efficient loads would cause frequent topology changes on the grid. There is a need for improvements on the power system's

simulation models to address the changes caused by the rise of emerging technologies, distributed renewable generation, electric vehicles, and electronic-based loads.

1.4 Methodology

The method will be based initially on a strong literature review on power systems harmonics and load modelling. Then, the modelling of four test systems will be performed in the software OpenDSS. This open-source software only requires a computer and some knowledge of its functionalities.

Qualitative and quantitative analyses on harmonic emissions and contributions of each component are performed using the simulations models from the current literature. Moreover, topology changes and variation on the system impedance are shown and compared in tables and graph plots.

Additional software such as MATLAB (THE MATHWORKS INC., 2018) is used to support simulations and data analyses. A deterministic approach is adopted.

1.5 Results and main contributions

The results are expected to promote a better comprehension of the modelling of linear and nonlinear loads and how they could impact the power system performance. As far as the author knows, there are not many works carried out on the field of load modelling for harmonic studies and harmonic sharing, which increase the value of the results presented in this dissertation.

This dissertation will contribute to a better comprehension of how the changes in the power system topology may impact harmonic-emission and propagation. The results obtained can serve as a parameter for the update on techniques for harmonic modelling for utilities, engineers and researchers. A disclosure of open-source tools for power systems analyses among industry and researchers can also be explored.

1.6 Dissertation layout

This dissertation is organized as follows:

Chapter 2 presents the literature review on power system harmonics. An overview is given to different methods to assess harmonics, what are the impacts of harmonics on electrical components and the relevance of “background harmonics” in power systems.

Chapter 3 focuses on key concepts for linear and nonlinear load modelling, along with a succinct description of the challenges for connection of distributed generations and electronic-based loads into the grid.

Chapter 4 describes some functionalities of the software OpenDSS, the parameter values used in the test systems, and the scenarios considered in simulations. The simulation results of the test systems are also presented here.

Chapter 5 provides analyses of the simulations of the different cases and a brief discussion on the observed results.

Finally, chapter 6 draws the conclusion, lists the possibilities for future work, and draws attention for the importance of a philosophical assessment on harmonics in power systems.

2. POWER SYSTEM HARMONICS

2.1 Initial considerations

This chapter gives a brief overview of power system harmonics, including the basic concepts and study domains, common types of harmonic sources, the effects of harmonics in electrical equipment, and the definition of “background harmonics”.

2.2 Power quality issues in the smart grid context

The term *power quality* (PQ) is applied to a wide variety of electromagnetic phenomena on power systems. Electric performance metrics and electromagnetic compatibility (EMC) refer to a broad field of definitions that has a strong overlap with power quality and specify requirements for equipment connected to the grid aiming for the intended functionalities and minimal decrease of life span (BOLLEN et al., 2017a; CIGRÉ JWG C4.24/CIREN, 2018). Fig. 2.1 shows a classification of possible PQ challenges in flexible power systems (*smart grids*).

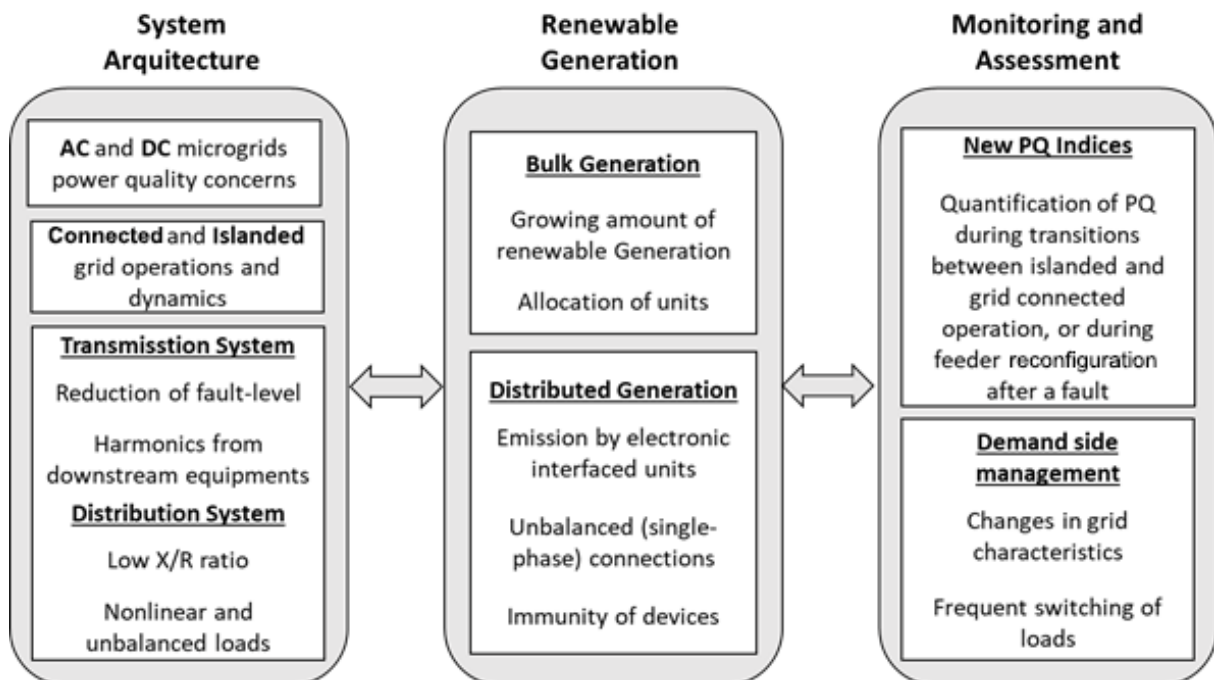


Fig. 2.1: PQ challenges in flexible electric networks.

In (BOLLEN et al., 2017a), the authors highlight the relevance of more research on the expected impact of changes in damping on the harmonic distortions at different voltage levels and in different types of networks. That is why topics such as nonlinear loads, changes in grid topology, and harmonic at different voltage level are covered in-depth in this dissertation.

2.3 Harmonics studies

Harmonic studies usually demand more detailed system models and simulation tools than those used for load flow or short-circuit analysis. Component modelling and harmonic assessment for modern power systems are not yet consolidated in the literature, which is scarce or has scattered information available. A review of the literature about modelling and simulation practices is being performed by task forces from CIGRÉ, through the working groups C4/B4.38 (CIGRÉ JWG C4/B4.38, 2019) and C4.605 (CIGRÉ WG C4.605, 2014). Also, the working group C4.24/CIREC addressed the impacts of DG and electronic-based loads (CIGRÉ JWG C4.24/CIREC, 2018). Reports of the mentioned task forces, along with publications from IEEE's Task Force on Harmonics Modelling and Simulation (IEEE PES, 2016) and a PhD thesis (RIBEIRO, 1985), are the major references of this dissertation work.

Some basic concepts about power systems harmonics are presented in this subsection. AC power systems are commonly operated for a single frequency of 50 Hz or 60 Hz, also called *fundamental frequency*. However, the expected ideal sinusoidal waveform is not reached, since real voltage and current waveforms contain distortions. Although transient effects are possible, only aspects related to steady-state distortion are discussed in this work.

A distorted wave can be represented as a sum of pure sine waves of different frequencies, through the application of *Fourier series* decomposition, hence a frequency multiple of the fundamental is called a *harmonic*. Harmonic distortion is caused by *nonlinear devices* – when the currents are not proportional to the applied voltages – connected to the power systems (DUGAN et al., 2012), that generate voltages with frequencies different from the supply frequency or absorb non-sinusoidal currents. Those devices can be classified into three categories, considering they are steady-state harmonic-emission sources (ARRILLAGA et al., 1997):

- 1) **Distributed non-linear components of small rating:** small single-phase power converters and low voltage appliances for end-users (*e.g.* personal computers, televisions, elevators, air conditioning, fluorescent lighting, rooftop PVs).
- 2) **Randomly varying nonlinear loads:** large and continuously varying arcing devices without adequate filtering are the biggest examples.
- 3) **Large power converters and FACTS:** Large ASDs (adjustable speed drives) are typical equipment in modern industrial facilities. There are many types of industrial applications that use direct current (DC) or alternate current (AC) drives in their processes. Flexible AC transmission systems (FACTS) devices also need special attention in harmonic studies.

The most common parameter used as an index for waveform quality is the *total harmonic distortion* (THD), as in (2.1):

$$THD = \frac{\sqrt{\sum_{h>1}^{h_{max}} C_h^2}}{C_1} \quad (2.1)$$

where C_h is the RMS value of the harmonic component h , and C_1 is the RMS value of the fundamental component.

The THD is given as a percentage of the fundamental and can be calculated for either voltage or current, considering harmonic components up to 50th order and excluding interharmonics (IEEE STD. 3002.8, 2018).

Harmonic voltage distortion limits aim to be a reference for recommended practice for system operators and users with shared responsibilities for harmonic control, thus, decreasing potential issues on equipment connected to the grid. The IEEE Std. 519 (IEEE STD. 519, 2014) establishes harmonic limits for voltages and currents for low, medium and high voltage systems. Table 2.1 displays the harmonic voltage limits for a weekly 95th percentile of 10-minute values.

Table 2.1: Harmonic voltage distortion limits (IEEE STD. 519, 2014).

Bus voltage at PCC (kV)	Individual harmonic distortion (%)	THD (%)
$V \leq 1.0$	5.0	8.0
$1.0 < V \leq 69$	3.0	5.0
$69 < V \leq 161$	1.5	2.5
$V > 161$	1.0	1.5

The Point of Common Coupling (PCC) is usually defined as the electrically nearest point to a particular load in a public power supply system, at which other loads could be connected (IEEE STD. 3002.8, 2018). This point is upstream of the installation at which the current or voltage distortion limits apply.

2.3.1 Study domain

Time-domain, frequency-domain, or a hybrid combination of these domains can be used to perform harmonic studies, with a wide preference for frequency-domain methods, because of its efficiency and accuracy to represent frequency-dependent behaviour in a transmission network (BONNER et al., 1996).

Frequency-domain

A frequency-domain formulation for harmonics can be reliable and efficient for steady-state solutions, as well as achieve shorter calculation times. Available methods are divided into frequency scan, harmonic penetration (either a direct method or an iterative harmonic analysis), and harmonic power flow methods (MEDINA et al., 2013). An overview of frequency-domain methods is given in Fig. 2.2.

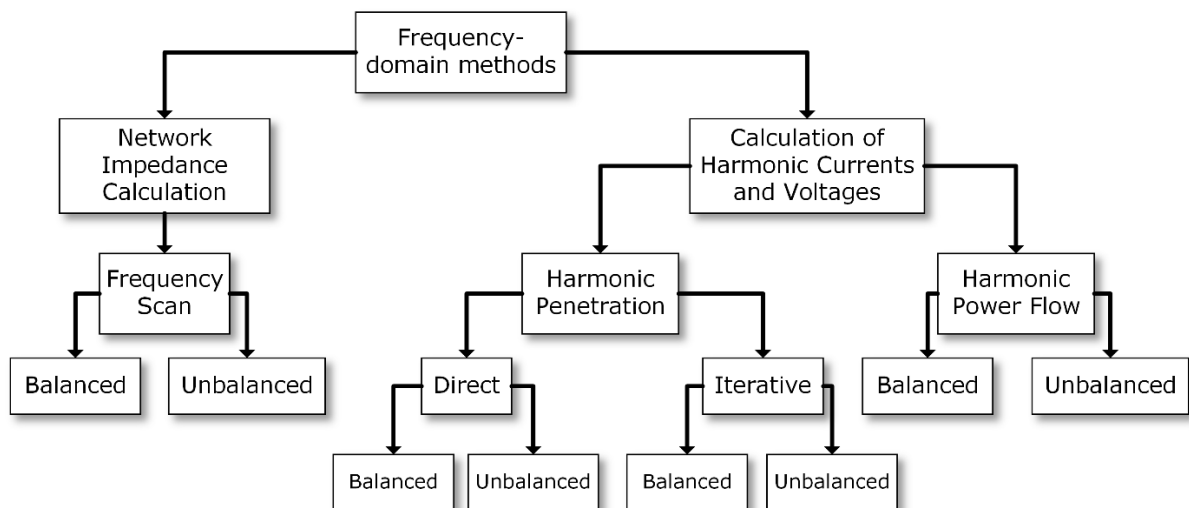


Fig. 2.2: Overview of frequency-domain analysis methods for harmonics studies (CIGRÉ JWG C4/B4.38, 2019).

Frequency scan is an analysis tool that can provide the grid impedance (or admittance) seen from a bus as a frequency-dependent variable, allowing the identification of parallel and series resonant points, and the frequencies at which voltage magnifications among two or more points of the power system may occur (BONNER et al., 1996). It is also used for filter design.

A sinusoidal unitary current source is injected at a certain system bus of the power system and the bus voltage response is calculated for all relevant frequencies. The admittance matrix is recalculated for each frequency step. Mathematically, this method is described by (2.2).

$$[I_h] = [Y_h][V_h] \quad (2.2)$$

where $[I_h]$ is nodal harmonic current vector, $[V_h]$ is the nodal harmonic voltage vector, and $[Y_h]$ is the harmonic admittance matrix. The resulting harmonic voltage in each bus represents the driving point impedance on the injection bus.

The *direct method* is a non-iterative method with a formulation like (2.2) for calculation of harmonic voltages and currents. It is a simple and accurate representation under normal conditions. However, the ideal current injection may not be accurate for arc furnace and power converters under resonance conditions, since the influence of harmonic voltages on the system impedance is not taken into account (MEDINA et al., 2013). Two approaches would improve accuracy. The first is using a nonideal current source with an estimated shunt harmonic impedance. Alternatively, a voltage source or a current re-injection could be applied.

An extension of the direct method is the *iterative harmonic analysis*. Initially, an estimation of the voltage supply is done to obtain the harmonic currents. Then, those currents are used to calculate the harmonic voltages. Harmonic currents are computed again in an iterative process until the changes on the solution step are small enough. This method has slow convergence and narrow stability margins (MEDINA et al., 2013).

Harmonic power flow methods, also known as *harmonic domain*, are Newton-type iterative algorithms which linear, nonlinear and time-varying components are represented and solved, as well as the harmonic and their coupling effects. Linearization around an operation point is the fundamental step of this method. In (MEDINA et al., 2013), other method variants can be found, including representation of dynamics harmonics, inter-harmonics, coupled admittance matrices for DC drives, multiphase and unbalanced harmonic analyses. For instance, one advantage of multiphase harmonics analysis is the assessment of the impact of single-phase harmonic loads and non-characteristic harmonics on distribution systems, once the aggregation of many small energy-saving home appliances can be significant (MEDINA et al., 2013; WATSON; SCOTT; HIRSCH, 2009).

Time-domain

This representation presents good accuracy of system behaviours by solving differential equations in steady-state mode. However, the modelling of frequency-dependent parameters in this mode may be difficult (ARRILLAGA et al., 1997). A great advantage of the time-domain solution is the accurate modelling of DC controls and devices operating in their nonlinear region (CIGRÉ JWG C4/B4.38, 2019). However, simulations of this method can be very slow for large systems, in particular, those with models with large time constants, such as synchronous machines (ARRILLAGA et al., 1997; MEDINA et al., 2013). Time-domain applications involve real-time simulations, modelling of power converters, active filtering implementation, and AC/DC harmonic studies for HVDC systems.

2.3.2 Background harmonics

An existing harmonic distortion in the network prior to the installation of nonlinear loads is called *background harmonics*. It is usually represented as a harmonic voltage source, or a voltage source behind an impedance (MEDINA et al., 2013), as seen in Fig. 2.3. Harmonic voltages at some buses and harmonic current injections at other buses can be solved by a hybrid solution, doing matrix partition and partial inversion.

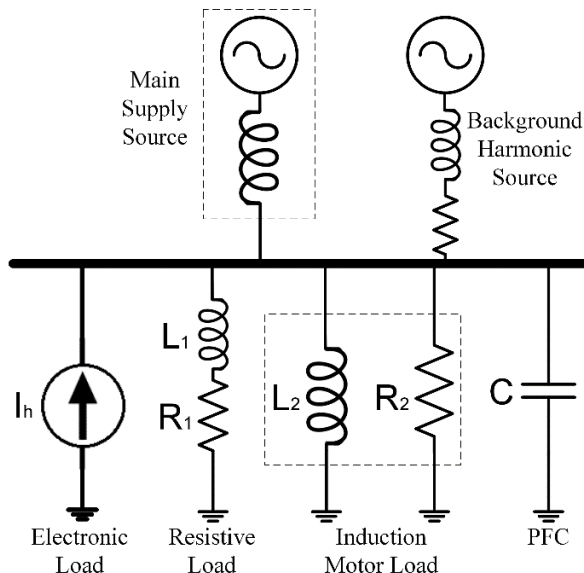


Fig. 2.3: Representation of background distortion for harmonic studies (BURCH et al., 2003).

A good design of a distribution network supplying nonlinear loads usually involves the calculation of harmonic current and voltages, thus, avoiding issues related to harmonic

distortion. Estimation of total harmonic current on a group of harmonic sources is a difficult task, due to the time-varying behaviour of the loads and background harmonics. In (ĆUK et al., 2013), a summation of harmonic currents in industrial facilities was analysed and compared with field measurements. In (BROWNE; PERERA; RIBEIRO, 2007; MACEDO et al., 2007; RIBEIRO et al., 2011), a series of harmonic distortion measurements and trend analysis were conducted during special sporting events, like the Soccer World Cup.

Backgrounds harmonics may amplify or attenuate the distortion at different harmonic orders, depending on the phase angle between the background distortion and the locally generated harmonics (BURCH et al., 2003). An arithmetical harmonic sum may be performed, leading to a conservative result. However, phase angles play an important role in harmonic summation, since several harmonic phasors could have a sum lower than the arithmetical (ĆUK et al., 2013).

In (SENRA; BOAVENTURA; MENDES, 2017) is demonstrated how harmonic currents of a nonlinear load can depend on the distortion of the voltage supply, based on measurements. Their contribution includes a method to assess current distortion draw by nonlinear loads without using time-domain simulations.

Some considerations on harmonic impedance estimation for LV networks are found in (ĆUK et al., 2012). The authors emphasised the need for more robust and precise linear load models for harmonic studies, both in magnitude and composition. Moreover, the authors indicated that the use of equivalent models without an overview of the impacts on all impedances can result in poor estimations of harmonic voltages and currents, which also impacts the evaluation of background harmonics.

In a recent publication (PAPIC et al., 2019), the authors approached the relation between background distortion at the PCC and customer facilities for determination of harmonic-emission responsibilities. Also, they stated that harmonic distortion at the PCC is caused by the supply side and the customer side. At last, the authors proposed a typical MV/LV test system supplying industrial loads to verify compliance with harmonic limits.

A report from CIGRÉ (CIGRÉ JWG C4/B4.38, 2019) gives several recommendations when measuring harmonics, including grid planning, component rating, prediction and propagation of the harmonic distortion within the grid. Measurement of background harmonics should be conducted for as long as possible since the harmonic levels can vary significantly over a short time or different seasons. Also, the harmonic percentile levels (95th or 100th) can

present significant differences; therefore, the used level depends on the type of the study, for instance, grid planning or component rating.

2.4 Effect of harmonics on electrical components

An increasing adoption of power electronic technologies – such as inverters for photovoltaic (PV) systems, adjustable-speed drives (ASD), battery energy storage systems (BESS) and electric vehicles (EV) – are expected to grow during the coming years, not only in quantities but also in size of installations (CIGRÉ JWG C4/C6.29, 2016).

However, high penetrations of these technologies may decrease the power performance metrics and amplify technical problems in distribution networks (GONZALEZ et al., 2016). For example, overvoltage and harmonic distortion are operational circumstances of power distribution systems that are becoming more relevant in a progressive smarter grid scenario (MONTENEGRO; DUGAN; RAMOS, 2015). A few more insights about harmonic-related issues are found in (BOLLEN et al., 2014; XU, 2004).

Nonlinear loads and switched devices are usually 40% of utility load (KALAIR et al., 2017), and the harmonics produced by them are injected back in the supply system, interacting with transformers, capacitor banks, electrical machines, and interfering on energy meters, electronic controllers and communication lines (DUGAN et al., 2012).

In transformers, harmonic distortion in current increases heating, which can be derived into three power loss components: conductor losses, eddy current losses, and core losses. Being a magnetic device, transformers can produce high amounts of harmonics when operated in the saturation region (ACHA et al., 1989). In (DUGAN et al., 2012), the authors stated that voltage distortion on motors induces high-frequency currents in the rotor, resulting in decreased efficiency, heating, vibration, high-pitched noises, and an overall shorter life span.

Capacitor banks are frequently related to problems involving harmonics, due to high voltage distortion during resonances that cause heating or blown fuses. Shunt capacitors are used for power factor correction (PFC). However, there are interactions with harmonic voltages and currents that change the system impedance and modify the profile of resonant points, which can bring excessive currents or overvoltages in case the harmonic sources are close to the resonant frequencies.

Moreover, many electronic devices have capacitive filtering components which can bring the first resonant frequency closer to the fundamental (CHAKRAVORTY et al., 2017). Grid-

side filters at large PV installations are referred as a cause of significant resonances at low frequencies in (CIGRÉ JWG C4.24/CIREDE, 2018), and the authors suggest that the input impedance of PV inverters should be considered for harmonic impedance studies. Also, one effect related to grid resonances is the possibility of the PV inverters become unstable and trip, under certain impedance circumstances.

Electronic equipment is sensitive to power pollution, for instance, “computers, telephone systems, and controllers may respond incorrectly to normal inputs, not respond at all, or give false outputs” (SUBJAK; MCQUILKIN, 1990). Malfunctions include errors in metering devices, false tripping of relays, and interference with motor controllers.

Communication interference can occur when distribution systems and communication circuits share a common path. Some types of interference are inductive coupling, interference with power line carrier systems, and relay malfunctions (SUBJAK; MCQUILKIN, 1990). A newer research topic is the study of the performance index of a power system in a scenario of increasing hosting of DG/DERs without exceeding power quality limits, a concept known as *hosting capacity*. A PV hosting capacity approach that relates harmonic injections with a voltage rise at the PCC is performed in (OLIVEIRA et al., 2018; OLIVEIRA, 2018).

Many utility systems are not prepared for the increasing penetration of distributed generation, taking the distribution grids to a new level of complexity. Thus, the use of system analysis tools for modelling this new scenario is required to achieve a better comprehension of grid behaviours under different levels of distributed generation (RADATZ et al., 2016).

2.5 Final considerations

This chapter brought attention to PQ challenges that may arise at flexible power systems, but it focused on the general aspects of power harmonics, including basic concepts, study domains, background harmonics, and possible impacts on electrical components. This latter can be synthesized as follows (IEEE STD. 3002.8, 2018):

- a. Increased losses in power equipment, cables, lines;
- b. Pulsating torque in rotating machinery;
- c. Increased insulation stress and, consequently, equipment ageing intensified;
- d. Amplification of voltage and currents due to resonances;
- e. Communication interference.

3. HARMONIC POWER SYSTEM LOADS

This chapter presents the aspects related to the harmonic modelling of electric components, including linear and nonlinear loads. Also, this chapter covers the existing modelling practices and the challenges for the integration of new generation types and electronic-based loads into the grid.

3.1 Introduction

Many load models used for power system studies still use the representation developed several years ago. The power system structure and load characteristics have been changed since then, but load models have not been adequately updated (CIGRÉ WG C4.605, 2014). Data from power flow solutions are usually used to model typical static load models (*i.e.* constant impedance / constant current / constant power). On the other hand, dynamic load models are usually represented by induction motor models. An impedance equivalent can be usually calculated from the active and reactive power but, for harmonic frequencies, the active power of a rotating machine does not exactly correspond to a damping value (ORTMEYER; HATZIADONIU; RIBEIRO, 2008).

Active and reactive power components are used for impedance equivalent representation for linear loads at the fundamental frequency, but it cannot be used directly at harmonic frequencies (BURCH et al., 2003). For instance, the authors mentioned that the power absorbed by rotating machines causes different behaviour on resonance damping, and they proposed a different approach for modelling. Heaters and incandescent lamps may also cause damping for propagating harmonics and changes in resonant frequencies in distribution systems (FRÖBEL; VICK, 2013).

Load characteristics play an important role in harmonic studies, since different load models may lead to different simulation results. Induction motors, synchronous motors, and most commercial and residential loads present a linear behaviour, while electronic-based power conversion technologies are usually nonlinear loads since they generate harmonics (BURCH et al., 2003).

One of the objectives of this dissertation work discusses on how aggregate linear load models impact harmonic studies, since their type, magnitude, and composition may change the resonance conditions and the voltage distortion in a power distribution system. However, it is not a simple task, because significant factors should be considered, such as the diversity of the loads, the lack of updated information on the load structure, the spatial and temporal load variability, and difficulties for assessment and validation of load models (CIGRÉ WG C4.605, 2014). For example, a variation of generation and loads cause time-varying harmonic currents, requiring additional statistical processing to calculate aggregated diversity indices (BOGALE, 2015). However, techniques and parameters for such processing are not yet consolidated.

3.2 Key concepts

For a better comprehension of specific aspects of load modelling, some concepts and definitions are presented below, based on (CIGRÉ WG C4.605, 2014; PEREZ TELLEZ, 2017).

Load aggregation

Load aggregation is a technique used to simplify load modelling by doing an equivalent aggregate load model, as it would not be easy to represent every device in a system. This can be performed at different voltage levels and buses, either through an analytical aggregation or by a measurement-based approach.

Load characteristics

The load characteristics are a set of parameters that characterise the electrical behaviour and the load response to changes in the power system. Some examples of characteristics are the active and reactive power dependence with voltage or frequency deviation, fundamental and harmonic currents, power factor, etc.

Load class

Load class refers to groups with a similar load composition and characteristics. Typical examples are the *industrial*, *commercial*, and *residential* classes. It is also known as a *consumer class*.

Load component

A load component is a single electrical device or a group of devices, which present power consumption and response to system variations similarly. An alternative definition of a load component is an aggregate load equivalent of similar devices.

Load composition

Also known as *load mix*, the load composition refers to the relative contribution of different types of loads to the actual aggregate demand of a group of loads connected at a single system bus. This term can be applied for the demand of a load component or a load class.

Load model

A load model is a representation of a load used for estimation, prediction, or analysis of load characteristics in power systems and their interactions. It is usually represented by a mathematical formulation – which may include exponential functions, differential equations, transfer functions, or polynomial structures – that characterise a physical interpretation of the power-voltage and frequency dependency.

Load profile

A load profile, or a load curve, is a representation of the power demand of a load over a time period, displaying the time-varying behaviour of power consumption. Typical time periods are *daily*, *weekly*, or *annual* profiles with a step of *15-minutes* or *hourly*.

3.3 Linear load models

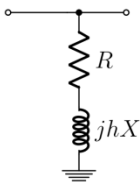
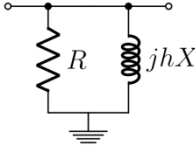
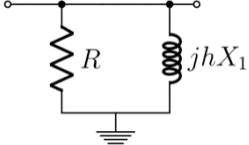
Linear loads include rotating motors and heating devices, which are the major portion of residential and commercial loads. They are not harmonic-emission sources, but they cause significant effects on the level of damping near resonant frequencies and can introduce parallel or series resonances.

Modelling of an aggregated harmonic load can be performed by either a component-based or a measurement-based approach (CIGRÉ WG C4.605, 2014). It is sensitive to load type, magnitude, and composition. A group of loads can be usually represented as an aggregated load for practical reasons, which should include distribution transformers, overhead lines, cables, and shunt elements (BONNER et al., 1996; BURCH et al., 2003) into a single reduced model

at a particular voltage level. If a load is not accurately represented, results could present unrealistic harmonic voltages or currents.

Three load models proposed in the literature (BURCH et al., 2003; ORTMEYER; HATZIADONIU; RIBEIRO, 2008; RIBEIRO, 1985) are analysed – a series model, a parallel model, and a motor model dedicated for a more specific characterisation of induction motors on an aggregated load. These load models are still used or discussed in recent publications about harmonics (AMINI; JALILIAN; POUR BEHBAHANI, 2019; BARAKOU et al., 2016; BUSATTO et al., 2019; EGGENSCHWILER et al., 2017). Their respective parameters are indicated in Table 3.1.

Table 3.1: Aggregated linear load models.

	<i>Series</i>	<i>Parallel</i>	<i>Motors</i>
Model Type			
Parameters	$R = P \cdot \frac{V^2}{P^2 + Q^2}$ $X = Q \cdot \frac{V^2}{P^2 + Q^2}$	$R = \frac{V^2}{P}$ $X = \frac{V^2}{Q}$	$R = \frac{V^2}{(1 - K) \cdot P}$ $X_1 = X_M \cdot \frac{V^2}{K_m \cdot K \cdot P}$

Legend

- P and Q : active and reactive power, respectively;
- V : rated line-to-line voltage, for a 3-phase system;
- K_m : install factor (≈ 1.2 pu)
- X_M : motor locked rotor reactance ($\approx 0.15 - 0.25$ pu)
- K : the fraction of motor load into the total load demand

The induction motor model uses the locked rotor reactance estimated from a function of the rated installed power (BURCH et al., 2003). However, when the nameplate rating is unavailable, the power flow could be used together with an install and a severity factors to account the differences between the rated power and power demand for the parameter calculation of a group of motors.

K_m is a number that defines the ratio between the total rated apparent power and the real active power flow flowing to the group of motors – correspond approximately to $1.2 \cdot X_M$ – and is related to the machine rating rather than the power drawn from the system. X_M typically ranges from 0.15 to 0.25 p.u.

K can be defined as the ratio between the real demand of inductive motors and the total real power flow from the whole load group (ABU-HASHIM et al., 1999; ORTMEYER; HATZIADONIU; RIBEIRO, 2008). The model parameters can be used either in dimensional units or per unit. Skin effect was not considered in the load models.

3.4 Nonlinear load models

Nonlinear loads draw distorted current through the supply system. Most of them include some electronic conversion devices such as an inverter or a rectifier. Several examples can be mentioned: ASDs, battery chargers, data centres, PVs, energy-efficient lights, among others. The difficulties of modelling nonlinear loads are related to the fact of them being harmonic sources and their electrical characteristics are not well represented using linear harmonic equivalent model (ARRILLAGA et al., 1997). Modelling of nonlinear loads should observe the following aspects (FUCHS; MASOUM, 2008):

- i. The type and topology of the loads;*
- ii. The interaction with the system impedance;*
- iii. Harmonic variation along the time.*

Modelling of iron-core reactors, transformers, electric arc furnaces, static var compensators, line-commutated converters, and cycloconverters are presented in (TSAI; LIU; CHANG, 2008). Nonlinear loads could be modelled as constant power load for the fundamental and as current sources at harmonic frequencies (BONNER et al., 1996), as shown in Fig. 3.1, with or without phase angle information. An ideal current source was mentioned as inaccurate for arc furnaces and electronic converters under resonant conditions, but they could be represented satisfactorily as a Thévenin equivalent voltage source model (IEEE STD. 3002.8, 2018; RIBEIRO, 1985).

An alternative to ideal current sources in iterative harmonic analyses is the Norton equivalent. A fixed harmonic current source at each iteration represents the load, and a Norton equivalent impedance can be used to improve convergence (CORRÊA, 2012), as in Fig. 3.2.

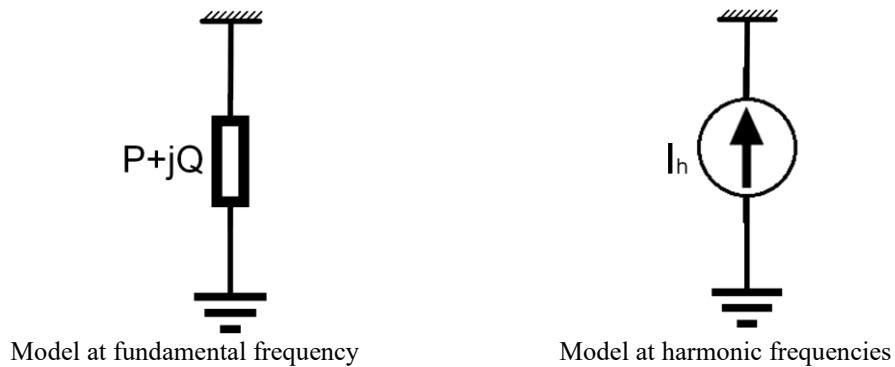


Fig. 3.1: Model for nonlinear loads as a current source (BONNER et al., 1996).

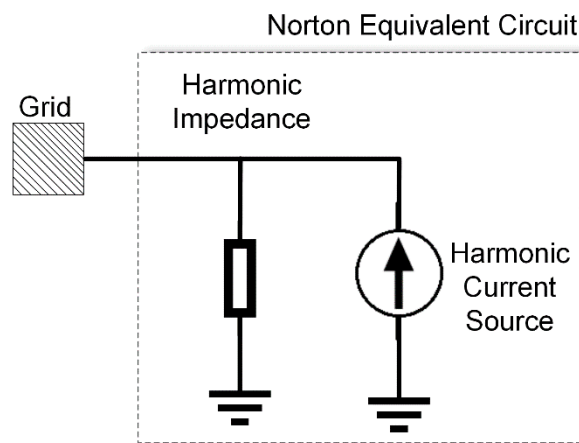


Fig. 3.2: Norton harmonic model of power electronic converters (CIGRÉ JWG C4/B4.38, 2019).

This model represents the harmonic emissions and the harmonic impedance of the device which can interact with the system impedance. Typical household electronic and commercial appliances used to be modelled as a single parallel harmonic current source (TSAI; LIU; CHANG, 2008) under acceptable conditions, *i.e.*, with a supply voltage distortion equal or below 10 % at the busbar of interest (IEEE STD. 519, 2014; OLIVEIRA et al., 2011).

Nonlinear loads are usually characterized by harmonic current sources, causing additional power losses in the system (IEEE STD. 3002.8, 2018). To interpret the harmonic voltages from the currents, it is necessary to know the harmonic impedance of the system, which can be a very complex task. Equivalent load types, compositions and the system impedance seem to have strong bonds to each other and their appropriate representation is very important for harmonics studies (ĆUK et al., 2012; ROBERT, 1997).

3.5 Network equivalent system for harmonic studies

An accurate modelling of network components and harmonic distortion sources are necessary to calculate the propagation of harmonics through the system. However, detailed information about components is very difficult to obtain and the system analyses usually have to proceed with whatever information is available with simpler equivalents (RIBEIRO, 1985). Moreover, the size and details of a network model may be limited for practical reasons, such as data confidentiality or just to speed up studies (CIGRÉ JWG C4/B4.38, 2019).

In that case, lines, cables, transformers, capacitors, loads are not represented in detail, but they can be represented by an equivalent system seen from the point of connection. The approach of (RIBEIRO, 1985; RIBEIRO; FONSECA, 1992) suggests the modelling of the first two resonance frequencies – parallel (ω_p) and series (ω_s) – characterized by a T circuit as seen at Fig. 3.3. This equivalent representation provides more accurate results than the short-circuit inductance, but it is recommended to use only at busbars distant from the point of interest.

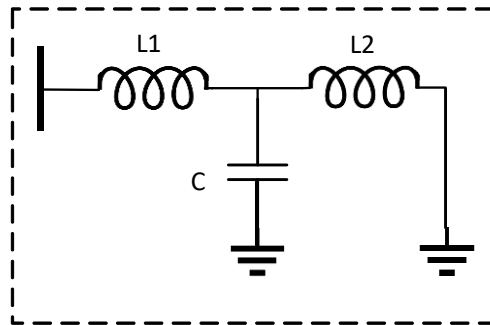


Fig. 3.3: Transmission system equivalent model.

The parameters L_1 , L_2 , and C of the system equivalent can be solved considering the two resonance frequencies, as indicated by (3.1), (3.2), and (3.3). Frequencies ω_p and ω_s are given in radians per second. Resistances in series with inductances can be added to attenuate the resonance peak.

$$L = L_1 + L_2 = \frac{(\text{nominal voltage, in kV})^2}{(\text{Short - circuit power, in MVA}) \cdot 2\pi f} \quad [\text{H}] \quad (3.1)$$

$$L_1 = L \cdot (\omega_p / \omega_s)^2 \quad [\text{H}] \quad (3.2)$$

$$C = \frac{L}{L_1} \left(\frac{1}{L_2 \cdot (\omega_s)^2} \right) \quad [\text{F}] \quad (3.3)$$

3.6 Challenges to the integration of DER and DG

New types of load and generation are increasingly being connected to the power grids, especially small-scale DG technologies, either directly connected or inverter-interfaced to the grid. In future scenarios, a large deployment of DER/DG will strongly impact active and reactive power demands (CIGRÉ WG C4.605, 2014).

The following aspects related to the insertion of DG will bring impacts on the power quality, and they are covered in detail in (BOLLEN; HASSAN, 2011):

- The increasing emission of disturbances by DG units, especially harmonics, voltage fluctuation, and unbalance;
- Insertion of single-phase generators may increase the voltage unbalance;
- Frequency dependence of the source impedance would bring more complexity for harmonic studies;
- The shift of generation from the transmission to distribution networks would weaken the grid. This could result in a wider spread of disturbances at the transmission system;
- DG is usually associated with voltage-source converters (VSC) which present a capacitive behaviour. Additional capacitance connected to the grid shifts actual resonances closer to the fundamental and may cause potential problems for DG inverters due to harmonic interactions (LENNERHAG; BOLLEN, 2018; WANG et al., 2011).

The harmonic emission shift to higher frequencies, where impedance models are not well developed, and the loss of accuracy on impedance estimation due to the resonance shift to lower frequencies are topics mentioned in a report of (DAPHNE; BOLLEN, 2018).

Assessment of harmonic emission is also important for passive filter design, especially for wind parks connected to transmission systems, because each new filter may cause resonance effects with background harmonics and complicate the detection of the main harmonic source (ROSS; CARLI; RIBEIRO, 2016). Thus, a system-wide approach to minimize harmonic distortion is preferred. In the context of this dissertation work, the authors (CASTRO et al., 2016) mention that changes in system topology and load composition of linear loads may affect the performance of harmonic filters.

Some other challenges for accurate modelling of converter-based DGs include the correlation between background harmonics and power converters, a better comprehension on how the system impedance influence harmonic emissions of the converter, and the development of a method for removing the influence of the connected grid on the measured characteristics (CIGRÉ JWG C4.24/CIREC, 2018). More details about the modelling of loads and power systems are available in (ARRILLAGA et al., 1997; CIGRÉ JWG C4/B4.38, 2019; RIBEIRO, 1985; SHARMA; RYLANDER; DORR, 2016).

3.7 Final considerations

The concept of DG and DERs within power systems have been presented as well as their technologies, which have been lately applied to the renewable energy field, considering their benefits and challenges over the years. The main impacts caused by this type of generation were conceptualised. Power quality consideration can be found in the following chapters in order to extend what has been discussed so far. The next chapter presents the test systems of distribution systems and industrial feeders, following some simulations performed in OpenDSS.

4. MODELLING AND SIMULATION OF POWER SYSTEMS

4.1 Initial considerations

This chapter presents the details of the electrical component modelling in OpenDSS, as well as the test systems simulated and used for harmonic analysis related to model type and composition, changes on system topology, and harmonic penetration in multiple voltage levels. The following sections present an introduction to OpenDSS, as well as the concepts on how to perform frequency scans and the calculation of voltage distortion using the software.

4.2 The OpenDSS

OpenDSS is a power flow simulation algorithm that performs the most varied analyses related to the planning of the electric distribution system and the quality of power. Also, the software performs analyses to meet the demands of future electric grids with distributed generation. For instance, *quasi-static* solution modes allow the execution of sequential simulations over time, and thus, system analysis can be performed at any time of the day (SEXAUER, 2012). Harmonics studies are performed in the frequency-domain by the software.

This software was introduced in 1997 under the name of DSS – *Distribution System Simulator*. In 2004, the DSS was acquired by EPRI Solutions, and it was released with an open-source license in 2008, in a version named OpenDSS (DUGAN; MONTENEGRO; BALLANTI, 2019). The main modes of software simulation are:

- Instantaneous power flow (*snapshot*);
- Daily power flow (*daily mode*);
- Annual power flow (*yearly mode*);
- Harmonic analysis;
- Dynamic analysis;
- Fault study;
- Monte Carlo fault study.

Since 2008, OpenDSS has become widely used around the world. One of the features that make it popular is the offered package of interfaces for simulation. The program was launched

with a *Component Object Model* (COM) interface, and recently the *Direct DLL* interface was released so that users could access program features on platforms incompatible with the COM interface (MONTENEGRO; DUGAN, 2017).

The COM interface can be controlled by software such as Python, MATLAB, and Microsoft Office tools, with an emphasis on *Visual Basic for Applications* (VBA). OpenDSS has recently come up with a version able to run parallel computing on modern multi-core computers. This version is called OpenDSS-PM (Parallel Machine) and is also freely available (MONTENEGRO; DUGAN, 2015, 2017).

4.3 Linear and nonlinear loads in OpenDSS

The load model in OpenDSS is a Power Conversion (PC) element that can be defined by its nominal power (kW , $kVAr$, kVA) and power factor (PF). It can be modified by load multipliers, daily or yearly load shapes, for example. By default, the load behaves as a current source, and its primitive Y matrix contains the impedance between the neutral of the load to the ground if existent (DUGAN; MONTENEGRO; BALLANTI, 2019). The load models can be characterized in different ways. There are eight options to define how the loads will vary with the voltage:

- *Constant real and reactive powers ($P + jQ$)*. This is the software default option and is widely used for power flow studies;
- *Constant impedance (Z) load*;
- *Constant real power (P) and quadratic reactive power (Q)*. Similar behaviour of a motor load;
- *Exponential*. By default, it is a real linear power (P) and a quadratic reactive power (Q). Used for feeder mix studies or voltage optimization measures;
- *Constant current magnitude (I)*. It may be used to represent rectifier type loads;
- *Constant real power (P) and fixed reactive power (Q)*;
- *Constant real power (P) and fixed reactance*;
- *ZIP model*. An array of 8 coefficients for weighting factors and cut-off voltage.

In any case, new considerations should be done for load modelling on harmonic analysis. The harmonic load model in OpenDSS is a Norton equivalent with a shunt admittance, as shown in Fig. 4.1. In OpenDSS, a *spectrum* object represents the harmonic distortion and it can be created and assigned to any *Power Conversion* element (e.g. loads, generators, voltage and current sources, as well as the *PVSystem* and *Storage* objects). Default spectra are also available.

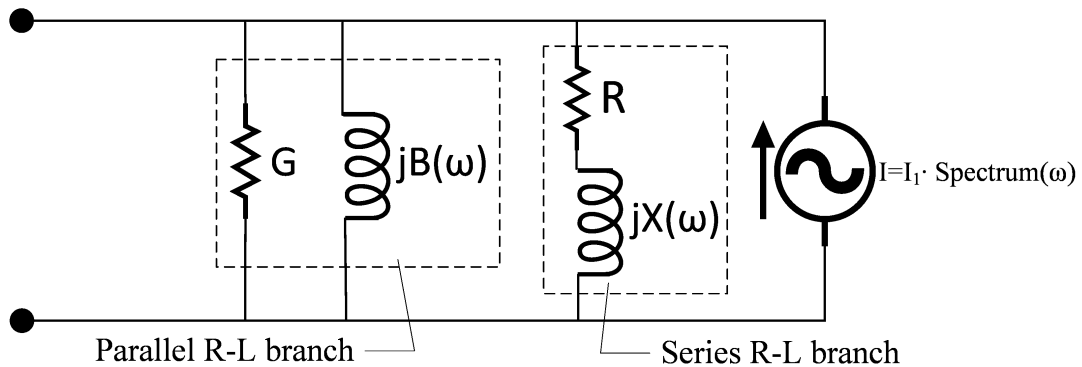


Fig. 4.1: Harmonic load model for OpenDSS.

By default, the admittance is composed by a parallel G - $B(\omega)$ branch and a series R - $X(\omega)$ branch, with half of the load specified to each one (50/50). Some options are available in the program to modify the load model in the harmonics mode, and the user can even neglect the load admittance branch to get nearly ideal current injections (ELECTRIC POWER RESEARCH INSTITUTE - EPRI, 2015).

One of the case studies presented in this dissertation will be focusing on the impacts of different load models representations and harmonic issues. Those issues derive from the changes in the power system impedance caused by the switching of capacitor banks and power conversion inverters from DERs. The solution analysis begins with a power flow solution in OpenDSS (*solve snapshot*) that must be accomplished before the harmonic solution (*solve mode = harmonics*) for all frequencies of interest. Thus, both the system impedance as a function of the frequency and the voltage distortion from each harmonic can be obtained from OpenDSS as described.

4.4 PV systems and DER in OpenDSS

All DER in the power grid is inserted in the simulations as either one of the following: a *PVSystem* object, a (negative) load, a generator, a voltage or current source. The power flow will automatically determine the phase angle of load or generator objects in a Norton-equivalent that represents those devices, along with their respective harmonic spectrum. Voltage sources and a *PVSystem* object use a harmonic voltage spectrum. The phase angle of a current source object (*Isource*) is difficult to be obtained, but its spectrum gives harmonic currents (not voltages). The current source is used in this work for the nonlinear harmonic emission.

Rooftop PV systems are the preferred type of generation in case studies. The input data necessary are the fundamental current magnitude and the harmonic spectrum as a percentage of the fundamental. That gives the inclusion of the basic behaviour of DERs for harmonic studies. Other modes include sequential-time harmonics-mode studies and quasi-static power flows that may be adapted for daily, weekly or annual simulations.

4.5 Case study: One-bus and three-bus test systems

The test systems presented in this subsection aim to evaluate the harmonic propagation as a function of different representations for load models and topology changes in the power grid. The load share on aggregated linear loads is interpreted here as seasonal behaviour on the load profiles, for instance, when the majority share is resistive (winter load) or inductive (summer load).

The first test feeder is shown in Fig. 4.2, and an extension of this system, with additional lines and loads connected, is displayed in Fig. 4.3. Their parameters can be seen in Table 4.1 (BURCH et al., 2003; RIBEIRO JR et al., 2019; VIEIRA et al., 2018).

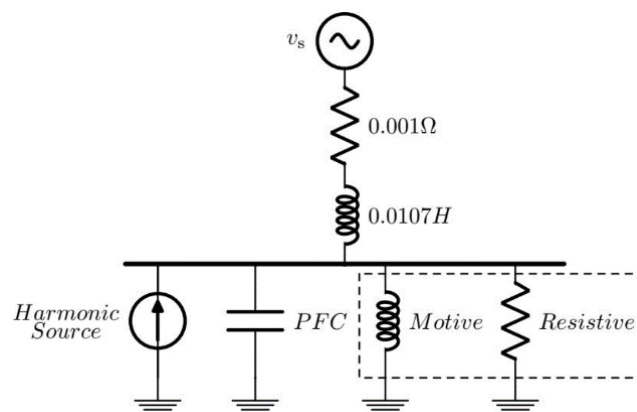


Fig. 4.2: One-line diagram of a 1-bus test system for harmonic studies.

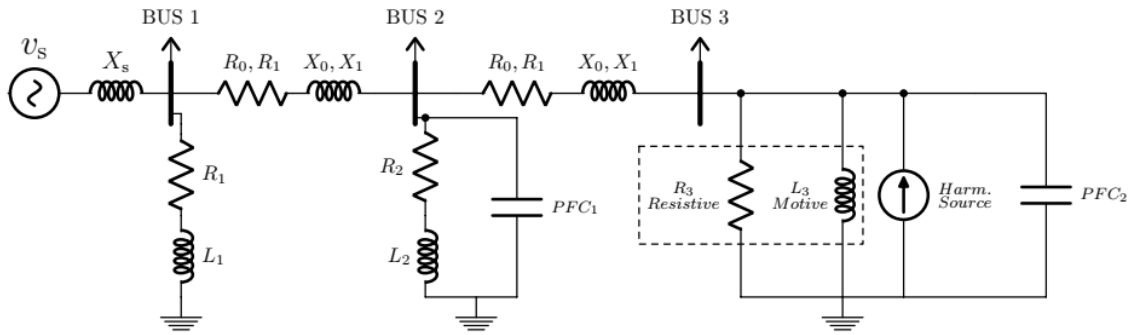


Fig. 4.3: One-line diagram of a 3-bus test system for harmonic studies.

Table 4.1: Technical parameters of 1-bus and 3-bus test systems.

Source Equivalent	$v_s = 13.8 \text{ kV}$	$S_{CC} = 30 \text{ MVA}$	$L_s = 0.0107 \text{ H}$
	$f = 60 \text{ Hz}$		$R_s = 0.0010 \Omega$
1-bus test system			
Load	$P = 743 \text{ kW}$	$Q = 247 \text{ kVAr}$	
PFC = PFC₂	$Q = -247 \text{ kVAr}$	$C = 5.4 \mu\text{F}$	$v_{nom} = 13.8 \text{ kV}$
Injected Harmonics (in A)	$I_5 = 0.840$	$I_7 = 0.601$	$I_{11} = 0.382$ $I_{13} = 0.323$
3-bus test system			
Bus 1	$P = 1 \text{ MW}$	$PF = 0.9 \text{ ind.}$	
Bus 2	$P = 2 \text{ MW}$	$PF = 0.9 \text{ ind.}$	$PFC_1 = 970 \text{ kVAr}$
Bus 3	Same parameters of the 1-bus test system		
Lines (5 km each)	$R_0 = 0.8767 \Omega/\text{km}$	$R_1 = 0.2112 \Omega/\text{km}$	
	$X_0 = 1.6847 \Omega/\text{km}$	$X_1 = 0.2510 \Omega/\text{km}$	

The source equivalent is the same for both systems. Symmetrical parameters of power lines describe a typical 185 mm² primary network conductor. Power factor correction (PFC) is a three-phase capacitor bank without losses. The current source represents a harmonic injection of electronic-based generation (*e.g.* inverters of photovoltaic generators). The dashed box represents the aggregated linear load, where the load models of the previous chapter (Table 3.1) are placed and analysed – Fig. 4.2 and Fig. 4.3 are indicated with a parallel model for motor loads. Skin effect, background harmonics, and unbalanced loads have not been considered.

Frequency scans on the connection point of the load models were done and the relation between system impedance and frequency can be seen in Fig. 4.4. Not only accurate inductances and capacitances are necessary for better estimation of the resonant frequencies, but also the resistances, which are responsible for the damping (DAPHNE; BOLLEN, 2018).

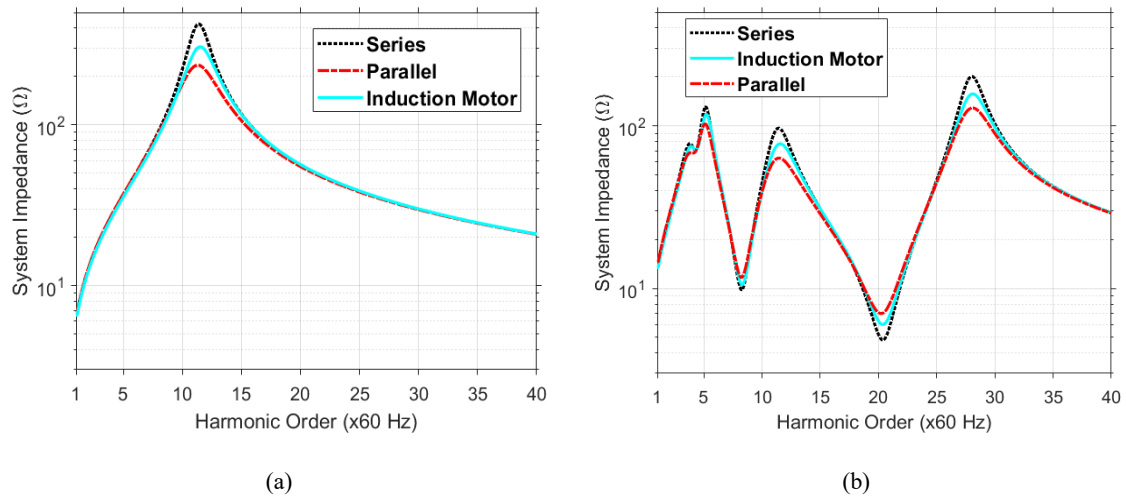


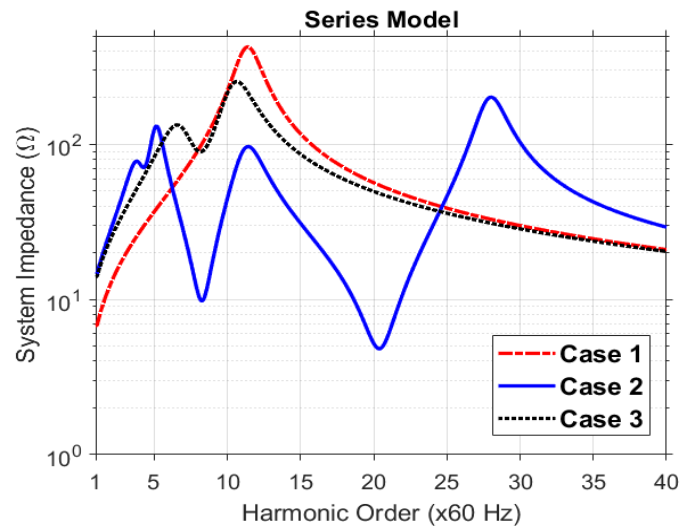
Fig. 4.4: Frequency scan for (a) test system 1 and (b) test system 2.

4.5.1 Model sensitivity of the load models and topology changes in the system

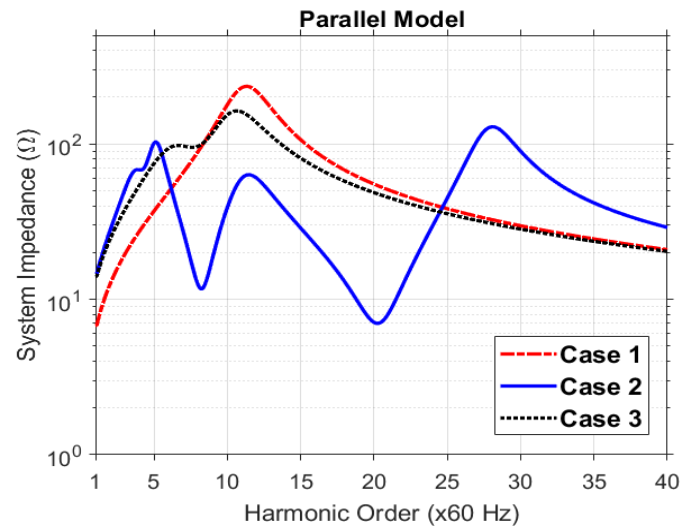
To verify the sensitivity of the aggregated load models for both load type and load composition, three scenarios corresponding to different grid topologies of the test systems are selected, which are stressed as follows:

- Case 1: refers to test system 1;
- Case 2: refers to test system 2, the way it was described;
- Case 3: also refers to system 2, with PFC₁ switched off (out of service).

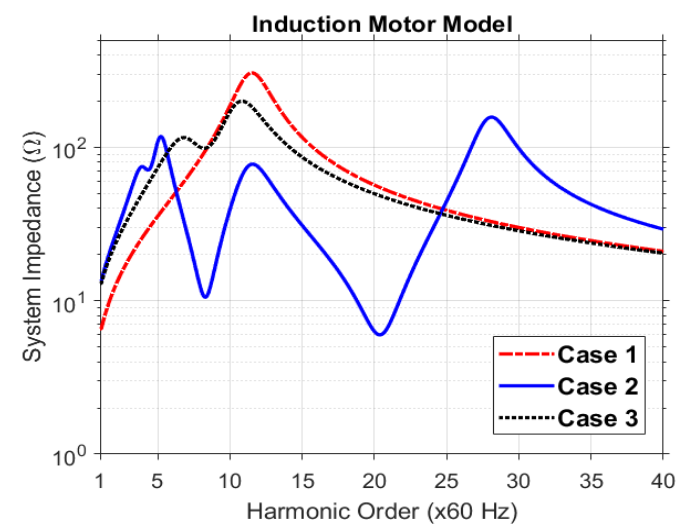
Model sensitivity consisted of analysing the aggregated load models composed of 50% of induction motors, and the remaining load is resistive. The frequency scan made clear the differences among the three load models, especially the peak impedance magnitudes, shown in Fig. 4.5. The voltage distortion analyses were done for Case 2 and 3 only, and the graphics are displayed in Fig. 4.6.



(a)



(b)



(c)

Fig. 4.5: Frequency response for each load model in each test case.

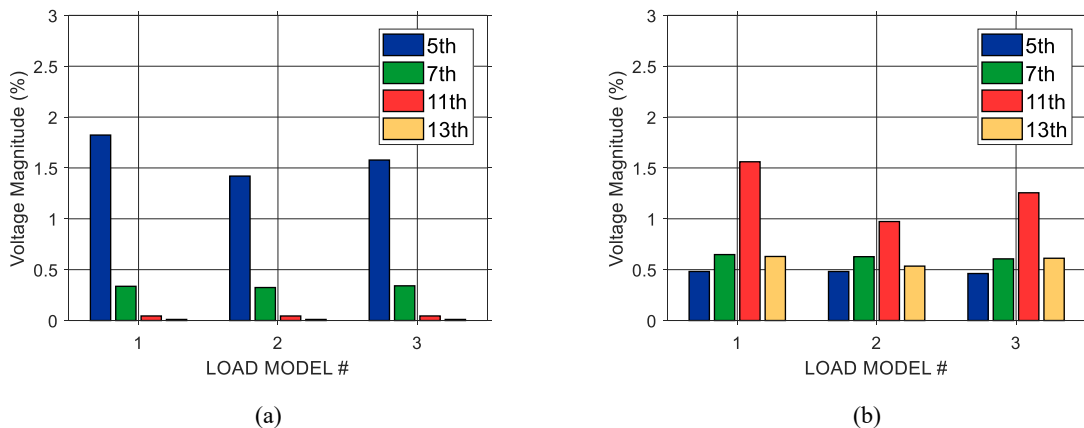


Fig. 4.6: Voltage distortion in busbar 3 for each load model in (a) case 2 and (b) case 3.

In Fig. 4.5, the first resonant peak moved from 11th harmonic on case 1 to the 5th harmonic on case 2, a situation caused by a topology change in the systems. Comparing the load models among each topology scenario, the series model presented the highest impedance magnitude, while the parallel model has the highest damping. The induction motor model 3 was shown to be balanced between the two values of impedance magnitude.

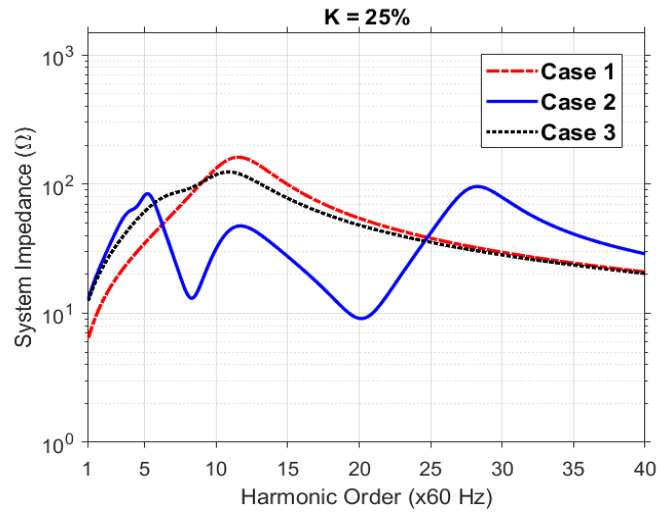
The same evaluation can be done in Fig. 4.6, by analysing the voltage distortion on the four harmonics of interest (5th, 7th, 11th, and 13th). Switching PFC₁ off led to a drastic profile change on the harmonic voltages, comparing case 2 to case 3.

4.5.2 Load composition (constant and varying PFC) of the load models

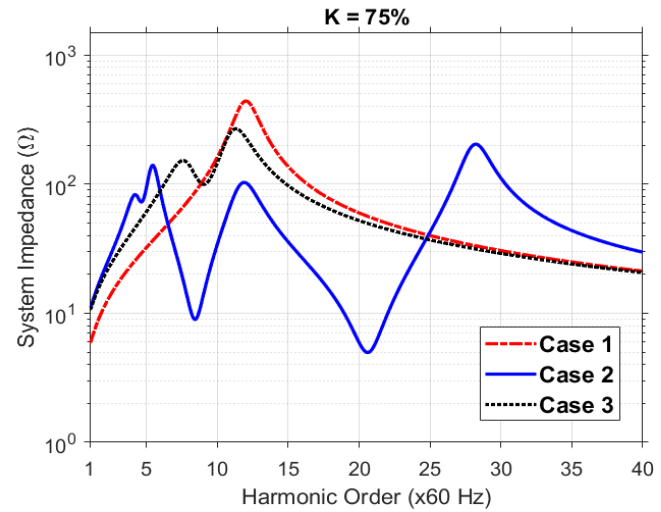
Load composition comprises the analysis of induction motor load only, considering three different mixture of the load – a share of motor loads corresponding to 25%, 75% or 90% of the total aggregated linear load, according to the equations presented in Table 3.1. The three cases were simulated, but in two different conditions:

- Power factor correction kept constant on the default case ($K = 0.5$);
- Power factor correction following the load variation.

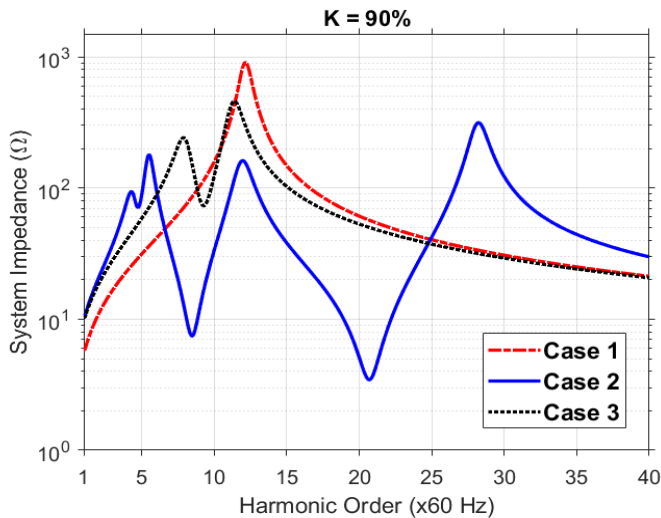
The plots with constant PFC (first condition) are shown in Fig. 4.7 and Fig. 4.8.



(a)

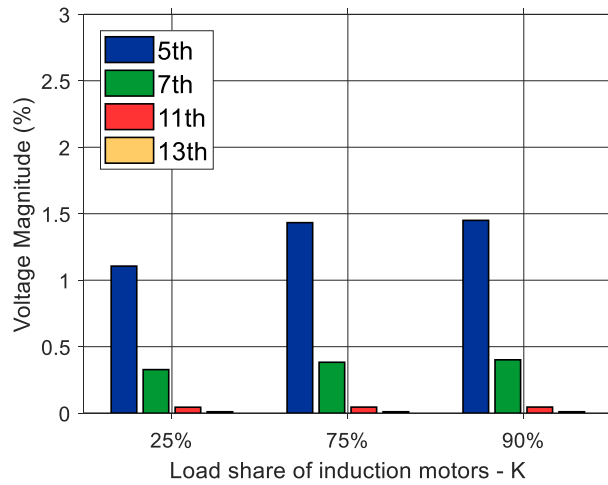


(b)

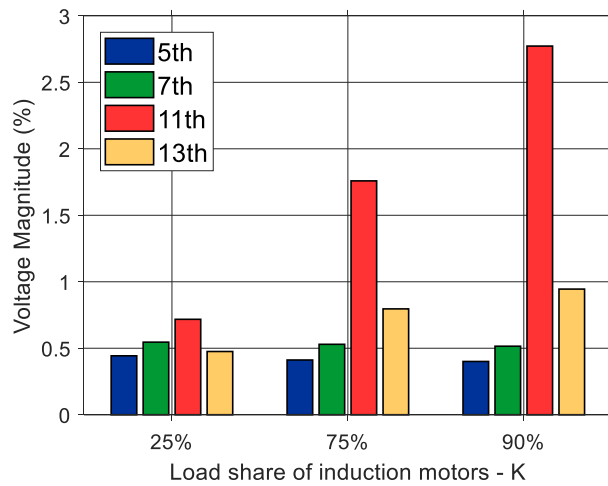


(c)

Fig. 4.7: Frequency response with PFC fixed and the load composition of induction motors corresponding to (a) 25%, (b) 75%, and (c) 90% of the total load demand.



(a)

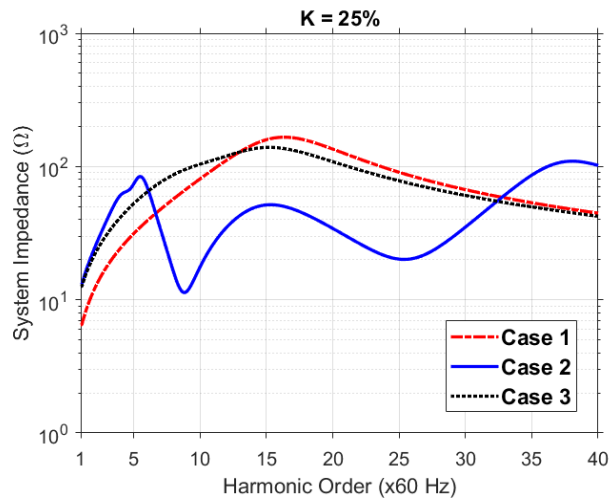


(b)

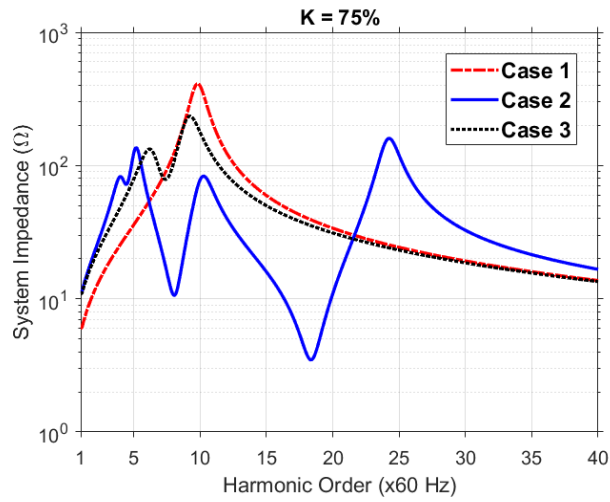
Fig. 4.8: Voltage distortion versus load composition, fixed PFC, at busbar 3 for (a) case 2 and (b) case 3.

When $K = 25\%$, the major share of the aggregated load is still resistive, causing large damping on impedance magnitudes, especially at resonant points. With the increase of induction motors, the damping declines, as seen in Fig. 4.7. The higher is the share of induction motors, the greater is the voltage distortion, as shown in Fig. 4.8. The case in which PFC is switched off (case 3) exhibited greater sensitivity than case 2.

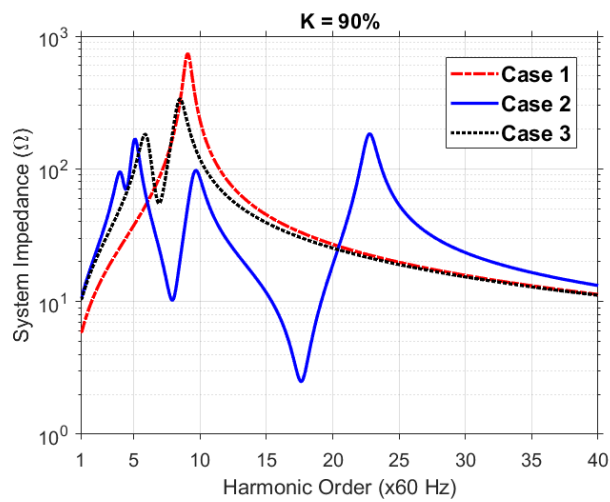
Now, the results with variable PFC with the load composition are shown in Fig. 4.9 and Fig. 4.10. In this condition, the capacitor bank is adjusted to match the reactive power consumption and correcting the power factor, thus, leading to a more realistic situation.



(a)

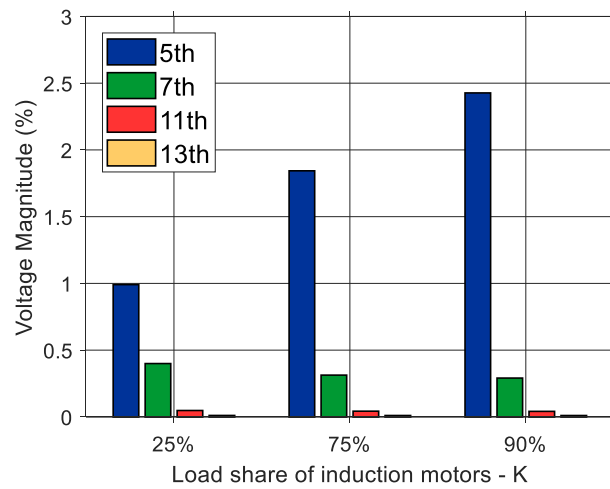


(b)

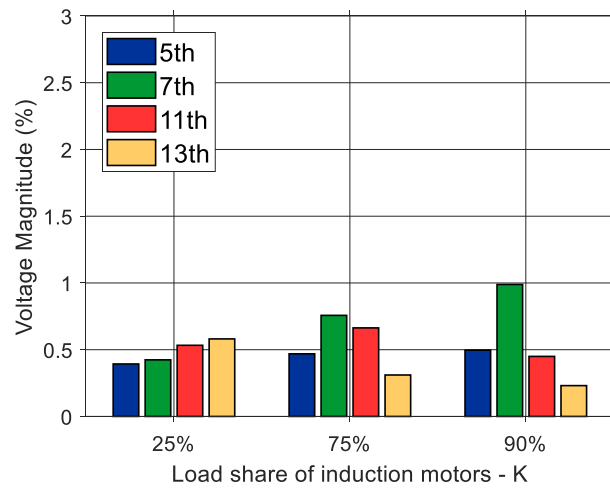


(c)

Fig. 4.9: Frequency response with variable PFC and the load composition of induction motors corresponding to (a) 25%, (b) 75%, and (c) 90% of the total load demand.



(a)



(b)

Fig. 4.10: Voltage distortion versus load composition, PFC variable. Seen from bus 3 for cases (a) 2 and (b) 3.

Similar impedance magnitudes are seen in Fig. 4.9, compared to the previous results, but variations occur in resonant frequencies, mostly because of the variable PFC capacitance. The voltage distortion displayed in Fig. 4.10 still increases with the growing share of induction motors. However, a higher sensitivity appeared on case 2 (normal operation) rather than case 3 (PFC switched off), a situation different from the previous condition.

4.6 Case study: Benchmark test system (industrial plant)

The test system presented in this subsection was proposed by the IEEE Task Force on Harmonics Modelling and it represents a typical MV/LV industrial network for harmonic studies (PAPIC et al., 2019). The test system is a 12-bus balanced industrial plant, 50 Hz, consisting of an equivalent supply with a rated short-circuit power of 3200 MVA, X/R ratio of 10, connected to a 110-20 kV substation, two loads directly connected on the main 20 kV-bus, and three 20-0.4 kV transformers supplied by separate MV lines. The parameters and system topology were adapted for frequency-domain simulation in OpenDSS and they are shown in Fig. 4.11 and Table 4.2, Table 4.3 and Table 4.4. The load, its harmonics spectrums and power factor capacitances are given in Table 4.5 and Table 4.6.

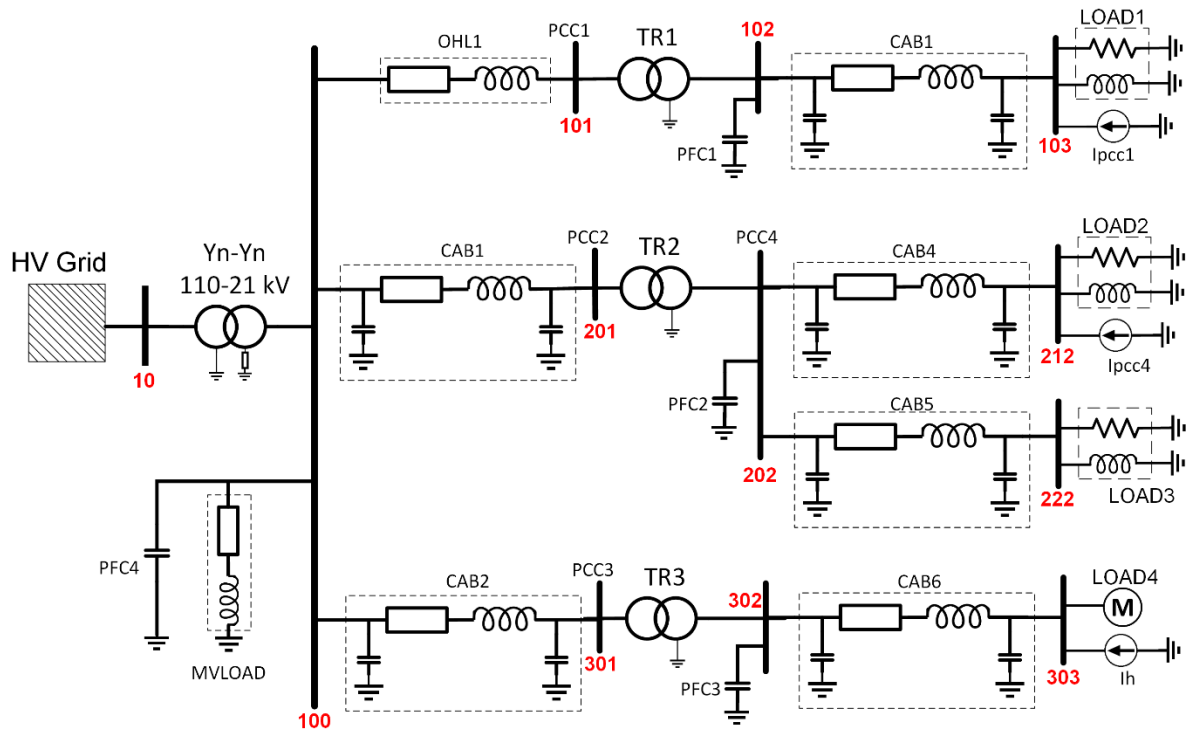


Fig. 4.11: One-line diagram of the industrial plant (adapted from (PAPIC et al., 2019)).

Table 4.2: Transformer data.

Transformer	TR01	TR02	TR03	TR04
Voltage and connection type (kV)	21-0.42 (Dyn)	21-0.42 (Dyn)	21-0.42 (Dyn)	110-21 (Yyn)
Rated power (MVA)	0.4	1	1	20
Leakage reactance (%)	4	6	6	11
Neutral resistance	0	0	0	80 (LV)

Table 4.3: MV line data.

Line / cable	OHL1	CAB1	CAB2
Rated voltage (kV)	20	20	20
Series impedance (Ω/km)	$0.57 + j0.1194$	$0.50 + j0.1414$	$0.006 + j0.09425$
Capacitance ($\mu\text{F}/\text{km}$)	–	90	90
Length (km)	1	2	1.5

Table 4.4: LV line data.

Line / cable	CAB3	CAB4	CAB5	CAB6
Rated voltage (kV)	1	1	1	1
Series impedance (Ω/km)	$0.006 + j0.09425$	$0.002 + j0.03142$	$0.002 + j0.06283$	$0.0015 + j0.01571$
Capacitance ($\mu\text{F}/\text{km}$)	0.5	0.2	0.3	0.1
Length (km)	1	1	1	1

Table 4.5: Load and power factor correction data.

Connection busbar	100	102	103	202	212	222	302	303
Real power (MW)	7.15	–	209	–	257	160	–	200
Reactive power (MVar)	2.09	–	105	–	99	51	–	96
Rated voltage (kV)	21	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Load connection (D/Y)	D	D	Y	–	Y	Y	–	D
PFC (MVar)	1.1	0.09	–	0.125	–	–	0.05	–
PFC resistance ($\text{m}\Omega$)	363.8	5.33	–	4.05	–	–	9.59	–
PFC connection (D/Y)	Y	D	–	D	–	–	D	–

Loads 1, 2 and 4 are nonlinear loads, and a harmonic current magnitude spectrum is associated with each one, as follows in Table 4.6. It is worth mention that LOAD MV (bus 100) is a series model, LOAD3 (bus 222) is parallel, and LOAD4 (Bus 303) follows the modelling proposed for motors in Table 3.1. LOAD2 (bus 212) was not changed, following the standard harmonic modelling for OpenDSS (50/50 between series and parallel models).

Table 4.6: Harmonic current spectrum.

Harmonic order (% of fundamental)	Load		
	LOAD1	LOAD2	LOAD4
5 th order	31.92	8.05	84.0
7 th order	17.54	3.82	60.1
11 th order	13.72	2.78	38.2
13 th order	2.84	1.68	32.3
15 th order	0.28	0.32	–

4.6.1 Case study A – Load composition

The aggregated load (200 kW, PF=0.9) at Bus 303 is simulated with different aggregated proportions of induction motors (K) and resistive loads as shown in Table 4.7. PFC remained fixed for all situations. For the aggregated load model, the initial parameters X_M is 0.15 pu, K_M equals to 1.2, and K_3 is 8, resulting in the resistance (R) and reactance (X) values of Table 4.7. Then, the resistive and motive powers were calculated for inserting the load in OpenDSS. A frequency scan and the voltage distortion are seen in Fig. 4.12 and Fig. 4.13, respectively.

Table 4.7: Parameters of the aggregate load used for case study A.

K (%)	R (Ω)	X (Ω)	PFC at Bus 302 (kVAr)
25	1.176	0.441	50
75	3.528	0.147	50
90	8.820	0.123	50

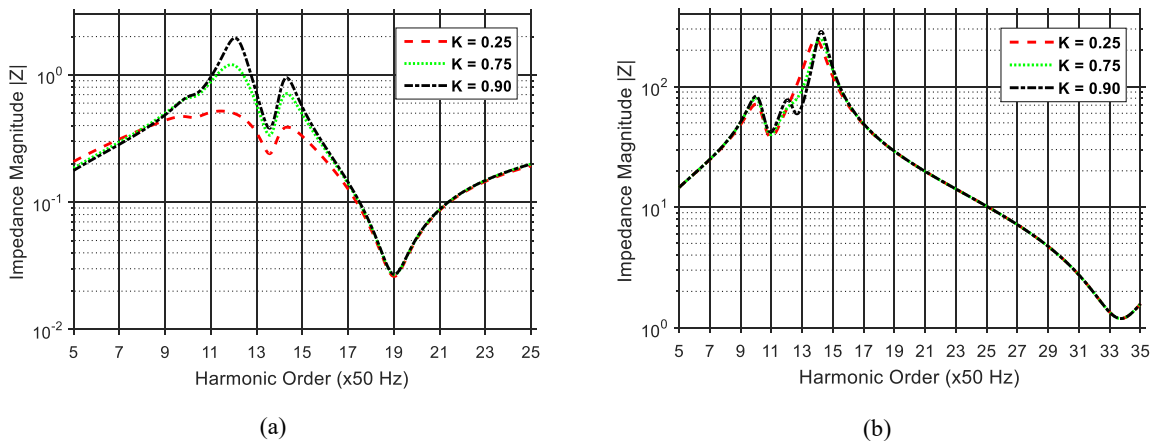
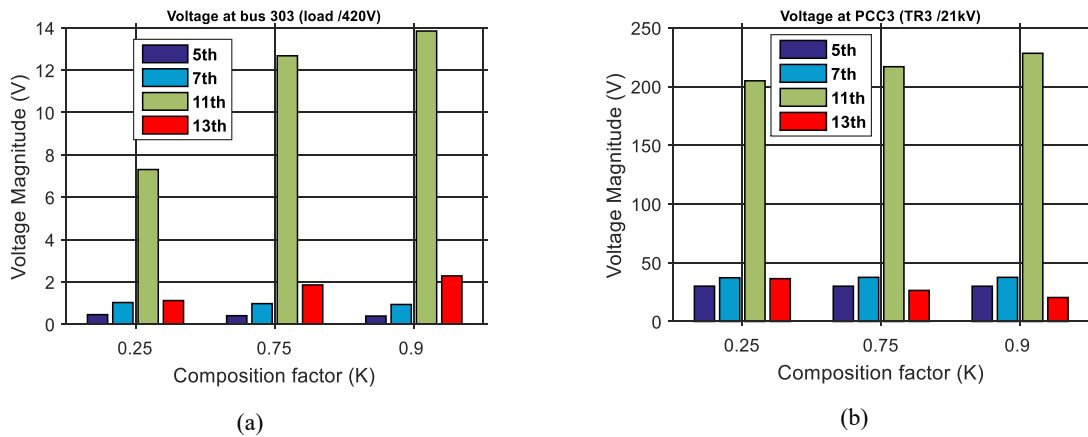
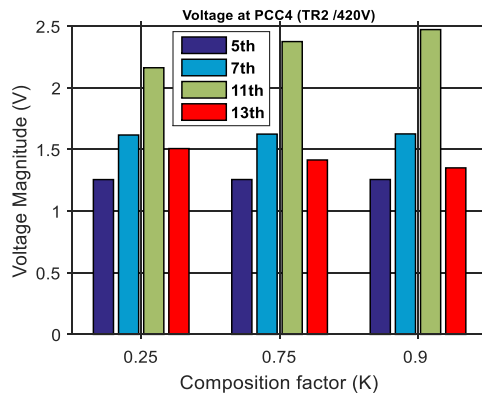


Fig. 4.12: Frequency scans seen from (a) LOAD4 - LV and (b) from PCC3 – MV.





(c)

Fig. 4.13: Voltage distortion for case A on (a) LOAD4 – LV, (b) PCC3 – MV, and (c) PCC4 – LV.

The frequency scan indicates low harmonic impedance on the LV-side of Bus 303, but a large variation among the load compositions around the resonant points. For PCC3, an MV-bus, the differences among the compositions are lower than the LV-bus, but the peak resonance reaches higher values. The voltage distortion plots corroborate this affirmative.

The plot (c) of Fig. 4.13 takes the voltage distortion on a line parallel to the points of (a) and (b). It shows that PCC4 is a bus electrically distant from the distortions caused by LOAD4, and the load composition causes minimum interference on that bus.

4.6.2 Case study B – Load composition plus reactive compensation

The load at Bus 303 was simulated with the same aggregation proportions between induction motors (K) and resistive loads as before, but now a reactive compensation follows the composition. The PFC was corrected to provide reactive compensation to the load on each scenario. The plots for frequency scan and voltage distortion are seen in Fig. 4.14 and Fig. 4.15, respectively.

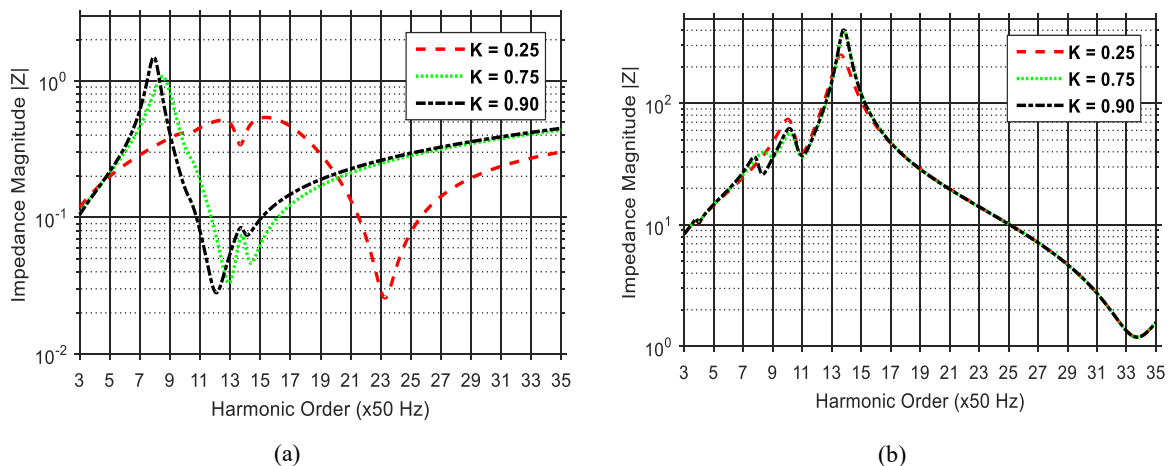


Fig. 4.14: Frequency scans seen from (a) LOAD4 – LV and (b) from PCC3 – MV for case B.

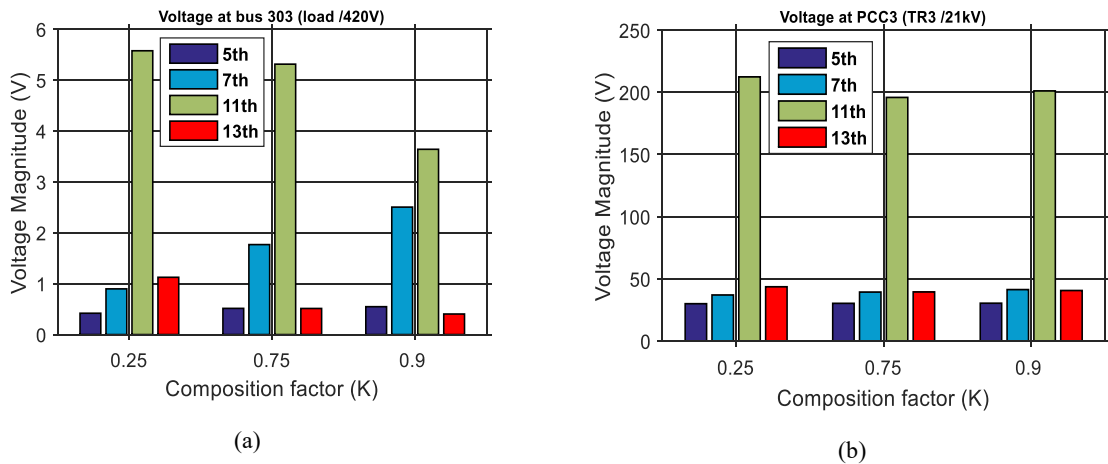


Fig. 4.15: Voltage distortion for case B on (a) LOAD4 – LV and (b) PCC3 – MV.

The frequency scan shows a high variability of the resonant points, both in magnitude and frequency. A major share of induction motors ($K = 0.9$) still has the highest resonant peak on the system impedance. However, a higher K caused a smaller voltage distortion, especially on the bus where the aggregated load is connected. This difference is less discernible in the MV-bus (Fig. 4.15-b).

4.7 Harmonic impedance considering different voltage levels

This subsection presents an investigation on harmonics in a power system at different voltage levels, using the frequency scan to identify the impedance profile. The line length at different voltage levels, the load composition, as well as the resonant frequencies of a T-equivalent system are objects of a parametric study. The power system was modelled as three-phase, 60 Hz, 230-kV supply, with five main buses and three voltage levels. The topology and electrical parameters are given in Fig. 4.16, and Table 4.8 to Table 4.12.

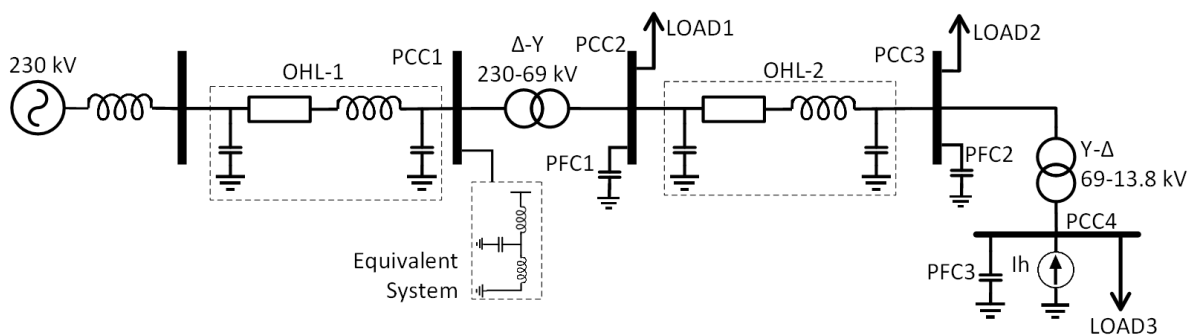


Fig. 4.16: One-line diagram of the 230-kV power system.

Table 4.8: Transformer data.

Transformer	230-69 kV	69-13.8 kV
Connection type	Dy	Yd
Rated power (MVA)	45	15
Leakage reactance (%)	10.6	10
Non-load losses (%)	0.18	0.107

Table 4.9: 69-kV line data (OHL2).

Z_1 (Ω /km)	0.07463+j0.34182
Z_0 (Ω /km)	0.28968+j 1.29655
C_1 (η F/km)	13.03047
C_0 (η F/km)	4.610135
Ground resistivity (Ω /m)	1500
Length (km)	20

Table 4.10: 230-kV line data (OHL1).

Conductor type	2x ACSR 795 AWG TERN		
Ground wires	2x Galvanized Steel Cable 3/8 in.		
Characteristic Impedance (Ω)	375		
Ground resistivity (Ω /m)	1500		
Length (km)	130		
Line geometry			
Phase	X (m)	Y tower (m)	Y minimum (m)
1	-3.4	25.6	15
2	0	30	20
3	3.4	25.6	15
0	-2.85	33.1	30
0	2.85	33.1	30

Table 4.11: Load and power factor correction data.

Connection busbar	PCC2	PCC3	PCC4
Real power (MW)	5.0	5.0	0.746
Reactive power (MVar)	0.83	0.83	0.247
Rated voltage (kV)	69	69	13.8
Load connection (D/Y)	Y	Y	Y
PFC (MVar)	0.83	0.83	0.247
PFC connection (D/Y)	Y	Y	Y

Table 4.12: Loads connected for the standard scenario.

	X_m	0.2	K_m	1.2
	K_3	8	$\tan(\phi)$	0.6634
Busbar	K (%)	R (Ω)	X (Ω)	PFC (kVAr)
PCC2	25	1270	634.8	829
PCC2	25	1270	634.8	829
PCC4	25	80.7	30.3	247

For the equivalent 230-kV system connected in PCC1, the equations presented in section 3.5 were used to build the representative T-branch. An $S_{SC} = 2000 \text{ MVA}$, a parallel frequency of 500 Hz, a series frequency of 1 kHz, and a resistance of 15 Ω were defined as the characteristic parameters of this equivalent system. All observations were made from PCC4, unless otherwise stated.

4.7.1 Varying the line length – 69 kV

This scenario is a sensitivity study of the system impedance seen from the 13.8 kV-bus (PCC4) as a function of the line length in the sub-transmission system (69 kV). The lengths vary from 20, 40 or 60 km and can be seen in Fig. 4.17.

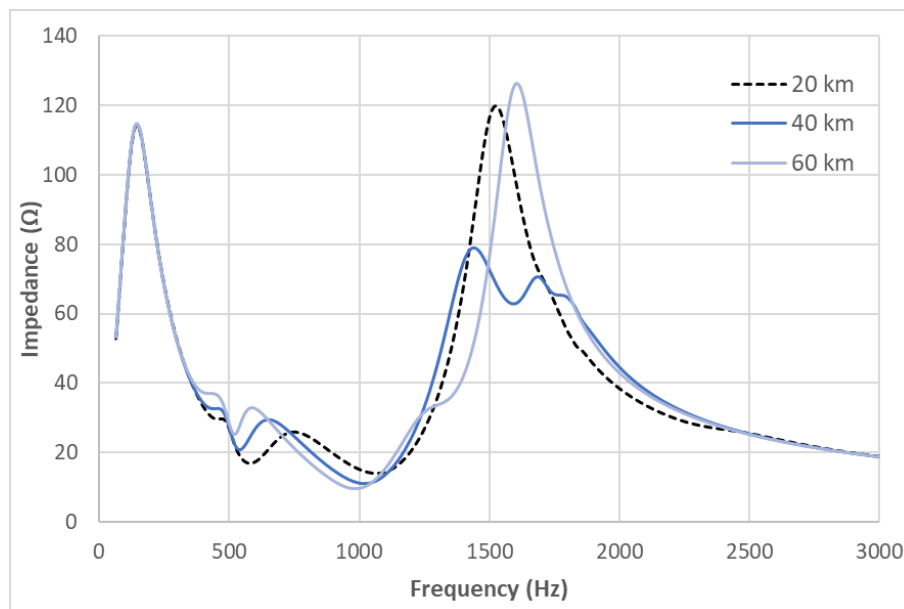


Fig. 4.17: Frequency scan as a function of the line length variation – 69 kV.

Variation of a 69 kV-based line length impacted frequency resonances around 500 Hz and 1500 Hz. It was expected an increase in the magnitude of peak resonances as function of the line length, but a major damping was observed for the length of 40 km. That would be an indicative of ferro resonance, since the system has two power transformers.

The system impedance is then observed with length variations around 40 km, in steps of 3 kilometres. This is a simple test to verify a possible ferro resonance condition by observing the sensitivity of the impedance to small length variations. Fig. 4.18 displays a high sensitivity around 1500 Hz for a line length of approximately 40 km, indicating a ferro resonance situation.

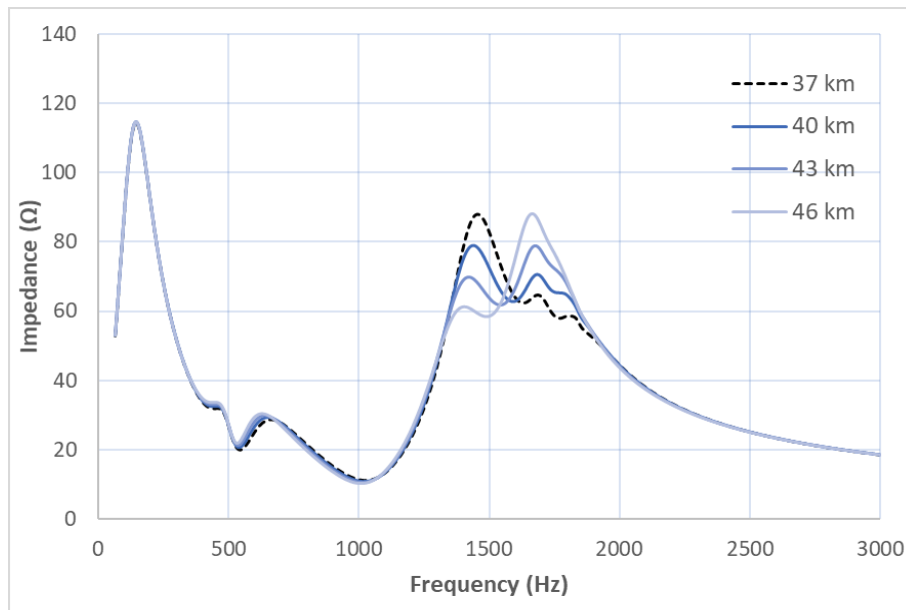


Fig. 4.18: Impedance sensitivity test to verify ferro resonance condition.

4.7.2 Varying the line length – 230 kV

A similar approach to the previous scenario was done for the transmission line at 230 kV. Lengths varied from 65 km (half the regular line length) to 390 km (three times the regular line length). The results are shown in Fig. 4.19 and Fig. 4.20.

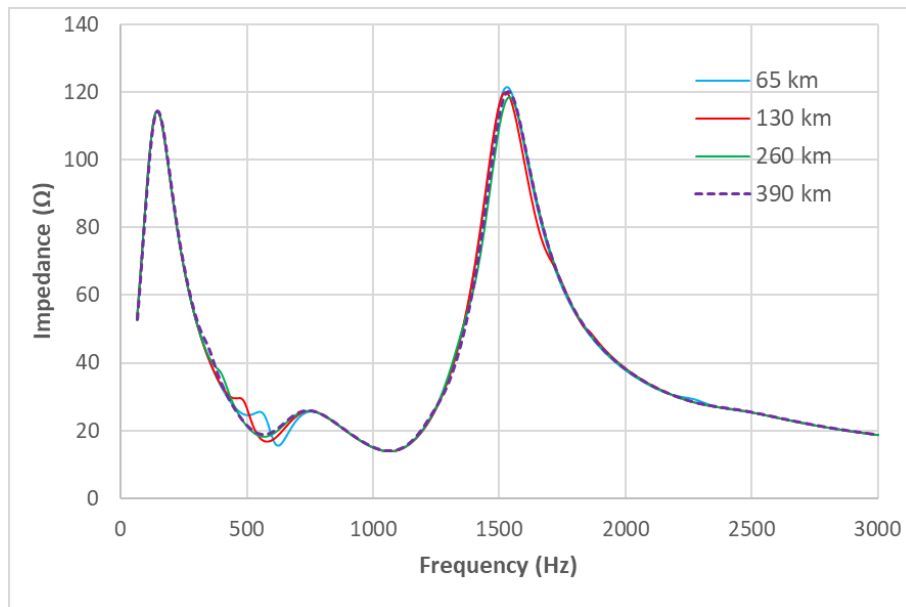


Fig. 4.19: Frequency scan as a function of the line length variation – 230 kV.

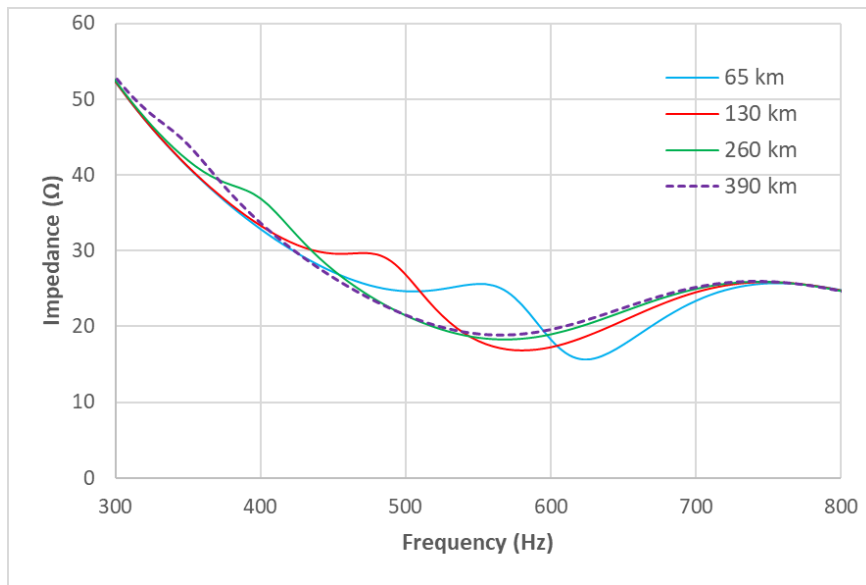


Fig. 4.20: Detail of the frequency scan around 500 Hz – 230 kV.

Small variations near 500 Hz was observed. This may be caused by the parallel resonance present in the equivalent system installed at 230 kV. Thinking about two parallel loads (A and B), and A tends to infinity, the resultant impedance is close to impedance B. But in overall, the results show that minor differences were observed for the 230-kV level.

4.7.3 Varying the load composition – 69 kV

Load composition is the main topic of this dissertation and a harmonic study as a function of three different load compositions were performed for this test system. The load parameters are in Table 4.13 and the frequency scan is shown in Fig. 4.21.

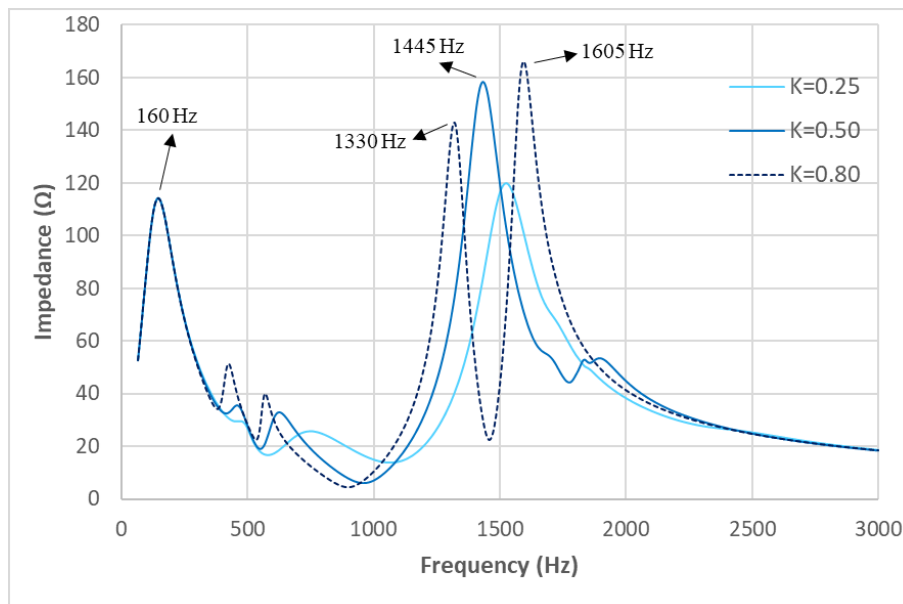


Fig. 4.21: Frequency scan as a function of load compositions – 69 kV.

Table 4.13: Load composition – 69 kV.

X_m	0.2	K_m	1.2
K_3	8	$\tan(\varphi)$	0.6634
K (%)	R (Ω)	X (Ω)	PFC (kVAr)
25	1270	634.8	829
50	1904	317	1659
80	4761	198	2654

The composition of the loads in the 69-kV level presented a great impact on the system impedance, both in frequency and magnitude. Impedance peak increased up to 35% among the cases. Aggregated loads major composed by motors ($K > 0.7$) tend to present higher impedance peaks and resonant frequencies than loads majorly resistive.

4.7.4 Varying the resonant frequency in the equivalent system – 230 kV

This scenario analyses the effects of different parallel resonances in the equivalent system connected at PCC1. The parallel resonances varied from 350 Hz to 800 Hz, while the series resonance remained constant. The result is seen in Fig. 4.22.

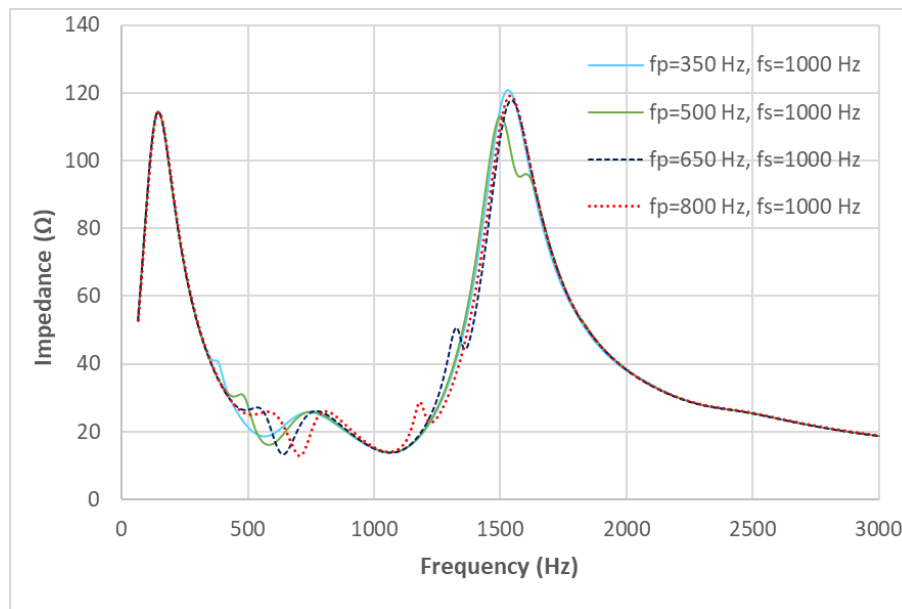


Fig. 4.22: Frequency scan as a function of resonances in the equivalent system – 230 kV.

Varying the resonances of the equivalent had small impacts on the overall system impedance, not causing severe changes nearby the parallel resonant points when observed from the MV-bus (PCC4).

4.7.5 Varying the short-circuit power at the equivalent system – 230 kV

The last scenario is a frequency scan evaluation of the equivalent system, disconnected from the main 230-kV system, for demonstration of the resonance peak sensitivity with the variability of the short-circuit power. Initially, three powers are analysed (1000, 2000, and 3000 MVA) for a series resistance of 15 Ω, and the frequency scan is shown in Fig. 4.23.

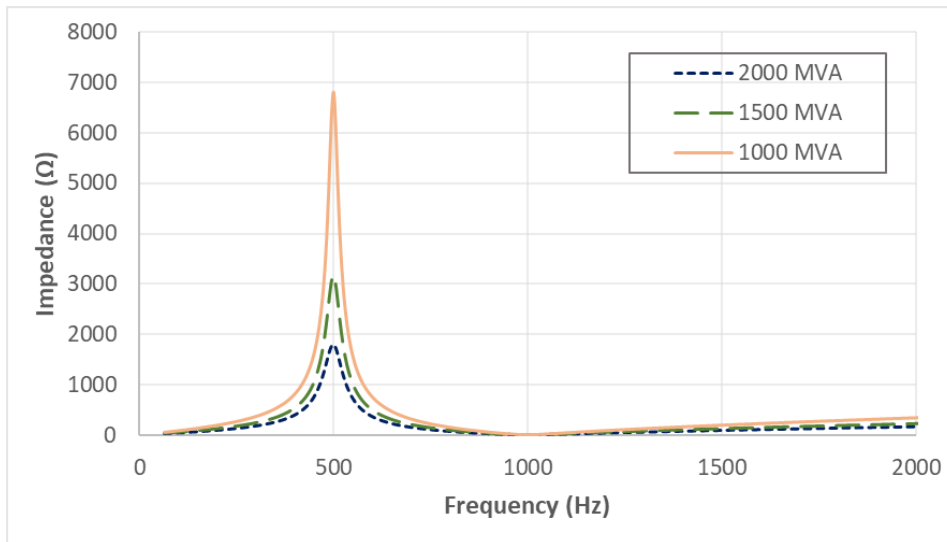


Fig. 4.23: Frequency scan as a function of the short-circuit power in the equivalent system.

It can be observed that the resonance peak increases as the short-circuit power decreases and that situation can be a concern, especially for weak power systems and microgrids. Now, the short-circuit power is analysed for the same three values but with a resistance of 150 Ω in series to each inductance, and the results are displayed in Fig. 4.24.

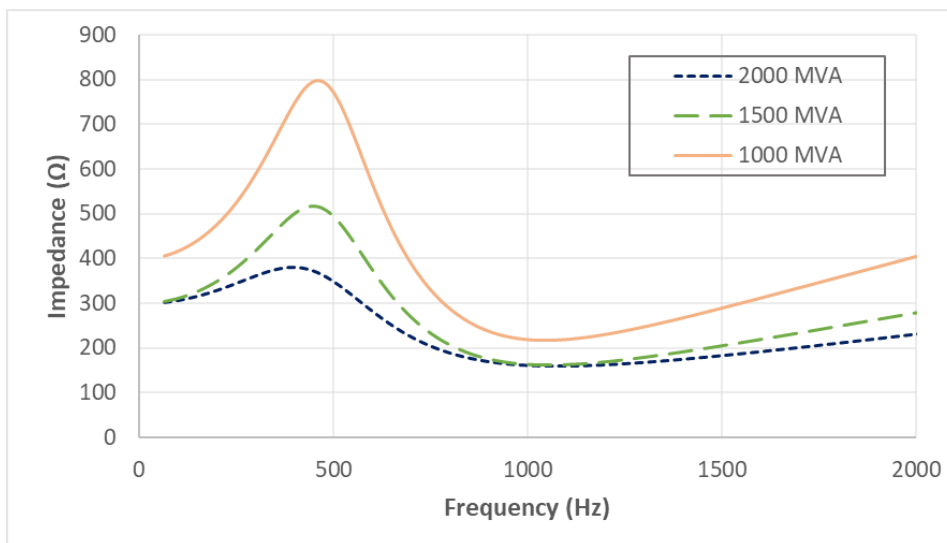


Fig. 4.24: Frequency scan as a function of the short-circuit power in the equivalent system and R=150 Ω.

This new scenario has a resistance ten times bigger than the previous one, and the resonance peak has decreased considerably. The most important aspect of this scenario is the variation of the parallel resonance frequency as a function of the short-circuit power (S_{SC}). The higher is S_{SC} , the higher the deviation becomes from the reference frequency of 500 Hz. This situation is in accordance with (RIBEIRO, 1985), in which the harmonic impedance was performed from real measurements of a 132 kV system.

Although OpenDSS was not the friendliest software for building equivalent loads using proper ohmic values or traditional units as Faraday and Henry, an alternative approach was performed using the *reactor* and *capacitor* models, which made possible the frequency scan, but the voltage distortion did not work as expected.

5. DISCUSSION OF THE RESULTS

The case studies have shown how different load models and compositions may impact harmonic analyses. Some observations are pointed below:

- Load composition has considerable influence over the magnitude and the frequency of the resonant peaks.
- Capacitors should be modelled as accurately as possible, including filters of PV inverters, smart grid devices, and other electronic-based loads.
- Most harmonic discrepancies using the aggregated linear load models occur particularly near the parallel resonant points of the grid. Incorrect modelling of linear loads may lead to unrealistic harmonics evaluations.
- The induction motor model was proposed for a low or moderate share of motors in an aggregated linear load. Therefore, this model is slightly superior to the series and parallel models in this study case.
- Despite the superiority of a load model for a specific range of frequencies, there are no arguments to support that one model can provide the best fitting for all frequency spectra.
- Representation of motor loads should not derive directly from power measurements, but instead, the locked-rotor impedance (for an induction motor) should be used as a parameter to correct the power demand.
- Topology changes modify the system impedance, including resonant points. Some studies may require evaluation of harmonics as a function of topology changes in order to address harmonic compliance.
- Network equivalents for harmonic studies should consider at least the first two resonant points, but it is not recommended to use an equivalent at busbars close to the point of common coupling (PCC) for harmonic evaluation.
- OpenDSS should be used carefully when modelling high voltages. Even if the result converges, some aspects can be lacking physical meaning due to unrealistic results.

5.1 Final considerations

Load models and system equivalents affect harmonic voltages in both magnitude and angle differences. Thus, the resonant frequencies might have impacts from all electrical components, and not just the transmission lines. Some aspects of load modelling are still unclear, such as the inclusion of uncertainties in project design and needs further investigation. For instance, background harmonics play an important role in harmonic studies, such as for hosting capacity evaluation on modern power systems and should be considered whenever is possible.

Parameters for the proper modelling of nonlinear loads are usually under commercial confidentiality, with restricted access to the manufacturer. An alternative solution is the assessment of harmonic component models through measurements; however, good verification methods are still pending.

6. CONCLUSION AND RECOMMENDATIONS

This master's dissertation presented a state-of-art of harmonic studies with a review focused on techniques for harmonic modelling in a smart grid scenario for power systems – including the insertion of DER and electronic-based loads. The main task aimed the proper modelling of electric components to address some challenges that may occur in power distribution networks with the increasing penetration of DG and energy-efficient loads, using the modelling tools existent in the open-source software OpenDSS.

The proposed cases presented a series of harmonic studies focusing on the impacts of aggregated linear loads modelling on the system impedance and voltages. The results show that different modelling representations have significant differences near the parallel resonant points, and load composition may impact voltage distortion and system resonance. Moreover, capacitors banks cause large impacts on harmonic resonances while resistive linear loads influence the harmonic damping, and therefore, they should be precisely represented in the simulations.

Harmonics studies usually have a minor concern for DG connection, however, with the insertion of new types of loads and more dynamic behaviours – *e.g.* electrical vehicles, demand response, and electronic-based loads – it is recommended doing harmonic studies for connection of new distributed generators and capacitors for power factor correction. There is a growing need in the electric power sector for not only improved measurement techniques for harmonics levels but also the estimation of future levels based on changing circumstances.

6.1 Recommendations for further work

- Perform a comprehensive evaluation of loads and distributed generators through experiments in real-time simulators and measurements done in distribution and transmission networks, for better understanding of electric performance metrics;
- Evaluate the application of different techniques, *e.g.* time-series, statistical analysis, clustering, artificial neural networks (ANN) for practical modelling and simulation of aggregated load models under different operating conditions.

- Assessment of uncertainties in harmonic studies at all frequencies (probabilistic harmonics approach), including non-harmonic frequencies. This includes properly addressing uncertainty in measurement errors, component modelling, filtering design, and data processing.
- Discuss and review the grid-codes, focusing on enhanced techniques involving the assessment of responsibilities for harmonic-emission in the presence of multiple sources and an investigation of the insertion procedures for harmonic filters in wind farms. Harmonic filters may difficult the detection of dominant harmonic sources, causing unnecessary resonances in the grid and adding financial costs on filters wrongly placed.
- Evaluate harmonic propagation in systems with high penetration of renewables – such as microgrids and weak distribution networks – and electronic-based converters, especially regarding new mitigation techniques using control techniques in power converters (CSI – Current Source Inverters and VSI – Voltage Source Inverters) along with an advanced metering infrastructure (AMI).
- With the advent of smart cities, lots of sensors, electronic devices, power systems, transportation, and communication networks would be interconnected. EMC and EMI are two areas of growing research interest in the context of smart cities, which harmonic studies have a considerable role in the progress of those fields.

6.2 Philosophical assessment of harmonics and distributed generation

Harmonics cause disturbances in the quality of power supply and they can be propagated to another point of the electrical power system because the system impedance is one dependent variable for this propagation.

Distributed generation is not the unique issue related to harmonic emission, but an aggregated effect of multiple distributed sources interacting with loads and the power grid is a concern, mainly because the possible undesired effects that interaction may cause. The technical and economic issues are usually focused on when thinking about possible solutions, but there are also environmental, social, and legal aspects that should be considered. Unfortunately, most

energy utilities and grid operators test only the technical and financial feasibility of distributed energy systems (VON WIRTH; GISLASON; SEIDL, 2018).

The integration of renewable energy sources should stimulate reflections on the different aspects in which it can impact, directly or indirectly. For example, the initial questions one could be asking are the following:

Are the investors in renewable sources not losing revenues coming from distribution and generation utilities, so that they burden the end-consumer to compensate economic losses?

And who should pay for changes in the electricity sector, lower carbon emissions and the mitigation of quality problems?

These issues do not yet have a definitive answer, since they address much larger but interacted issues, such as the impact on energy tariffs in social classes, social justice in access to the electricity grid, and ethical aspects related to the generalized individualization of profits and socialization of costs within the electric sector.

One aspect involving harmonics and distributed generation that can be highlighted is the responsibility of harmonic emission in power grids (MINAMI, 2018). The definition of harmonic responsibility among stakeholders – whether it is the distribution or transmission utility, the investor, the prosumer, or even the regular end-consumer – should consider social, environmental, legal aspects, and not just an economic criterion to achieve the social welfare. For example, is it convenient to increase the costs for the consumer and benefit only the investors or the utilities? The poor implementation of DG in distribution systems can increase dispute between stakeholders (OLIVEIRA, 2018). That is why robust legislation is needed to ensure that neither party is unfairly burdened.

Another aspect to be considered is the increase of jobs derived from the integration of renewables to the power grid. This is a positive impact because it creates a range of downstream jobs in infrastructure projects, system operation, maintenance, manufacturing, among others (ODARNO; MARTIN; ANGEL, 2015). Good energy policies along with competitive investors and qualified workforce are essential points for promoting social welfare, economic growth and environmental sustainability.

Equality is a term that tends to consider stakeholders in a uniform manner and tends to ignore typical aspects of each. Social fairness is a more suitable term to describe the philosophical aspects mentioned. All the issues addressed in this sub-topic were brought to the

reader's attention because they are relevant subjects, but often ignored or left in the background when designing investment guidelines and engineering projects involving distributed renewable generation. These questions are left here for more detailed reflection in future works and are not addressed in this dissertation.

PUBLISHED AND SUBMITTED PAPERS

Book chapter:

RIBEIRO JR., L.C.; VIEIRA, F.L.; BONATTO, B.D.; RIBEIRO, P.F.; SOUZA, A.C.Z. Modelling and Simulation of Active Electrical Distribution Systems Using the OpenDSS. In: **Decision-Making Applications in Modern Power Systems**. Ch.5. Elsevier Academic Press (accepted). 2019.

Conference paper:

VIEIRA, F.L.; RIBEIRO, P.F.; BONATTO, B.D.; OLIVEIRA, T.E.C. Harmonic Studies in OpenDSS Considering Renewable DG and Aggregate Linear Load Models. **13th IEEE International Conference on Industry Applications (INDUSCON)**, São Paulo, BR, p. 202–207, 2018. DOI: [10.1109/INDUSCON.2018.8627343](https://doi.org/10.1109/INDUSCON.2018.8627343)

Other publications:

VIEIRA, F.L.; SANTOS, P.H.M.; CARVALHO FILHO, J.M.; LEBORGNE, R.C.; LEITE, M.P. A Voltage-Based Approach for Series High Impedance Fault Detection and Location in Distribution Systems Using Smart Meters. **Energies**, v. 12, n. 15, p. 3022, 2019. DOI: [10.3390/en12153022](https://doi.org/10.3390/en12153022)

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APPENDIX A - Simulation codes for OpenDSS and MATLAB

One-bus test system

Model Sensitivity – Frequency Scan (OpenDSS)

```
//-----//
//Nome: Francinei L Vieira # e-mail: nei@unifei.edu.br
//-----//
//Test system 1 - Harmonic Analysis - Model Sensitivity
//-----//

clear
set defaultBaseFrequency=60
!set datapath="%homepath%\OneDrive\EC331\Modelagem OpenDSS\DSS Files"

//-----//
//Eq. Thevenin
//-----//
new circuit.Test1_11kv bus1=12 !ok
~ basekv=13.8 pu=1.0 basefreq=60 mvasc3=30 mvasc1=30

//-----//
// READ IN SCAN SPECTRUM; NUMHARM WILL BE SET TO ACTUAL POINTS FOUND
New spectrum.harmspec numharm=1000 csvfile=spectrum_isource.csv
// Define a spectrum for the scan source
New spectrum.Scanspec numharm=1000 csvfile=ScanSpectrum.csv

// SET DEFAULT SOURCE HARMONICS TO FUNDAMENTAL ONLY
// ALL OTHER FREQUENCIES WILL BE ZERO (SHORTED)
Spectrum.defaultvsources.numharm=1

// KEEP LOADS FROM INJECTING HARMONICS, TOO
// ALL CURRENTS BUT FUNDAMENTAL WILL BE ZERO (OPEN)
Spectrum.defaultLoad.numharm=1

//-----//
//Harmonic Source
//-----//
new isource.Ih1 bus1=12.1 phases=1 amps=1 spectrum=Scanspec

//-----//
//Capacitor bank - Power Factor Correction
//-----//
new capacitor.PFC bus1=12 kvar=247 kv=13.8
```

Model Sensitivity – Frequency Scan (MATLAB)

```
% Example of using Matlab - Test system 1 - Model Sensitivity (Z)
clear; clc

% execute DSSStartup.m
[DSSStartOK, DSSObj, DSSText] = DSSStartup;

if DSSStartOK
    DSSText.command='set datapath= "C:\Users\neill0k\OneDrive\EC331\Modelagem
OpenDSS\DSS Files"'
    DSSText.command='Compile (Model Sensitivity - Freq_scan.dss)'; %OpenDSS
complimentary code
    % Set up the interface variables
    DSSCircuit=DSSObj.ActiveCircuit;
    DSSSolution=DSSCircuit.Solution;
    DSSText.Command='New Monitor.Zscan element=isource.Ih1 1 mode=0';
```

```

for m=1:3 % Test of the three load models
    if m==1
        DSSText.Command='new Load.m1 bus1=12 kv=13.8 kw=371.5 pf=0.833
%seriesRL=100';
        DSSText.Command='set NeglectLoadY=N';
        DSSText.Command='new Load.Res bus1=12 kv=13.8 kw=371.5 pf=1 %seriesRL=100';
    elseif m==2
        DSSText.Command='edit Load.m1 bus1=12 kv=13.8 kw=371.5 pf=0.833
%seriesRL=0';
        DSSText.Command='set NeglectLoadY=N';
        DSSText.Command='edit Load.Res bus1=12 kv=13.8 kw=371.5 pf=1 %seriesRL=0';
    elseif m==3
        DSSText.Command='edit Load.m1 bus1=12 kv=13.8 kw=185.75 kvar=1486
%seriesRL=0';
        DSSText.Command='set NeglectLoadY=N0';
        DSSText.Command='edit Load.Res bus1=12 kv=13.8 kw=371.5 pf=1 %seriesRL=0';
    end

    DSSText.Command='Solve';
    DSSText.Command='solve Mode = harmonic';

    % display the result
    disp(['Result=' DSSText.Result])
    if DSSSolution.Converged
        a = 'Solution Converged';
    else
        a = 'Solution did not Converge';
    end
    disp(a)

    % export voltages and Plot - call function
    DSSMon=DSSCircuit.Monitors;
    DSSMon.name='Zscan';
    Volt(m,:) = ExtractMonitorData(DSSMon,1,1.0);
    Volt(m,1)=Volt(m,2);
    Order(m,:)= ExtractMonitorData(DSSMon,0,216000.0);
end

data = [Order(1,:); Volt];
freq = length(csvread('scanspectrum.csv'));
%Graph Plot
figure(2)
semilogy(Order(1,:),Volt(1,:),'k:',Order(2,:),Volt(2,:),'r-
.',Order(3,:),Volt(3,:),'c',...
'LineWidth',2) %Order(4,:),Volt(4,:),
grid
vet(1:(round(freq/12)+3)/2)=0;
c=1;
vet(1)=1;
for c=1:15
    vet(c+1)=5*c;
end
axis([1 40 3 5*10^2])
ax = gca;
ax.FontSize = 12;
ax.TickDir = 'out';
ax.XTick = vet(1:11);
legend({'Series','Parallel','Induction Motor'],'FontSize',13,'FontWeight','bold',...
'Location','northeast')
xlabel('Harmonic Order (x60 Hz)')
ylabel('System Impedance (\Omega)')
dlmwrite('Graphs\Model Sensitivity - Freq Scan\FSdata.csv',data)

else
    a = 'DSS Did Not Start';
    disp(a)
end

```

Constant Load Composition – Frequency Scan (OpenDSS)

```

//-----//
//Nome: Francinei L Vieira # e-mail: nei@unifei.edu.br

```

```

//-----//
//Test system 1 - Harmonic Analysis - Load composition (fixed)
//-----//

clear
set defaultBaseFrequency=60

//-----//
//Equival. Thevenin
//-----//
new circuit.Test1_13kv bus1=12 !ok
~ basekv=13.8 pu=1.0 freq=60 mvasc3=30 mvasc1=30

//-----//
// READ IN SCAN SPECTRUM; NUMHARM WILL BE SET TO ACTUAL POINTS FOUND
New spectrum.harmspec numharm=1000 csvfile=spectrum_isource.csv
// Define a spectrum for the scan source
New spectrum.Scanspec numharm=1000 csvfile=ScanSpectrum.csv

// SET DEFAULT SOURCE HARMONICS TO FUNDAMENTAL ONLY
// ALL OTHER FREQUENCIES WILL BE ZERO (SHORTED)
Spectrum.defaultvsources.numharm=1

// KEEP LOADS FROM INJECTING HARMONICS, TOO
// ALL CURRENTS BUT FUNDAMENTAL WILL BE ZERO (OPEN)
Spectrum.defaultLoad.numharm=1

//-----//
//Harmonic Source
//-----//
new isource.Ih1 bus1=12.1 phases=1 amps=1 spectrum=Scanspec

//-----//
//Capacitor bank - Power Factor Correction
//-----//
new capacitor.PFC bus1=12 kvar=247 kv=13.8

// ADD SOME MONITORS TO CAPTURE THE RESULTS
// SINCE SCAN SOURCE IS 1 A, THE VOLTAGE = IMPEDANCE
New Monitor.Zscan element=isource.Ih1 1 mode=0

```

Constant Load Composition – Frequency Scan (MATLAB)

```

% Example of using Matlab - Test system 1 - Load Composition
clear; clc

% execute DSSStartup.m
[DSSStartOK, DSSObj, DSSText] = DSSStartup;

if DSSStartOK
    DSSText.Command='Compile (C:\Users\neill0k\OneDrive\EC331\Modelagem OpenDSS\DSS
Files\Load Comp - Freq_scan.dss)';
    % Set up the interface variables
    DSSCircuit=DSSObj.ActiveCircuit;
    DSSSolution=DSSCircuit.Solution;

    % Solve executes the solution for the present solution mode.
    freq = length(csvread('scanspectrum.csv'));
    for m=1:3
        if m==1 %Model 4 - Induction motor >> K = 0.25
            DSSText.Command='new Load.m1 bus1=12 kv=13.8 kw=557.25 kvar=1486
%seriesRL=0';
            DSSText.Command='set NeglectLoadY=N';
            DSSText.Command='new Load.Res bus1=12 kv=13.8 kw=557.25 pf=1 %seriesRL=0';
        elseif m==2 %Model 4 - Induction motor >> K = 0.75
            DSSText.Command='edit Load.m1 bus1=12 kv=13.8 kw=185.75 kvar=4458
%seriesRL=0';
            DSSText.Command='edit Load.Res bus1=12 kv=13.8 kw=185.75 pf=1 %seriesRL=0';
        elseif m==3 %Model 4 - Induction motor >> K = 0.9
            DSSText.Command='edit Load.m1 bus1=12 kv=13.8 kw=74.3 kvar=5349.6
%seriesRL=0';
            DSSText.Command='edit Load.Res bus1=12 kv=13.8 kw=74.3 pf=1 %seriesRL=0';
        end
    end
end

```

```

DSSText.Command='Solve';
DSSText.Command='Solve Mode = harmonic';

% display the result
disp(['Result=' DSSText.Result])
if DSSSolution.Converged
    a = 'Solution Converged';
else
    a = 'Solution did not Converge';
end
disp(a)

% export all the voltages to csv and read back in and Plot
DSSMon=DSSCircuit.Monitors;
DSSMon.name='Zscan';
Volt(m,:) = ExtractMonitorData(DSSMon,1,1.0);
Volt(m,1)=Volt(m,2);
Order(m,:)= ExtractMonitorData(DSSMon,0,216000.0);
end

data = [Order(1,:); Volt];
freq = length(csvread('scanspectrum.csv'));
%Graph Plot
semilogy(Order(2,:),Volt(2,:),'r-.',...
    Order(3,:),Volt(3,:),'g',Order(1,:),Volt(1,:),'k:', 'LineWidth',2)
grid
vet(1:(round(freq/12)+3)/2)=0;
c=1;
for c=1:length(vet)
    vet(c)=2*c-1;
end
axis([1 50 4 10^3])
ax = gca;
ax.FontSize = 11;
ax.TickDir = 'out';
ax.XTick = vet;
legend({'K = 0.25','K = 0.75','K = 0.90'},'FontSize',12,'FontWeight','bold',...
    'Location','northeast')
xlabel('Harmonic Order (x60)')
ylabel('Impedance Magnitude')
dlmwrite('Graphs\Load Comp FS\dataLCZ.csv',data)

else
    a = 'DSS Did Not Start';
    disp(a)
end

```

Varying Load Composition – Frequency Scan (OpenDSS)

```

//-----//
//Nome: Francinei L Vieira # e-mail: nei@unifei.edu.br
//-----//
//Test system 1 - Harmonic Analysis - Var. Load composition
//-----//

clear
set defaultBaseFrequency=60

//-----//
//Eq. Thevenin
//-----//
new circuit.Test1_13kv bus1=12 !ok
~ basekv=13.8 pu=1.0 basefreq=60 mvasc3=30 mvasc1=30

//-----//
// READ IN SCAN SPECTRUM; NUMHARM WILL BE SET TO ACTUAL POINTS FOUND
New spectrum.harmspec numharm=1000 csvfile=spectrum_isource.csv
// Define a spectrum for the scan source
New spectrum.Scanspec numharm=1000 csvfile=ScanSpectrum.csv

// SET DEFAULT SOURCE HARMONICS TO FUNDAMENTAL ONLY
// ALL OTHER FREQUENCIES WILL BE ZERO (SHORTED)

```

```

Spectrum.defaultvsources.numharm=1

// KEEP LOADS FROM INJECTING HARMONICS, TOO
// ALL CURRENTS BUT FUNDAMENTAL WILL BE ZERO (OPEN)
Spectrum.defaultLoad.numharm=1

//-----//
//Harmonic Source
//-----//
new isource.Ih1 bus1=12.1 phases=1 amps=1 spectrum=Scanspec scantype=none

// ADD SOME MONITORS TO CAPTURE THE RESULTS
// SINCE SCAN SOURCE IS 1 A, THE VOLTAGE = IMPEDANCE
New Monitor.Zscan element=isource.Ih1 1 mode=32

```

Varying Load Composition – Frequency Scan (MATLAB)

```

% Example of using Matlab - Case 1
clear; clc

% execute DSSStartup.m
[DSSStartOK, DSSObj, DSSText] = DSSStartup;

if DSSStartOK
    DSSText.Command='Compile (C:\Users\neill0k\OneDrive\EC331\Modelagem OpenDSS\DSS
Files\Varying PFC - Freq_scan.dss)'; %change directory
    % Set up the interface variables
    DSSCircuit=DSSObj.ActiveCircuit;
    DSSSolution=DSSCircuit.Solution;

    % Solve executes the solution for the present solution mode, which is "snapshot".
    freq = length(csvread('scanspectrum.csv'));
    for m=1:3 %Three parameters for the load model
        if m==1 %Model 4 - Induction motor >> K = 0.25
            DSSText.Command='new Load.m1 bus1=12 kv=13.8 kw=557.25 kvar=1486
%seriesRL=0';
            DSSText.Command='set NeglectLoadY=N0';
            DSSText.Command='new Load.Res bus1=12 kv=13.8 kw=557.25 pf=1 %seriesRL=0';
            DSSText.Command='new capacitor.PFC bus1=12 kv=13.8 kvar=123.23';
        elseif m==2 %Model 4 - Induction motor >> K = 0.75
            DSSText.Command='edit Load.m1 bus1=12 kv=13.8 kw=185.75 kvar=4458
%seriesRL=0';
            DSSText.Command='edit Load.Res bus1=12 kv=13.8 kw=185.75 pf=1 %seriesRL=0';
            DSSText.Command='edit capacitor.PFC bus1=12 kv=13.8 kvar=369.69';
        elseif m==3 %Model 4 - Induction motor >> K = 0.9
            DSSText.Command='edit Load.m1 bus1=12 kv=13.8 kw=74.3 kvar=5349.6
%seriesRL=0';
            DSSText.Command='edit Load.Res bus1=12 kv=13.8 kw=74.3 pf=1 %seriesRL=0';
            DSSText.Command='edit capacitor.PFC bus1=12 kv=13.8 kvar=443.62';
        end

        % Solve
        DSSText.Command='Solve';
        DSSText.Command='Solve mode = harmonic';

        % display the result
        disp(['Result=' DSSText.Result])
        if DSSSolution.Converged
            a = 'Solution Converged';
        else
            a = 'Solution did not Converge';
        end
        disp(a)

        % export all the voltages to csv and read back in and Plot
        DSSMon=DSSCircuit.Monitors;
        DSSMon.name='Zscan';
        Volt(m,:) = ExtractMonitorData(DSSMon,1,1.0);
        Volt(m,1)=Volt(m,2);
        Order(m,:)= ExtractMonitorData(DSSMon,0,216000.0);
    end

    data = [Order(1,:); Volt];
    %Graph Plot

```

```

figure(1)
semilogy(Order(1,:),Volt(1,:), 'k:', Order(2,:), Volt(2,:), 'r-.', ...
          Order(3,:), Volt(3,:), 'g', 'LineWidth', 2)
grid
vet(1:(round(freq/12)+3)/2)=0;
c=1;
for c=1:length(vet)
    vet(c)=2*c-1;
end
axis([1 max(vet)-4 1 10^3])
ax = gca;
ax.FontSize = 12;
ax.TickDir = 'out';
ax.XTick = vet;
legend({'K = 0.25', 'K = 0.75', 'K = 0.90'}, 'FontSize', 13, 'FontWeight', 'bold', ...
       'Location', 'northeast')
xlabel('Harmonic Order (x60)')
ylabel('Impedance Magnitude')
dlmwrite('Graphs\Varying PFC\data_Z.csv', data)

else
    a = 'DSS Did Not Start';
    disp(a)
end

```

Three-bus test system

OpenDSS main code

main.dss

```

/*-----*/
//Code by: Francinei L Vieira # e-mail: nei@unifei.edu.br
/*-----*/
Test system 2 - Primary Feeder - Modeling of Linear Loads
/*-----*/

clear
set defaultBaseFrequency=60
/*-----*/
//Eq. Thevenin
/*-----*/
new circuit.Test2_PrimF bus1=10
~ basekv=13.8 pu=1.0 mvasc3=30 mvasc1=30 basefreq=60
~ x1r1=10 x0r0=10

redirect spectrums.dss
redirect capacitors.dss
redirect isources.dss
redirect LineCodes.dss
redirect lines.dss
redirect loads.dss

new monitor.Zscan element=isource.Ih12 terminal=1 mode=32

```

spectrums.dss

```

// READ IN SCAN SPECTRUM; NUMHARM WILL BE SET TO ACTUAL POINTS FOUND
New spectrum.harmspec numharm=1000 csvfile=spectrum_isource.csv
// Define a spectrum for the scan source
New spectrum.Scanspec numharm=1000 csvfile=ScanSpectrum.csv

// SET DEFAULT SOURCE HARMONICS TO FUNDAMENTAL ONLY
// ALL OTHER FREQUENCIES WILL BE ZERO (SHORTED)
Spectrum.defaultvsources.numharm=1

```



```

// KEEP LOADS FROM INJECTING HARMONICS, TOO
// ALL CURRENTS BUT FUNDAMENTAL WILL BE ZERO (OPEN)
Spectrum.defaultLoad.numharm=1

Capacitors.dss

// Dados dos capacitores.
New Capacitor.PFC1 Bus1=11 phases=3 kvar=970 kV=13.8
!~ conn=delta R=[ .00533 .00533 .00533 ]

New Capacitor.PFC2 Bus1=12 phases=3 kvar=247 kV=13.8

Isources.dss

//Z Scan - Bus 12
//-----//
new isource.Ih12 bus1=12 phases=3 amps=1 spectrum=harmSpec scantype=none

linecodes.dss

//LineCodes
New linecode.LT1 nphases=3 BaseFreq=60 Units=km //CPFL
r1=0.2112
x1=0.2510
r0=0.8767
x0=1.6847
c1=0
c0=0

New Linecode.336ACSR_2/0N // From DSS
~ nphases=3 r1=0.169572 x1=0.380901 r0=0.468887 x0=1.28077 c1=11.4840901770342
c0=5.04542390260387
~ units=km baseFreq=60 normamps=655 emergamps=655 faultRate=0.1 pctperm=20 repair=3

Lines.dss

//Lines and cables
New Line.L1 Phases=3 Bus1=10 Bus2=11 LineCode=LT1 Length=5 units=km
New Line.L2 Phases=3 Bus1=11 Bus2=12 LineCode=LT1 Length=5 units=km

Loads.dss

//Load 1
new load.Load1 bus1=10 kv=13.8 kw=1000 pf=0.9 %seriesRL=100 Spectrum=defaultLoad
new load.Load2 bus1=11 kv=13.8 kw=2000 pf=0.9 %seriesRL=100 Spectrum=defaultLoad

!Motor
new load.M3 bus1=12 kv=13.8 kw=371.5 pf=0.833 %seriesRL=100 Spectrum=defaultLoad
set neglectLoadY=N
new load.R3 bus1=12 kv=13.8 kw=371.5 pf=1 %seriesRL=100 Spectrum=defaultLoad

Model sensitivity - Frequency Scan (MATLAB)

% Model sensitivity - Freq. Scan for Case 2 and 3
clear; clc

% execute DSSStartup.m
[DSSStartOK, DSSObj, DSSText] = DSSStartup;

if DSSStartOK
    DSSText.command='Compile (C:\Users\neill0k\OneDrive\EC331\Modelagem OpenDSS\DSS
Files\Case2_Prim_dist_syst\main.dss)';
    %DSSText.command='Compile (C:\aptis-sg2\Francinei\OneDrive\EC331\Modelagem
OpenDSS\DSS Files\Case2_Prim_dist_syst\main.dss)';
    Set up the interface variables
    DSSCircuit=DSSObj.ActiveCircuit;
    DSSSolution=DSSCircuit.Solution;

```

```

Solve executes the solution for the present solution mode.
cap = input('Deseja o capacitor no Nó 2? S/N\n','s');
if isempty(cap)
    cap = 'S';
end
switch cap
    case {'S','s'}
        DSSText.Command='edit capacitor.PFC1 Bus1=11 phases=3 kvar=970 kV=13.8
enable=Y';
    case {'n','N'}
        DSSText.Command='edit capacitor.PFC1 enable=N';
    end

Measurement from load side (bus 12) or from source side (bus 10)
DSSText.Command='edit isource.Ih12 phases=1 spectrum=scanspec bus1=12.1'; % <<<<----
--
DSSText.Command='new monitor.zscan element=isource.Ih12 1 mode=32 enabled=N';

for m=1:3
    if m==1 %Serie
        DSSText.Command='edit Load.M3 bus1=12 kv=13.8 kw=371.5 pf=0.833
%seriesRL=100';
        DSSText.Command='set NeglectLoadY=N';
        DSSText.Command='edit Load.R3 bus1=12 kv=13.8 kw=371.5 pf=1 %seriesRL=100';
    elseif m==2 %Parallel
        DSSText.Command='edit Load.M3 bus1=12 kv=13.8 kw=371.5 pf=0.833
%seriesRL=0';
        DSSText.Command='set NeglectLoadY=N';
        DSSText.Command='edit Load.R3 bus1=12 kv=13.8 kw=371.5 pf=1 %seriesRL=0';
    elseif m==3 %Ind. Motor
        DSSText.Command='edit Load.M3 bus1=12 kv=13.8 kw=185.75 kvar=1486
%seriesRL=0';
        DSSText.Command='set NeglectLoadY=N0';
        DSSText.Command='edit Load.R3 bus1=12 kv=13.8 kw=371.5 pf=1 %seriesRL=0';
    end

    DSSText.Command='Solve';
    DSSText.Command='Solve Mode = harmonic';

    display the result
    disp(['Result=' DSSText.Result])
    if DSSSolution.Converged
        a = 'Solution Converged';
    else
        a = 'Solution did not Converge';
    end
    disp(a)

    export all the voltages to csv and read back in and Plot
    DSSMon=DSSCircuit.Monitors;
    DSSMon.name='Zscan';
    Volt(m,:) = ExtractMonitorData(DSSMon,1,1.0);
    Volt(m,1)=Volt(m,2);
    Order(m,:)= ExtractMonitorData(DSSMon,0,216000.0);
end

data = [Order(1,:); Volt];
freq = length(csvread('scanspectrum.csv'));
Graph Plot
figure(2)
semilogy(Order(1,:),Volt(1,:), 'k:',Order(3,:),Volt(3,:), 'c',...
    Order(2,:),Volt(2,:), 'r-.', 'LineWidth',2)
grid
vet(1:20)=0;
c=1;
vet(1)=1;
for c=1:length(vet)-11
    vet(c+1)=5*c;
end
axis([1 max(vet)-5 3 0.5*10^3])
ax = gca;
ax.FontSize = 12;
ax.TickDir = 'out';
ax.XTick = vet(1:9);
legend({'Series','Induction Motor','Parallel'],'FontSize',13,'FontWeight','bold',...

```

```

        'Location','best')
xlabel('Harmonic Order (x60 Hz)')
ylabel('System Impedance (\Omega)')
    if upper(cap)=='S'
        dlmwrite('Graphs\ModelSens\Fsdata.csv',data)
    else
        dlmwrite('Graphs\ModelSens\Fsdata_noCap1.csv',data)
    end

end

else
    a = 'DSS Did Not Start';
    disp(a)
end

Model sensitivity - Voltage Distortion (MATLAB)

% Model sensitivity - Voltage Dist. Case 2 and 3
clear; clc

% execute DSSStartup.m
[DSSStartOK, DSSObj, DSSText] = DSSStartup;

if DSSStartOK
    DSSText.Command='Compile (C:\Users\neill0k\OneDrive\EC331\Modelagem OpenDSS\DSS
Files\Case2_Prim_dist_syst\main.dss)';
    % Otherwise, change directory

    % Set up the interface variables
    DSSCircuit=DSSObj.ActiveCircuit;
    DSSSolution=DSSCircuit.Solution;
    % Control of source or load measurement
    DSSText.Command='edit isource.Ih12 bus1=12 phases=3 spectrum=harmspec';
    % DSSText.Command='edit monitor.Zscan element=load.load1'; %Source side on

    % Optionals: Capacitor at bus 2
    cap = input('Deseja o capacitor no NODE 2? S/N\n','s');
    if isempty(cap)
        cap = 'S';
    end
    switch cap
        case {'S','s'}
            DSSText.Command='edit capacitor.PFC1 enable=Y';
        case {'n','N'}
            DSSText.Command='edit capacitor.PFC1 enable=N';
    end

    % Solve executes the solution for the present solution mode.
    for m=1:3
        if m==1 %Serie
            DSSText.Command='edit Load.M3 bus1=12 kv=13.8 kw=371.5 pf=0.833
%seriesRL=100';
            DSSText.Command='set NeglectLoadY=N';
            DSSText.Command='edit Load.R3 bus1=12 kv=13.8 kw=371.5 pf=1 %seriesRL=100';
        elseif m==2 %Parallel
            DSSText.Command='edit Load.M3 bus1=12 kv=13.8 kw=371.5 pf=0.833
%seriesRL=0';
            DSSText.Command='set NeglectLoadY=N';
            DSSText.Command='edit Load.R3 bus1=12 kv=13.8 kw=371.5 pf=1 %seriesRL=0';
        elseif m==3 %Ind. Motor
            DSSText.Command='edit Load.M3 bus1=12 kv=13.8 kw=185.75 kvar=1486
%seriesRL=0';
            DSSText.Command='set NeglectLoadY=N';
            DSSText.Command='edit Load.R3 bus1=12 kv=13.8 kw=371.5 pf=1 %seriesRL=0';
        end

        DSSText.Command='Solve';
        DSSText.Command='Solve Mode = harmonic';

        % display the result
        disp(['Result=' DSSText.Result])
    end
end

```

```

    if DSSSolution.Converged
        a = 'Solution Converged';
    else
        a = 'Solution did not Converge';
    end
    disp(a)

    % export all the voltages to csv and read back in and Plot
    DSSMon=DSSCircuit.Monitors;
    DSSMon.name='Zscan';
    Volt(m,:) = ExtractMonitorData(DSSMon,1,1.0*13800/(sqrt(3)*100));
    Order(m,:)= ExtractMonitorData(DSSMon,0,216000.0);
end

data = [Order(1,:); Volt];
freq = length(csvread('spectrum_isource.csv'));
%Graph Plot
figure(2)
b=bar([data(2,2:5);data(3,2:5);data(4,2:5)],...
    'LineWidth',1);
b(1).FaceColor = '[0 .2 .6]';
b(2).FaceColor = '[0 .6 .2]';
b(3).FaceColor = '[1 .2 .2]';
b(4).FaceColor = '[1 .8 .4]';

grid
ax = gca;
ax.YLim = [0 3];
ax.FontSize = 13;
ax.TickDir = 'out';
ax.XTickLabel = [1 2 3];
legend({'5th', '7th', '11th', '13th'}, 'FontSize',16,...
    'Location','northeast')
xlabel('LOAD MODEL #')
ylabel('Voltage Magnitude (%)')
dlmwrite('Graphs\ModelSens\Fs_Vdata.csv',data)

else
    a = 'DSS Did Not Start';
    disp(a)
end

```

Benchmark test system (industrial plant)

Only the core code in OpenDSS will be described here

main.dss

```

/*-----//
//Code by: Francinei L Vieira (nei@unifei.edu.br)
//-----
Test system 3 - Harmonic Analysis
IEEE-PES Task Force on Harmonics Modeling
DOI 10.1109/TPWRD.2018.2817542
-----*/

clear
set defaultBaseFrequency=50
/*-----//
//Eq. Thevenin
//-----*/
new circuit.Test2_TF bus1=BSource
~ basekv=110 pu=1.0 mvasc3=3200 mvasc1=3200
~ x1r1=10 x0r0=10

redirect spectra.dss
redirect transformers.dss
redirect LineCodes.dss

```

```

redirect lines.dss
redirect capacitors.dss
redirect Isources.dss
redirect loads.dss

```

spectra.dss

```

//-----//
// READ IN SCAN SPECTRUM; NUMHARM WILL BE SET TO ACTUAL POINTS FOUND
New spectrum.harmspec numharm=1000 csvfile=spectrum_isource.csv

// Define a spectrum for the scan source
New spectrum.Scanspec numharm=1000 csvfile=ScanSpectrum.csv

// Define a spectrum for DC Loads
New spectrum.iPCC1 numharm=1000 csvfile=spectrum_iPCC1.csv
New spectrum.iPCC4 numharm=1000 csvfile=spectrum_iPCC4.csv

// SET DEFAULT SOURCE HARMONICS TO FUNDAMENTAL ONLY
// ALL OTHER FREQUENCIES WILL BE ZERO (SHORTED)
Spectrum.defaultvsources.numharm=1

// KEEP LOADS FROM INJECTING HARMONICS, TOO
// ALL CURRENTS BUT FUNDAMENTAL WILL BE ZERO (OPEN)
Spectrum.defaultLoad.numharm=1

```

transformers.dss

```

// Transformers
// TR4 - Source bus
new transformer.TR4 phases=3 windings=2 basefreq=50 conns=(wye, wye)
~ kVs=(110, 21) kVAs=(20000, 20000) taps=(1, 1) Xhl=11
~ wdg=1 bus=BSource.1.2.3.0
~ wdg=2 bus=100.1.2.3.4
//Neutral Resistor
new reactor.R4neut phases=1 bus=100.4 R=80 X=0

new transformer.TR1 phases=3 windings=2 basefreq=50 conns=(delta, wye)
~ kVs=(21, .42) kVAs=(400, 400) taps=(1, 1) Xhl=4
~ wdg=1 bus=101.1.2.3
~ wdg=2 bus=102.1.2.3.0

new transformer.TR2 phases=3 windings=2 basefreq=50 conns=(delta, wye)
~ kVs=(21, .42) kVAs=(1000, 1000) taps=(1, 1) Xhl=6
~ wdg=1 bus=201.1.2.3
~ wdg=2 bus=202.1.2.3.0

new transformer.TR3 phases=3 windings=2 basefreq=50 conns=(delta, wye)
~ kVs=(21, .42) kVAs=(1000, 1000) taps=(1, 1) Xhl=6
~ wdg=1 bus=301.1.2.3
~ wdg=2 bus=302.1.2.3.0

```

linecodes.dss

```

New linecode.HL1 nphases=3 BaseFreq=50
~ rmatrix = [0.57 | 0 0.57 | 0 0 0.57]
~ xmatrix = [0.119377 | 0 0.119377 | 0 0 0.119377 ]
~ cmatrix = [0 | 0 0 | 0 0 0]

New linecode.CBa nphases=3 BaseFreq=50
~ rmatrix = [0.5 | 0 0.5 | 0 0 0.5]
~ xmatrix = [0.1413675 | 0 0.1413675 | 0 0 0.1413675 ]
~ cmatrix = [90 | 0 90 | 0 0 90]

New linecode.CBb nphases=3 BaseFreq=50
~ rmatrix = [0.006 | 0 0.006 | 0 0 0.006]
~ xmatrix = [.0942478 | 0 .0942478 | 0 0 .0942478 ]
~ cmatrix = [.5 | 0 .5 | 0 0 .5]

New linecode.CBc nphases=3 BaseFreq=50
~ rmatrix = [0.002 | 0 0.002 | 0 0 0.002]

```

```
~ xmatrix = [.0314159 | 0 .0314159 | 0 0 .0314159 ]
~ cmatrix = [.2 | 0 .2 | 0 0 .2]
```

```
New linecode.CBd nphases=3 BaseFreq=50
~ rmatrix = [0.002 | 0 0.002 | 0 0 0.002]
~ xmatrix = [.062832 | 0 .062832 | 0 0 .062832 ]
~ cmatrix = [.3 | 0 .3 | 0 0 .3]
```

```
New linecode.CBe nphases=3 BaseFreq=50
~ rmatrix = [0.0015 | 0 0.0015 | 0 0 0.0015]
~ xmatrix = [0.015708 | 0 0.015708 | 0 0 0.015708 ]
~ cmatrix = [.1 | 0 .1 | 0 0 .1]
```

lines.dss

```
//Lines and cables
//Lines
New Line.OHL1 Phases=3 Bus1=100 Bus2=101 LineCode=HL1 Length=1
units=km
New Line.CAB1 Phases=3 Bus1=100 Bus2=201 LineCode=CBa Length=2
units=km
New Line.CAB2 Phases=3 Bus1=100 Bus2=301 LineCode=CBa Length=1.5
units=km

//Cables
new line.CAB3 Phases=3 Bus1=102 Bus2=103 LineCode=CBb Length=1
units=km
new line.CAB4 Phases=3 Bus1=202 Bus2=212 LineCode=CBc Length=1
units=km
new line.CAB5 Phases=3 Bus1=202 Bus2=222 LineCode=CBd Length=1
units=km
new line.CAB6 Phases=3 Bus1=302 Bus2=303 LineCode=CBe Length=1
units=km
```

capacitors.dss

```
// Capacitor Banks Data

New Capacitor.Cap1 Bus1=102 phases=3 cuf=597 kvar=90 kV=0.42 conn=delta
~ R=[ .00533 .00533 .00533 ]

New Capacitor.Cap2 Bus1=202 phases=3 cuf=786 kvar=125 kV=.42 conn=delta
~ R=[ .00405 ] XL=[ '.215 .314159 *' ]

New Capacitor.Cap3 Bus1=302 phases=3 cuf=332 kvar=50 kV=0.42 conn=delta
~ R=[ .00959 ]

New Capacitor.CapMV1 Bus1=100 phases=3 cuf=8.75 kvar=1100 kV=21 conn=wye
~ R=[ .3638 ] XL=[ '.5 .314159 *' ]
```

Isource.dss

```
//Z Scan - Bus 12
//-----//
new isource.IhMotor bus1=303 amps=1 spectrum=scanspec scantype=pos
```

loads.dss

```
//MV Load
new load.MVload bus1=100 kv=21 kw=7150 kvar=2090 conn=delta %seriesRL=100
spectrum=defaultload
```

```

//Load PCC1
new load.MCC1      bus1=103 kv=.42 kw=209 kvar=105 conn=wye spectrum=iPCC1

//Load PCC2
new load.MCC2      bus1=212 kv=.42 kw=257 kvar=99 conn=wye spectrum=iPCC4
new load.load3     bus1=222 kv=.42 kw=160 kvar=51 conn=wye %seriesRL=0
spectrum=defaultload

//Load PCC3
new load.IndMotor bus1=303 kv=.42 kw=200 kvar=96 conn=delta %seriesRL=0
spectrum=defaultload
// spectrum=harmspec
// Harmonic spectrum is represented by an Isource

```

230-kV power system

Only the core code in OpenDSS will be described here. This test case was performed with only two DSS code files.

Main.dss

```

/*-----//
//Code by: Francinei L Vieira (nei@unifei.edu.br)
-----//
Test system 4 - Distribution + Subtransmission w/ NL Loads
-----*/

clear
set defaultBaseFrequency=60
set Datapath=(C:\ !Put the destination folder of the main DSS file
Users\neill0k\OneDrive\EC331\Modelagem OpenDSS\DSS Files\Case2b_NL_loads\
/*-----//
//Eq. Thevenin - Voltage source
//-----*/
new circuit.Test2b bus1=Grid.1.2.3
~ basekv=230 pu=1.04 Angle=30 frequency=60
~ mvasc3=12000 mvasc1=12000

redirect spectra.txt

!LINE DEFINITIONS
// Transmission Line - Vl Conde-Castanhal (230 kV) - 130 km
New linecode.VlConde nphases=3 BaseFreq=60 rho=1500 units=km !2 cond / bundle
~ rmatrix = [0.17072688 | 0.14220770 0.18557946 | 0.13410571 0.14122077 0.17072688]
~ xmatrix = [0.77753125 | 0.40814947 0.76820549 | 0.40176833 0.40814947 0.77753125]
~ cmatrix = [9.7519111 | -1.9947061 9.9888968 | -1.7068593 -1.9947061 9.7519111]

New Line.230KV Bus1=Grid Bus2=B230_PCC Length=130 units=km
~ normamps=1400 emergamps=1722 linecode=VlConde

// LT 795MCM 69 kV
New Linecode.3-795_4/0N_L nphases=3 r1=0.074627 x1=0.341816 r0=0.289683 x0=1.29655
~ c1=13.0304661299389 c0=4.61013513324754 units=km rho=1500 baseFreq=60 normamps=970
~ emergamps=970 pctperm=20 repair=3

new line.69kv bus1=B69a bus2=B69b length=20 units=km linecode=3-795_4/0N_L

!PCC DEFINITIONS-----//
//Secondary TR69-13.8
New Line.PCC-13_8 bus1=B13_PCC bus2=B13 Length=1 Phases=3 R1=1e-4 X1=0.0 R0=1e-4 X0=0.0
C1=0.0 C0=0.0
//Secondary TR230-69
New Line.PCC-69 bus1=B69_PCC bus2=B69a Length=1 Phases=3 R1=1e-4 X1=0.0 R0=1e-4 X0=0.0

```

```

C1=0.0 C0=0.0
//Primary TR230-69
New Line.PCC-230 bus1=B230_PCC bus2=B230 Length=1 Phases=3 R1=1e-4 X1=0.0 R0=1e-4 X0=0.0
C1=0.0 C0=0.0
// Equivalent Load
New Line.PCC-Tequiv bus1=B230 bus2=B230_eq Length=1 Phases=3 R1=1e-4 X1=0.0 R0=1e-4
X0=0.0 C1=0.0 C0=0.0

/*-----//
!Transformers -----*/
New Transformer.TR230_69 Phases=3 Windings=2 Xhl=10.6 kVs=[230, 69] conns=(delta, wye)
~ buses=[B230, B69_PCC] kVAs=[45000, 45000] mintap=0.9 maxtap=1.1 sub=yes
~ %noloadloss=0.18 !assumed
~ %Rs = (0.12,0.12) emergHkva = 60000 taps=[1 1.05]

New Transformer.TR69_13 Buses=[B69b,B13_PCC] kVs=[69 13.8] %Rs=(0 0) XHL=10 conns=(wye,
delta)
~ %noloadloss=0.107 kVAs=[15000 15000] tap=1.04 sub=yes

//-----//
!LOAD DEFINITION - T-equivalent (L in mH)

new reactor.L1a phases=1 bus1=B230_eq.1 bus2=Tmid.1 kv=230 R=15 LmH=17.54020
new reactor.L1b phases=1 bus1=B230_eq.2 bus2=Tmid.2 kv=230 R=15 LmH=17.54020
new reactor.L1c phases=1 bus1=B230_eq.3 bus2=Tmid.3 kv=230 R=15 LmH=17.54020

new reactor.L2abc phases=3 bus1=Tmid kv=230 R=15 LmH=52.6206
new capacitor.C1abc phases=3 bus=Tmid kv=230 cuf=1.925504

!Load Bus 13.8 kV
new isource.Ih1 bus1=B13.1 phases=1 amps=1 spectrum=Scanspec
new capacitor.PFC bus1=B13 kvar=247 kv=13.8
!Model 4 - Induction motor
new Load.MOT_13 bus1=B13 kv=13.8 kw=185.75 kvar=1486 %seriesRL=0 model=2
new Load.RES_13 bus1=B13 kv=13.8 kw=371.5 pf=1 %seriesRL=0 model=2

!Load Bus 69kV (B69a)
new capacitor.PFC_69 bus1=B69a kvar=829.26 kv=69
!Model 4 - Induction motor
new Load.MOT_69a bus1=B69a kv=69 kw=3750 kvar=7500 %seriesRL=0 model=2
new Load.RES_69a bus1=B69a kv=69 kw=3750 pf=1 %seriesRL=0 model=2

!Load Bus 69kV (B69b)
new capacitor.PFC_69b bus1=CH1 kvar=829.26 kv=69
!Model 4 - Induction motor
new Load.MOT_69b bus1=CH1 kv=69 kw=3750 kvar=7500 %seriesRL=0 model=2
new Load.RES_69b bus1=CH1 kv=69 kw=3750 pf=1 %seriesRL=0 model=2

!SWITCH DEFINITIONS-----//
New Line.SW_1 bus1=B69b.1.2.3 bus2=CH1.1.2.3 Phases=3 Switch=y r1=1e-4 r0=1e-4
x1=0.000 x0=0.000 c1=0.000 c0=0.000

!CONTROLS DEFINITION-----
New Swtcontrol.SW_1_Ctrl basefreq=60 Delay=0.0 Action=closed SwitchedObj=Line.SW_1
SwitchedTerm=2 lock=open enabled=y

!MONITORS -----//
!new monitor.PCC1 element=Line.PCC-13_8 terminal=1 mode=32
!new monitor.PCC2 element=Line.PCC-69 terminal=1 mode=32
!new monitor.PCC3 element=Line.PCC-230 terminal=1 mode=32
!new monitor.PCCeq element=Line.PCC-Tequiv terminal=1 mode=32
new monitor.FreqScan element=Isource.Ih1 terminal=1 mode=32

!Initiate solution and start simulation
set voltagebases = [230 69 13.8]
CalcVoltageBases
!Set Controlmode=Time

solve
set mode=harmonic

```


spectra.txt

```
!SPECTRA

// READ IN SCAN SPECTRUM; NUMHARM WILL BE SET TO ACTUAL POINTS FOUND
New spectrum.harmspec numharm=1000 csvfile=spectrum_ismource.csv
// Define a spectrum for the scan source
New spectrum.Scanspec numharm=1000 csvfile=ScanSpectrum.csv

// SET DEFAULT SOURCE HARMONICS TO FUNDAMENTAL ONLY
// ALL OTHER FREQUENCIES WILL BE ZERO (SHORTED)
Spectrum.defaultvsources.numharm=1

// KEEP LOADS FROM INJECTING HARMONICS, TOO
// ALL CURRENTS BUT FUNDAMENTAL WILL BE ZERO (OPEN)
Spectrum.defaultLoad.numharm=1
```