University of Alberta

Methods to Mitigate Harmonics In Residential Power Distribution Systems

by

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Abstract

The excessive waveform distortions in the present power distribution systems are produced mainly by the large number of residential loads. Such distributed sources of harmonics cannot be easily treated by the traditional mitigation methods, which have been commonly applied for concentrated and easily detectable industrial distorting loads.

This thesis presents new harmonic mitigation techniques necessary for managing this new situation. The proposed strategies are supported by several analytical and simulation studies. Different options for both active and passive centralized and distributed filters are investigated and compared to determine their different technical and economic aspects. Overall, the results of extensive studies confirm that the novel zero-sequence harmonic filter and the new scheme of the low-voltage distributed active filters introduced in this thesis are promising solutions for the increasing harmonic problems in residential feeders.

Acknowledgement

I would like to express my sincere appreciation to Dr. Wilsun Xu. This research and dissertation would not have been possible without his guidance and great supervision. I will always be proud to say I had the privilege of being his student, and I hope to have learned enough to succeed in my future career.

I also thank my parents Hamid and Fatemeh for supporting me in so many different ways. They supported my coming to Canada and my desire to spend another two years in university for graduate studies. This is also extensive to my siblings, Nima, Shisa and Mahsa, who have always loved me.

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Chapter 1

Introduction

Harmonic distortion has been always one of the major concerns in the area of electrical power quality. Because of their potential negative impacts, the uncontrolled flow of harmonics in power systems has been always prevented by employing various mitigation methods. Traditionally, the dominant harmonic sources were usually associated with some industrial loads at known locations. Then, in most cases, the customers with the major distorting loads were asked to install harmonic filters, which prevented the excessive harmonic distortions from entering the supply system. Standards and guidelines have been developed in the literature to plan effective mitigation measures to control the harmonic distortions in such situations [1]-[3]. Therefore, the power utility companies have successfully managed to supply the nonlinear loads of industrial customers without any noticeable issue.

However, after the start of the 21st century and the widespread penetration of modern nonlinear electronic devices into the regularly used home appliances, the nature of harmonic sources has significantly changed. From the easily detectable concentrated loads of the past, the major harmonic sources have evolved into several small ones dispersed throughout the whole distribution system. This trend has raised serious concerns regarding the capability of the traditional methods to manage this new harmonic situation. This introductory chapter presents an overview of the harmonics in the modern distribution systems. Then, the traditional mitigation methods are reviewed. Next, the need to develop new techniques is discussed. Finally, this chapter presents the scope and outline of this thesis.

1.1 Harmonics in Modern Distribution Systems

Several modern home appliances such as compact fluorescent lights, LCD TVs and personal computers generally inject a large amount of harmonic currents into their supply systems. The massive growth in usage of such energy-efficient consumer electronic devices has resulted in significant distortions to the voltage and current waveforms in the present power distribution systems. Although each of the devices is not individually a large source of harmonics, the collective effect is so noticeable that the excessive waveform distortions in urban distribution systems are becoming increasingly dominated by the harmonics of residential loads [4]- [7].

The high levels of harmonic distortion in a power system increase the risk of different troublesome and unwelcome effects. For example, several serious problems associated with the harmonics of residential feeders (telephone interference is the most common problem) have been recently experienced by the utility companies in Alberta, Canada. Because of their energy-saving feature, nonlinear electronic devices will probably continue their rapid penetration into the power systems and possibly cause a severe harmonic situation in the near future.

The uniqueness of this new harmonic condition raises serious doubts and concerns regarding the effectiveness of the existing standards and practices for managing and mitigating the distortions in the present distribution systems. As a result, research on advanced and efficient mitigation methods which can be properly planned in accordance with the new characteristics of the modern harmonic sources is obviously needed.

1.2 Traditional Mitigation Methods and the New Challenges

Traditionally, specific industry customers known to the utilities possessed the dominant harmonic sources. Consequently, the harmonic problems were identified and treated by installing passive harmonic filters at the Point of Common Coupling (PCC) of the major distorting loads so that the filter effectiveness was easily assessed and verified [3],[8]-[10]. However, the situation becomes quite complicated with the presence of harmonic-generating residential loads. Such small harmonic sources are widely and randomly dispersed across the system.

Several researches have tried to develop possible mitigation measures for this new situation. For Medium-Voltage (MV) applications, shunt passive harmonic filters are generally the most popular solution for harmonic problems in the power industry, due to these filters reasonable cost and reliability [11],[12]. Therefore, various design methods have been proposed and developed in the literature for installing passive harmonic filters to mitigate the dispersed harmonic sources in a distribution feeder [13]-[15]. Moreover, complex optimization algorithms have been also developed for placing the filters when the distorting loads are distributed along the feeder [15]-[17]. Nonetheless, the treatment of distributed harmonic sources is still challenged by several difficulties such as the lack of a practical and comprehensive technique of filter design and placement. For instance, the proposed passive filter designs in the literature vary from case to case, depending on the feeder characteristics. Moreover, in order to mitigate all the harmonic orders (3^{rd}, 5^{th}, 7^{th}, etc.) several passive filter branches will be needed, and this requirement will increases the implementation cost. As well, severe harmonic amplifications caused by the parallel resonance between the passive filters and the system are always possible [12],[18]. Most of the issues associated with the shortcomings of passive filters can be addressed by employing active harmonic filters [19],[20], but they have never been a popular choice in industry practices, due to their high cost and insufficient reliability in the MV-level applications.

Another unique characteristic of the harmonics associated with residential loads involves the Zero-Sequence (ZS) harmonics. Unlike the industrial loads, most of the residential loads are single-phase. This fact leads to the creation of ZS harmonic currents in three-phase distribution systems. High levels of ZS harmonics are often observed in a distribution system feeding residential loads nowadays. These harmonics can add up in the neutral conductor, creating problems such as neutral voltage/current raise [21],[22]. They are also the main culprit of interference problems with the adjacent telephone lines [23], [24]. Because ZS harmonics may also lead to problems similar to those caused by positive- or negative-sequence harmonics, the excessive ZS harmonic distortions can be problematic in a distribution system. Therefore, the ZS harmonics must be considered when researching the harmonic mitigation solutions for modern residential feeders.

1.3 Harmonic Mitigation Objectives

In general, excessive harmonic distortions in a distribution system can cause several problems such as the following [1],[2],[25]:

- Electromagnetic interference with adjacent telephone lines [26]
- Transformers or capacitor banks overheating
- Premature ageing of the insulation of the electrical plant components
- Errors in metering devices or malfunction of sensitive electronic devices

- Neutral overheating or voltage rise [21],[22]
- High level of harmonic penetration into the power transmission systems

In order to manage the risks and hazards associated with the problems listed above, harmonic mitigation strategies are essential for both solving the existing problems and preventing potential problems in future. In other words, the main objectives in planning to mitigate harmonics in a distribution feeder can be classified into the following two categories.

1) Mitigating a single-point problem: In this category, the mitigation measures are used for a specific problem (such as one of those listed above) which has already occurred in a system due to the high level of harmonic distortions. For example, the ZS harmonics in a section of a feeder may have caused interference with its adjacent telephone lines, or a capacitor bank in the system might be overloaded by extra amounts of harmonics. In such cases, the problem will be approached with a specific mitigation objective focused only on the troublesome harmonic components in the affected location. For example, in a telephone interference case, filtering the ZS harmonics in the involved power-line sections will be sufficient to solve the problem.

2) System-wide harmonic mitigation: In this approach, the purpose is to suppress the harmonic distortions throughout the whole system to reduce the possibility of any harmonic-caused problem in the future, thereby ensuring the system's safe operation. Moreover, all of the system's sensitive devices such as the metering devices will also benefit from the distortion-free voltage/current waveforms. Besides, the amount of harmonics penetrated into the transmission systems is also controlled and the power losses associated with harmonics are avoided as well by this approach.

This thesis proposes new methods and conducts studies to address the technical needs and implementation issues associated with achieving both of these harmonic mitigation approaches in a residential distribution system. For example, a thorough design guideline is developed to mitigate the single-point problems caused by the ZS harmonics. The thesis also introduces and investigates methods for accomplishing system-wide harmonic mitigation in a distribution system.

1.4 Thesis Scope and Outline

The scope of this thesis is to develop thorough and effective methods for mitigating the harmonics produced by the residential loads in a distribution feeder. Most of the past research in the field of harmonic suppression focused only on the lumped, large and known industrial loads. However, the harmonic distortions in the modern distribution systems are dominated by the large number of randomly dispersed sources associated with residential loads. Hence, new issues and concerns challenge the management of the new harmonic situation. Some of the key questions that this thesis is aimed to answer are as follows.

1. What are the unique characteristics of the residential distorting loads? Which aspects of the traditional mitigation methods must be improved and extended to become effective for such modern harmonic sources?

2. What are the effective methods to manage the high levels of ZS harmonics emerging in the residential distribution feeders?

3. How can system-wide harmonic mitigation in a feeder serving residential customers be achieved? What is the role of passive and active harmonic filters in this context? What are the proper sizing and design methods?

4. Where should the harmonic filters be located in a system with dispersed harmonic sources? Should either several distributed small filters or a few centralized bulky filters be used? Which solution is more cost-effective? What are each method's technical advantages?

5. Can the filters be installed in the low-voltage secondary levels of the distribution systems as well? If so, what are the advantages and challenges associated with such a scheme?

In order to address the concerns highlighted in the above questions, this thesis introduces several new methodologies and also conducts supporting technical studies. The following paragraphs summarize the organization of the thesis and describe the main topics and research discussed in each chapter.

Chapter 2 reviews the overall process of harmonic build-up in a modern residential distribution system. The main characteristics of the North American distribution feeders that affect the present harmonic situation are also discussed. The two systems used to examine different mitigation schemes are also introduced in this chapter. The chapter also discusses the modeling techniques employed in this thesis to develop a comprehensive platform for all of the simulation studies. The models are used in the later chapters to perform several Harmonic Load Flow (HLF) studies to assess the efficiency of the different harmonic mitigation strategies.

Chapter 3 presents a novel technique to mitigate ZS harmonics in power distribution systems. The method is based on the concept of passive ZS harmonic filters including Yg/Δ transformers. However, its basic configuration has been expanded to create a double-tuned filtering feature. This feature makes it possible to trap two ZS harmonics with only one filter and is especially attractive for solving harmonic-caused telephone interference problems. A method for sizing and loading assessment of the filter is also proposed in this chapter. As sample application, the proposed filter package is applied to mitigate a telephone interference problem. Issues such as filter location, the number of filters required and the effectiveness of filtering ZS harmonics produced by distributed residential loads are also investigated in this chapter.

As discussed earlier, a comprehensive and practical methodology for designing passive MV filters to mitigate harmonics produced by the dispersed residential loads is still unavailable. Chapter 4 develops a simplified design guideline for MV filter applications for treating the modern harmonic situation. All of the special characteristics of distributed harmonic sources are considered in the design process. In this chapter, the final MV passive filter packages are sized for both of the studied systems.

Since the harmonic sources are dispersed in a residential feeder, the harmonic filters can be also distributed all over the system. Indeed, instead of a bulky centralized filter in the primary feeder, several small low-voltage filters can be installed in the secondary levels of a distribution system. Chapter 5 presents a novel mitigation scheme based on low-voltage distributed active filters. In each secondary system, the filters can either be attached to the service transformer or configured as a meter collar inserted into the revenue meter socket of one of the customers. Various analytical and simulation studies are conducted in this chapter to develop the proper specifications and requirements of such a filtering scheme in order to achieve an effective system-wide harmonic mitigation.

Chapter 6 presents a comprehensive comparison between the MV passive filter solution (discussed in Chapter 4) and the distributed active filter scheme (introduced in Chapter 5). The economic issues and the technical aspects are considered to identify the strategy with the most overall advantages.

Finally, this thesis's main conclusions and suggestions for future research in this field are summarized in Chapter 7.

Chapter 2

Harmonics Build-up in Modern Distribution Systems

The first critical step in planning an effective harmonic mitigation strategy is to correctly understand and characterize the harmonic sources. Technically speaking, proper system models and theoretical principles are required to formulate and quantify the harmonic situation in the system. After such models and principles have been developed, effective mitigation measures can be proposed and assessed. As discussed earlier, this task can be quite challenging for researchers studying modern distribution systems where the dominant sources of distortion are the large number of nonlinear residential appliances. Such harmonic sources have a random and time-varying nature and unlike traditional lumped and large harmonic loads, are dispersed all over a system. Traditionally, a set of data consisting of the harmonic spectrum of the distorting load and the system characteristic at the PCC (including system harmonic impedances and background harmonics) was sufficient to conduct a harmonic filter design and study. However, defining such a simple set of data is not possible for the modern situation where several harmonic sources are dispersed in the system, and no single connecting point can be identified as the PCC.

As a result, the first essential step is to establish theoretical principles and system models that properly formulate and represent such modern sources of harmonic pollution. Recently, researchers at the PDS lab at University of Alberta, Canada developed a comprehensive simulation platform to represent distributed harmonic sources in a residential power system[6],[7],[27],[28]. This thesis employs those models and simulation techniques which are developed based on a bottom-up approach to quantify the harmonic build-up in the residential feeders. After developing the required models, an in-house Harmonic Load Flow (HLF) program [29] is used to perform simulations for different case studies to examine the proposed mitigation strategies.

This chapter is organized as follows. Section 2.1 describes the general characteristics of the power distribution systems in North America. Section 2.2 explains the bottom-up modeling approach employed for performing HLF simulations in a residential feeder. The parameters and characteristics of the selected feeders for conducting this thesis's studies are given in section 2.3. Section 2.4 lists the main harmonic indices of interest used in this thesis to evaluate different harmonic mitigation methods. Finally, section 2.5 establishes a precise mitigation objective that will be used as the design criteria to develop system-wide harmonic suppression plans in Chapter 4 and Chapter 5.

2.1 Distribution Systems in North America

Figure 2.1 shows a typical schematic of a North American distribution system supplying residential loads. The system is consisting of the primary and secondary feeders. The primary feeder transfers the electrical power from substation to several service transformers. Each secondary system consists of a service transformer and the various houses supplied by it. As shown in the figure, the houses are connected to 120V voltage level of the service transformers through the secondary conductors.

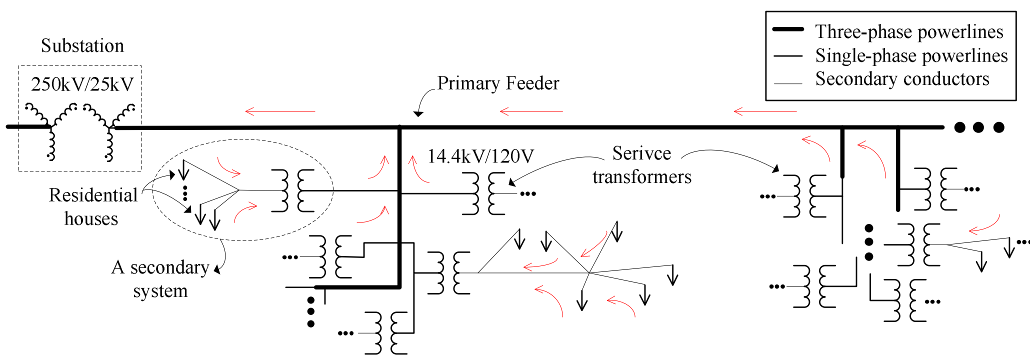


Figure 2.1 A generic schematic of a residential distribution feeder in North America.

Nonlinear home appliances inside the houses are the major harmonic sources in this system. As illustrated by the red flash arrows in the figure, each residential customer injects a portion of harmonics to the system which penetrate to the primary feeder and finally flows toward the substation.

2.2 Harmonic Modeling of Residential Loads

For the studies conducted in this thesis, the residential harmonic sources are quantified and modeled employing the bottom–up probabilistic approach introduced in [6],[7],[27],[28]. This method provides aggregated harmonic load models for the distribution service transformers inside a feeder supplying residential houses. The modeling technique can be summarized in the following steps [7],[28]:

1) The types of regularly used electrical home appliances by the customers in the study area are recognized.

2) The number of appliances per each household is estimated.

3) The probabilistic switch-on daily profile for each type of appliances is established based on their typical daily usage patterns.

4) The model is developed for different times during a day. For each time snapshot, appliances that are ON are modeled as the constant power loads in the fundamental frequency and for the harmonic frequencies; current sources are used to model nonlinear loads, whereas linear appliances are represented by impedances.

5) The aggregated harmonic model for a residential house is built.

6) The residential houses are connected to the secondary system models.

In order to reduce the complexity and computation time duration of primary system simulations, it is essential to establish equivalent models for each secondary system supplied by the feeder [28]. Based on a similar method as in [28], the equivalent models are generated and verified, then, each group of a service transformer and its supplied residential houses are substituted by their equivalents in the system model. (Appendix A explains the details of developing the aggregated models). Multiphase PI models are used for all of the overhead lines and underground cables (including the single and double-phase ones as well) inside the feeder. Neutral wire is also included by employing multiphase models [28]. Finally, the developed models are employed in an In-House multiphase HLF program [29] to perform the simulation studies. As the models are time-varying during a day, the obtained results are for different times of the day.

2.3 Description of Studied Systems

The harmonic mitigation studies of this thesis are conducted on two distribution systems as follows.

a) An ideal system supplying residential loads which are evenly distributed along the feeder. This system can represent the generic characteristics of residential distribution systems and will be referred as the 'ideal feeder' in this thesis.

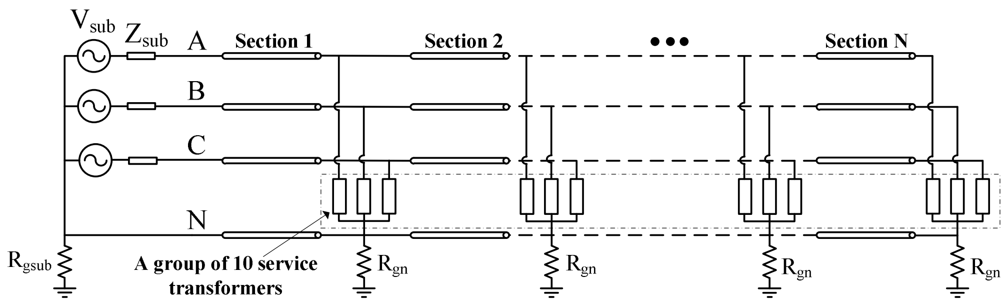


Figure 2.2 Schematic view of the ideal feeder circuit

b) An actual distribution feeder supplying some residential customers operated by a utility company in Edmonton, Canada. The excessive harmonic distortions in this feeder have caused some severe problems such as telephone interference. As shown in Figure 2.3, this feeder is supplying two large residential neighborhoods in the south areas of Edmonton (encompassed by the circles in the figure) and will be referred as the 'actual feeder' in this thesis. By including such system in the study platforms, the effectiveness of the proposed mitigation schemes can be also examined for the real-world applications.

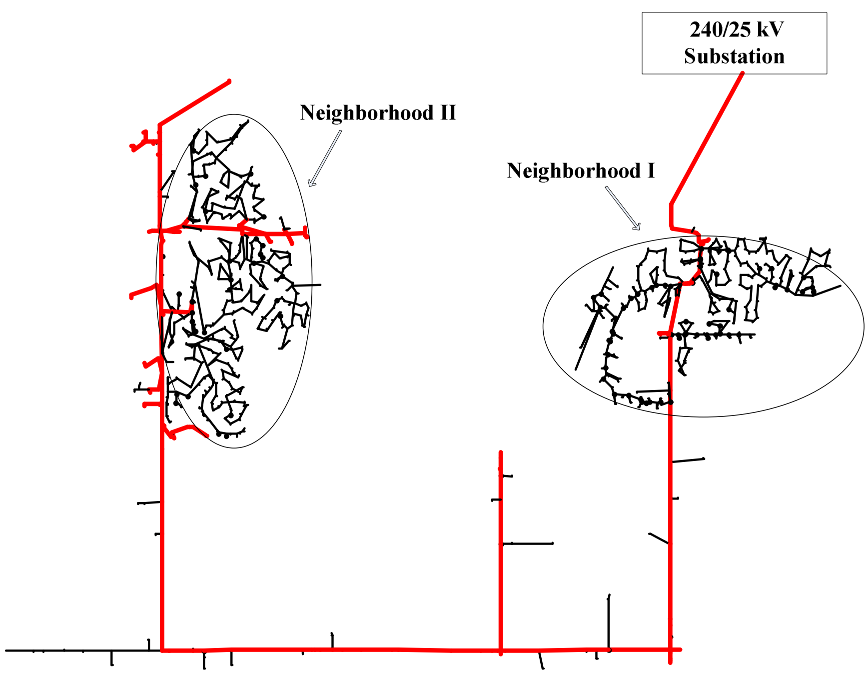


Figure 2.3 Schematic view of the actual distribution feeder chosen for studies.

The main characteristics and parameters of these two systems are given in Table 2.1 and Table 2.2.

Table 2.1 Main system parameters of the studied feeders.

System Parameter		Ideal Feeder	Actual feeder
Substation	Voltage level	25 kV (LL-rms)	25 kV (LL-rms)
	Fault level	242 MVA	305 MVA
	Equivalent impedance (Z_{sub})	Z_+= 0.688 + j2.470 Ω Z_0= 0.065 + j2.814 Ω	Z_+= 0.035 + j2.05 Ω Z_0= 0.053 + j2.161 Ω
Main Trunk	Grounding resistance (R_{gsub})	0.15 Ω	0.15 Ω
	Power-line type	Overhead line	Underground cable: 52% Overhead line: 48%
	Number of sections	15	-
	Length of each section	1km	-
	Total length	15km	15.68km
	Grounding span	75m	75m
Loads	Grounding resistance(Rgn)	15 Ω	15 Ω
	Lateral branches type	No lateral branch	Underground cable
	Number of service Transformers	450	506
	Distribution of service transformers	30 per each section (150 per each phase)	Neighbourhood I: 206 Neighbourhood II: 300
	Total supplied power	4.5MW	8.79MW
	Number of houses per each service transformer	10	Varied [a]

[a] The number of houses assigned to each service transformer depends on its real daily average kW power load data provided by the utility company. The average power of each house is assumed to be around 1kW.

Table 2.2 Conductor type, impedance and admittance of the feeder power-lines

	Conductor type	Impedance (Ω/km)	Admittance (μS/km)
Overhead power-line	336.4 ACSR	Z_+= 0.188+j0.401 Z_0= 0.366+j1.854	B=3.3
Underground cable	500Al XLPE 25kV DBUR	Z_+= 0.209+j0.2203 Z_0= 0.5338+j0.1486	B=98

2.4 Indices of Interest

In order to quantify and compare the effect of different mitigation methods on the distribution system harmonics, the following indices are adopted in this thesis:

1. Individual and Total Demand Distortion of the harmonic current (IDD and TDD as defined in [2]) in the feeder substation which exactly quantify the harmonic content penetrating to the transmission level from the distribution feeder as well as being a rough measure of the harmonic currents flowing along the feeder.

2. Individual and Total Harmonic Distortion of the voltage (IHD and THD as defined in [2]) average along all the feeder sections. Such indices provides a rough measure of feeder overall harmonic pollution.

In order to avoid showing the data for all the three phases of a system, the dominant sequence component of each harmonic order is adopted in the studies. For example, the zero-sequence and negative-sequence components are selected for the 3rd and 5th harmonic orders, respectively. Additionally, Instead of presenting and analyzing the whole 24-hours profiles of the simulation results, the 'daily 95% percentile' value is adopted for most of the studies in this thesis. For each index, the daily 95% percentile value means that 95% of the time, the index is below this value. [7],[27]-[29].

In some of the cases, the decrease percentages of the above indices are also shown to facilitate comparisons among the effectiveness of different mitigation strategies. For instance, percentage decrease of current TDD is defined as below,

$$\textit{Percentage decrease of } TDD_I(\%) = \frac{TDD_I^{Before} - TDD_I^{AfterMitigation}}{TDD_I^{Before}} \times 100 \tag{2.1}$$

2.5 System-wide Harmonic Mitigation Objective

In order to finalize the design and planning of any harmonic mitigation scheme, a specific criterion is needed. For the traditional harmonic problems, this criterion has been generally specified by the limits introduced by the standard guidelines such as the IEEE std. -519 ([2]) and IEC 1000-3-6 ([30]). The philosophy of these standards is based on the large, lumped and known harmonic sources. The customers possessing the distorting loads (which are usually industrial ones) are strictly demanded by the supplier utility to install harmonic filters (or modify their loads) in order to comply with the standard criteria. Therefore, in such cases, each harmonic filter installed by the individual customer is designed and sized accordingly to assure the dictated harmonic current and voltage limits are not violated.

However, the scenario is totally different for the harmonic situation in the modern distribution systems where the dispersed residential loads are the dominant harmonic sources. Although the excessive harmonic distortions are known to be caused by the large number of nonlinear home appliances, utilities cannot force each residential customer to modify loads or install filters to mitigate the harmonic problems. Therefore, in the present case, the utilities somehow own the problem and it is eventually their own responsibility to plan and even pay for the proper harmonic mitigation schemes. In addition, the rapid growth of nonlinear home appliances must also be considered in this scenario. Indeed, the fixed and constant harmonic limits (such as in IEEE std. -519) may not be effective in this case. For example, although utilities can plan for mitigation measures to reduce the present harmonic levels of their systems in accordance with such fixed standards, the limits may be violated again in the near future by the significant increase of the harmonic sources.

Currently, a general and comprehensive standard able to account for all the described characteristics of the modern harmonic situation in the residential feeders is not available. The author believes that the utilities will need to develop such guidelines in the near future to manage the harmonic distortions in their operated feeders. The proper harmonic limits must be determined by compromising between the mitigation costs and severity of the existing harmonic problems.

As a result, a tentative criterion is adopted in this thesis to assess different system-wide harmonic mitigation measures in a residential power distribution system. The mitigation objective is defined as a 75% decrease in the harmonic distortion indices of the system. Based on this definition and according to the adopted indices of interest discussed in the previous section, an effective harmonic mitigation plan for a residential distribution system can be defined as a scheme which leads to at least a 75% decrease in both the current TDD in the substation and the voltage THD average over the feeder. This harmonic suppression goal will be employed as the design criterion in Chapter 4 and Chapter 5 to finalize the design of the centralized and the distributed filters for the studied feeders.

Chapter 3

Proposed Zero-Sequence Harmonic Filters[1]

As discussed earlier, unlike the industrial loads, the residential distorting loads are significant sources of Zero-Sequence (ZS) harmonics. Therefore, developing proper harmonic filters for the ZS harmonics is an essential part of a harmonic mitigation plan for the residential feeders. This chapter presents novel topologies and effective methods for designing and planning ZS harmonic filters. The developed theories and methodologies are applied to solve an actual telephone interference problem caused by excessive ZS harmonics in an actual distribution feeder.

The chapter is organized as follows: First, a brief review on the conventional ZS harmonic filters and their technical issues is presented in section 3.1. Next, section 3.2 describes the topology of the proposed ZS filter and its characteristics (such as the frequency response, equations for parameter selection). Section 3.3 discusses the filter design issues such as filter loading assessment and components size selection, thereby providing a general design guideline. Section 3.4 investigates the application for solving telephone interference problems. In addition to serving as an illustrative example, application issues of the proposed filters specific to telephone interference problems are studied.

3.1 Review on ZS Harmonic Filters

Among different harmonic filter topologies, the so-called ZS filters are very popular for suppression of ZS harmonics. This section presents a brief review on the conventional passive ZS filters (The active types of ZS filters are not considered in the studies of this chapter because of their cost and reliability issues for the Medium-Voltage (MV) applications. It must be noted that the ZS harmonics can be only treated in the MV level of the primary feeders where the power-lines are three-phase).

[1] A version of this chapter has been submitted for publication: P. Bagheri, W. Xu, "A Technique to Mitigate Zero-Sequence Harmonics in Power Distribution Systems", *IEEE Transactions on Power Delivery*.

A few passive ZS filters have been successfully used to mitigate ZS harmonics in commercial systems [31]. Their variations have also been proposed for application in primary distribution systems. Such filters have various topologies. All share the same idea of creating low zero sequence impedance to trap ZS harmonics. The ZS filters can be broadly classified into two types. The first type has a positive (and negative) sequence impedance so it affects the flow of non-zero-sequence harmonics. A representative example of such filters is the star-connected capacitors grounded through an inductance (Figure 3.1 (b) and (c)) [32]-[34]. The inductance is tuned to cause a low ZS impedance. The main advantage of this topology is that by adding a three-phase inductor (Figure 3.1 (c)), the capacitors can be tuned to filter positive and negative sequence harmonics as well. The downside is that the filter can affect the 60Hz power flow and can lead to positive or negative sequence resonances ([18]) at other frequencies.

The second type of ZS filters is based on the concept of grounding transformer [31]. Such a filter behaves as an open circuit at positive and negative sequences so it has no impact on normal power system operation and on non-zero-sequence harmonics. One of the examples is the zig-zag transformer-based filter (Figure 3.1 (a)) [35]. A drawback of this filter is that it needs a nonstandard transformer. Another example consists of a Yg/Δ transformer with a tuned capacitor inserted into the delta winding (Figure 3.2(a)) [36]. It is well known that a Yg/Δ transformer can sink ZS currents (This capability is the principle of a grounding transformer). By inserting a capacitor into the delta loop and adjusting the capacitor size, a very low ZS impedance can be created at a desired harmonic frequency. It leads to an attractive ZS filter topology without the shortcomings of other ZS filter configurations.

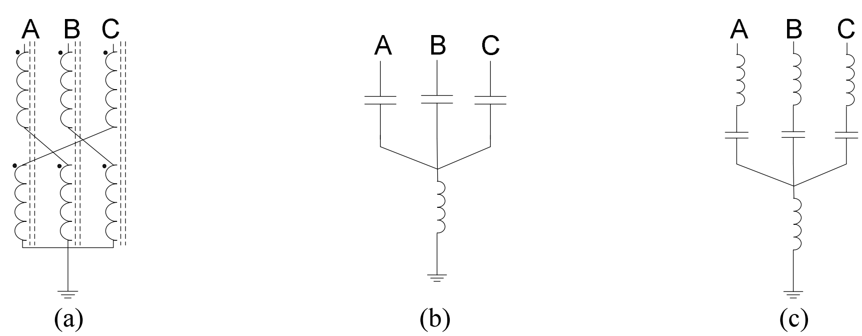


Figure 3.1 The conventional ZS harmonic filters: (a) zig-zag transformer-based (b) star-type (c) star-type including a three-phase inductor.

3.2 Proposed Double-Tuned ZS Filter

Built on the work of [31] and [36], this chapter presents a novel double-tuned, transformer-based ZS filter. Since the filter can trap two ZS harmonics, it is very attractive to solve problems that involve two dominant harmonics, such as the telephone interference problem. Telephone interference is normally caused by the ZS 9th and 15th harmonics (For more information about telephone interference, refer to section 3.4.2). In fact, the proposed filter is conceived originally as a tool to solve telephone interference problems. The use of only one single-tuned ZS filter will have difficulty in solving these problems.

The proposed ZS harmonic filter is developed by expanding the conventional ZS filters consisting of Yg/Δ transformers. This new double-tuned topology is depicted in Figure 3.2 (b).

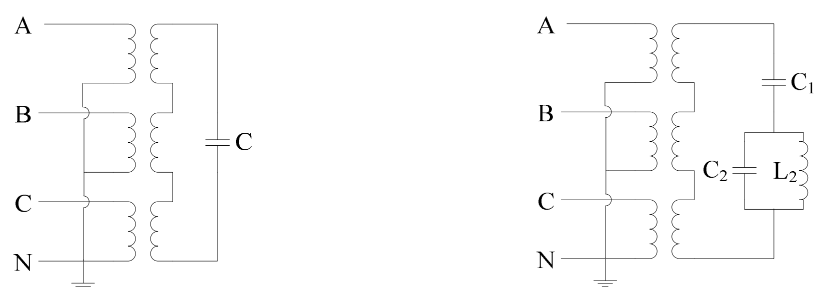


Figure 3.2 The transformer-based ZS filter topologies: (a) conventional single-tuned version (b) proposed double-tuned version.

In Figure 3.3, a sample ZS impedance frequency scan of the proposed filter tuned to both the 9th and 15th harmonic frequencies is shown and compared with the single-tuned version.

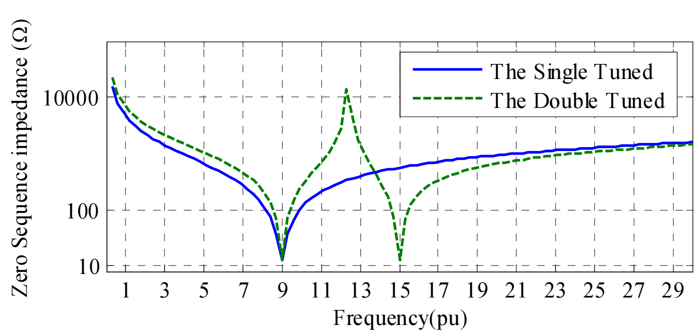


Figure 3.3 Zero-sequence frequency scan of the designed filters

The theoretical principles of the proposed filter can be understood by studying this filter's equivalent ZS circuit. Figure 3.4 (a) shows a single-tuned ZS filter, illustrating how to derive its equivalent ZS circuit. A ZS voltage (V0) is applied to the filter. The Kirchhoff's Voltage Law (KVL) implies that, in the secondary side of the transformer,

$$3a\overline{V_0} = 3(R_T + jh\omega_0 L_T)\frac{\overline{I_0}}{a} + \frac{1}{jh\omega_0 C}\frac{\overline{I_0}}{a}, \tag{3.1}$$

where a is the transformer secondary to primary winding ratio, ω_0 is the power fundamental frequency(rad/sec), h is the harmonic order, and R_T and L_T are transformer winding resistance (Ω) and leakage inductance (H), transferred to the secondary side, respectively. From (3.1), the equivalent ZS impedance of the filter at harmonic order h can be calculated:

$$Z_{f0}(h) = \frac{\overline{V_0}}{\overline{I_0}} = \frac{1}{a^2}\{R_T + j(h\omega_0 L_T - \frac{1}{h\omega_0 3C})\}. \tag{3.2}$$

Next, the equivalent ZS circuit of the filter can be established as depicted in Figure 3.4 (b). Equation (3.2) shows that the capacitor can be tuned to make the reactance part of the filter impedance zero for a specific harmonic. In this case, the filter impedance at the tuned harmonic would be only the transformer winding resistance value transferred to the primary side. For example, to tune the filter to the 9th harmonic (by making the reactance part of (3.2) zero), the required capacitor size can be calculated as follows:

$$C = \frac{1}{3h^2\omega_0^{\ 2}L_T} = \frac{1}{243\omega_0^{\ 2}L_T}. \tag{3.3}$$

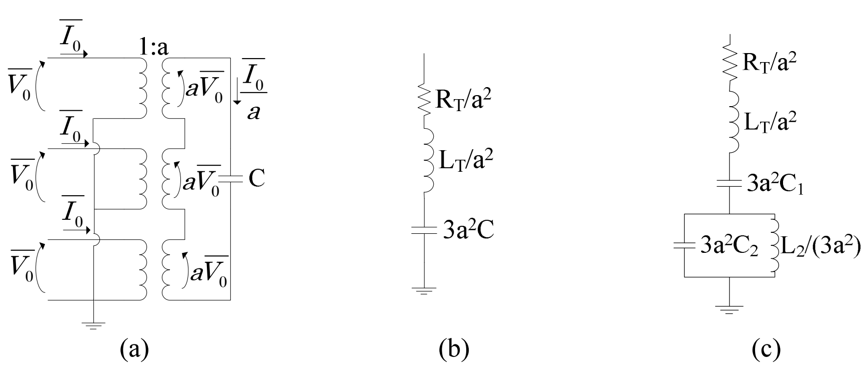


Figure 3.4 (a) The ZS filter (b) The equivalent ZS circuit of single-tuned ZS Filter (c) The equivalent ZS circuit of the double-tuned ZS Filter

With a similar procedure, the equivalent ZS circuit of the proposed double-tuned ZS filter can be derived as shown in Figure 3.4 (c). The obtained equivalent ZS circuit is very similar to the conventional double-tuned filters shown in Figure 3.5(b). Therefore, the proper component sizes of the proposed double-tuned ZS filter can be also derived by using a similar mathematical approach as follows [1]:

According to [1], the equivalent impedances of two parallel conventional single-tuned filters (Figure 3.5 (a)) close to their tuned harmonic frequencies are almost the same as those of a conventional double-tuned configuration (shown in Figure 3.5 (b)), subject to the following relationships among their component parameters:

$$\begin{cases} C_x = C_a + C_b \ , \ L_x = \dfrac{L_a L_b}{L_a + L_b} \\ C_y = \dfrac{C_a C_b (C_a + C_b)(L_a + L_b)^2}{(L_a C_a - L_b C_b)^2} \\ L_y = \dfrac{(L_a C_a - L_b C_b)^2}{(C_a + C_b)^2 (L_a + L_b)} \end{cases} \tag{3.4}$$

To establish the mathematical expressions for a double-tuned ZS filter tuned to the harmonic orders h_i and h_j, two single-tuned ZS filters separately tuned to h_i and h_j can be considered with the respective capacitor sizes of C_i and C_j, as in (3.5):

$$C_i = \frac{1}{3h_i^2 \omega_0^2 L_T}, \ C_j = \frac{1}{3h_j^2 \omega_0^2 L_T}. \tag{3.5}$$

The two parallel single-tuned filters (shown in Figure 3.5 (a)) are supposed to represent the equivalents of the two single-tuned ZS filters; therefore, their inductors and capacitor sizes are subject to the following relationships:

$$\begin{cases} L_a = \dfrac{L_T}{a^2}, \ L_b = \dfrac{L_T}{a^2} \\ C_a = 3a^2 C_i, \ C_b = 3a^2 C_j \end{cases} \tag{3.6}$$

Figure 3.5 (a) Two paralleled conventional single-tuned filters (b) The conventional double-tuned filter.

The component sizes of the double-tuned ZS filter can be obtained by using the equations set of (3.4). The only challenging issue involves L_x, which is the transformer leakage inductance. By comparing Figure 3.4 (c) and Figure 3.5(b), L_x is observed to be equal to L_T/a^2, on the other hand, according to (3.4), L_x has to be

$$L_x = \frac{L_a L_b}{L_a + L_b} \overset{(3.6)}{=} \frac{L_T}{2a^2} \tag{3.7}$$

To overcome this problem, one can divide the impedance value of every component of the double-tuned filter by two (i.e., divide/multiply the inductance/capacitance values by two) in order to satisfy (3.7) while keeping the tuned harmonic frequencies of the filter unchanged:

$$\begin{cases} C_x = 2(3a^2 C_1),\ C_y = 2(3a^2 C_2) \\ L_x = \frac{1}{2}(\frac{L_T}{a^2}),\ L_y = \frac{1}{2}(\frac{L_2}{3a^2}) \end{cases}. \tag{3.8}$$

Finally, combining equations (3.4), (3.6) and (3.8) leads to the final expressions for deriving the component sizes of the proposed ZS double-tuned filter as follows,

$$C_1 = \frac{C_i + C_j}{2}, \tag{3.9}$$

$$C_2 = \frac{2C_i C_j (C_i + C_j)}{(C_i - C_j)^2}, \tag{3.10}$$

$$L_2 = \frac{3L_T (C_i - C_j)^2}{(C_i + C_j)^2}, \tag{3.11}$$

where C_i and C_j are the capacitors tuned for the single-tuned ZS filters as defined in (3.5). For both the double-tuned and single-tuned ZS filters, the filter equivalent ZS impedance at the tuned frequencies is equal to transformer winding resistance referred to the primary side. For the filter to be effective, this resistance must be smaller than the system impedance.

3.3 Filter Construction & Design

Creating a low-resistance transformer does not involve any technical difficulties. However, constructing a ZS filter by using a specially designed MV transformer is highly uneconomical and must be avoided. A distribution utility company often has thousands of service transformers. If such transformers can be used, the filter cost can be reduced significantly. Furthermore, the LC components of the filter can be treated as the "loads" of the transformer. Installing a filter then becomes the same as adding a new "customer" to the system. To this end, the impedance characteristics of common service transformers have been investigated. The results show that one three-phase or three single-phase service transformers in the range of total 100kVA to 450kVA are sufficient to create an effective ZS filter. The secondary side voltage can be 480V or 208V. As a result, the proposed filter becomes a very attractive method for mitigating ZS harmonics.

The transformer size can be determined by comparing the system impedance with the transformer resistance (see Section 3.4.4). A more accurate size determination may be accomplished through Harmonic Load Flow (HLF) studies. Once the transformer size is selected, specification of the other filter components can be derived by using equations (3.3) or (3.5), (3.9)-(3.11) for the single tuned or the double-tuned versions, respectively.

Another factor to consider is that the transformer must not be overloaded by the harmonics it traps. This consideration creates the need to determine the loading conditions of the filter transformer. For this purpose, an index called the TLL (Transformer Loading Level) is developed. The details are presented in the Appendix B. If the index exceeds 1pu (indicating that the transformer is overloaded), a larger transformer must be utilized. The calculation of TLL becomes a part of the filter design process.

For assessing the loading of the capacitors, guidelines are already provided in the standards [37]. For the capacitors inside a ZS filter, however, their capacitance must not be changed in case of overloading (because the capacitances are strictly determined by the transformer specifications as in (3.9)-(3.10)). Therefore, to alleviate the loading of such capacitors, one has to increase their rated voltage and kvar without altering their capacitance (uF).

Based on the above considerations, the overall design procedure of the proposed ZS filters is presented in Figure 3.6. The filter placement procedure is dependent on the type of the problem to be solved. In Section 3.4.3, the filter locating issues specific to a telephone interference problem will be discussed.

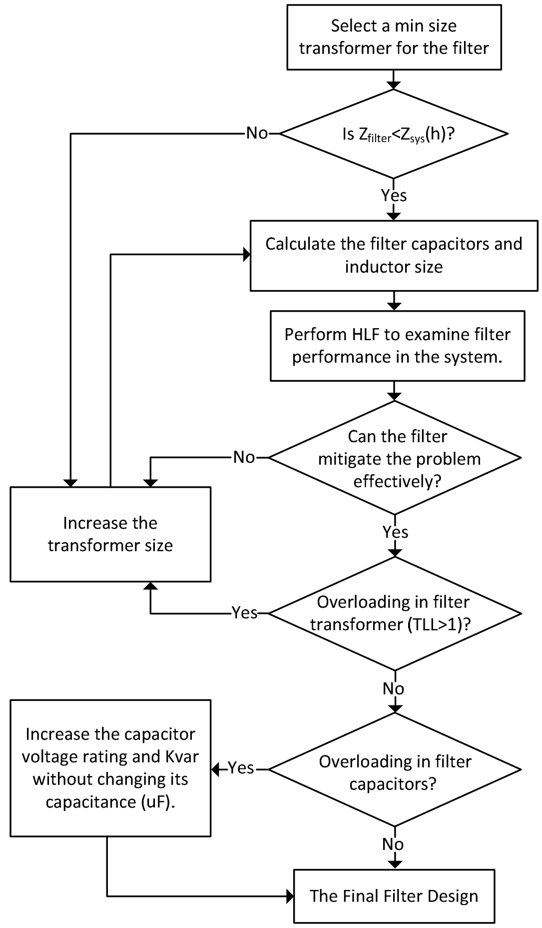


Figure 3.6 The flowchart of design procedure for the proposed ZS filters

3.4 Application Example

The proposed ZS filter and its design procedure were tested by solving a telephone interference problem faced by an actual system. Telephone interference is probably the most common issue caused by ZS harmonics. Subsection 3.4.1 presents some information regarding the studied telephone interference problem. In subsection 3.4.2, the telephone interference problem is quantified and a mitigation objective is established. The number of required filters and their placement issues are discussed in subsection 3.4.3. Next, in subsection 3.4.4, the ZS filters are designed based on the proposed procedure. Different filter case studies are also performed and discussed in this section. At the end, subsection 3.4.5 evaluates loading of the designed filters based on the proposed methodology.

3.4.1 Problem Description

The studied telephone interference problem is associated with the actual feeder introduced in Chapter 2. As shown in Figure 3.7, a telephone-line is experiencing severe disturbing noises induced by the feeder's adjacent overhead sections. The sections in parallel with the overhead power lines are shown by the dashed lines in Figure 3.7 (The effect of the underground sections in noise induction is negligible since the neutral conductor is very close to the phase conductors in an underground cable and also carries the whole returning current, canceling out the overall generated electromagnetic field). The ZS filters will be examined by the developed simulation platform described in Chapter 2. Additionally, since the neutral wires are also included by the multi-phase models, the telephone lines can be also added to the model for the interference level assessment. For this case, two sample parallel conductors are also included in the system model for representing the involved telephone line sections (dashed lines in Figure 3.7).

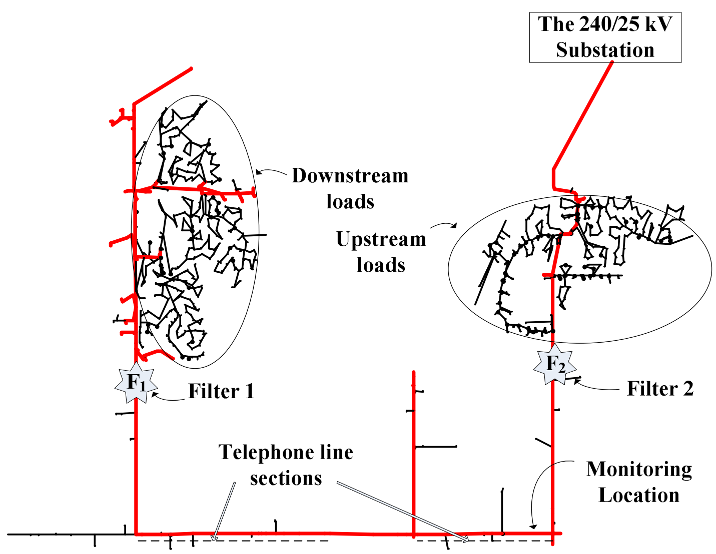


Figure 3.7 The schematic view of the studied distribution feeder

3.4.2 Telephone Interference Mitigation Objective

The ZS component of the harmonic currents in an overhead power-line is the dominant source of the noise induction on the adjacent telephone lines [26],[38]. Most of the ZS component of a harmonic current is dominated by the triplen harmonic orders such as 3rd, 9th, 15th. As well, for the telephone interference, the "C-message" factors determine the contribution of each harmonic frequency to the disturbing noise [26],[38].

The C-message factors, which are presented in [38] (shown in Table 3.1) are derived on the basis of the sensitivity of the human ear and the vulnerability of the communication circuits to different noise frequencies.

Table 3.1 C-message weighting factors for different harmonic frequencies

Harmonic order	1	3	5	7	9	11	13	15
C-message weighting factor	0.001	0.033	0.150	0.309	0.488	0.684	0.861	0.966

The factor is very small for the 3rd harmonic compared to that for the higher-order ones. Since the magnitude of harmonic orders higher than the 15th in residential distribution system is negligible, the 9th and 15th ZS harmonic orders can be identified as the main contributors to a telephone interference problem. Therefore, the proposed double-tuned filter will be tuned to the 9th and 15th harmonic frequencies.

As recommended by [38], the actual interference level can be quantified by multiplying the induced voltage of each harmonic frequency on the communication line by its corresponding C-message factor. Therefore, an index called the 'C-Message Weighted Voltage' (CMWV) can be defined as below:

$$CMWV_h = w_h V_h , \tag{3.12}$$

where V_h and w_h are the induced voltage of hth harmonic frequency on the telephone line and its corresponding C-message weighting factor, respectively. Next, the total value of the CMWV determined by (3.12) can exhibit the total interference level:

$$CMWV_{total} = \sqrt{\sum_{h=1,3,...} CMWV_h^{\ 2}} . \tag{3.13}$$

The above index was adopted for this thesis to assess the effectiveness of the mitigation techniques for the telephone interference problem. The mitigation objective used to find the final filter design was set to be a 75% decrease of the total interference level ($CMWV_{total}$).

3.4.3 Filter Location

In order to effectively mitigate a telephone interference problem, the installation of harmonic filters must eliminate the troublesome ZS harmonic currents in the power-line sections causing the disturbance. This section investigates the required number of filters and their appropriate placement in the studied feeder (shown in Figure 3.7).

During the normal system condition, most load-generated harmonic currents flow to the substation due to the low supply system impedance. The ideal location for installing the filter to mitigate the telephone interference problem is at the downstream side of the telephone line such as location 'F1' shown in Figure 3.7. The filter is expected to sink the harmonics produced by the downstream loads. Thus, these harmonics will not travel upstream and interfere with the telephone line upstream. However, an important issue must be addressed here: *Will the filter also attract the harmonics from the upstream loads?* If the filter does so, it may not be able to reduce the telephone interference level. HLF simulation results can determine whether this issue will be a problem or not. If a problem is caused in the mitigation, then two filters will be required, and the second one will need to be installed at the location between the telephone line and the upstream loads (labelled by F2 in Figure 3.7).

3.4.4 Filter Design Results

For selecting the transformer size, some of the typical sizes of the three-phase transformers used by the utility company in their 25kV voltage level distribution systems are listed in Table 3.2. The ZS impedance of the filter at the tuned harmonics obtained by each of the transformer sizes is also provided in the last column.

Table 3.2 The (ZS) filter impedance obtained by different sizes of transformers

Transformer				$Z_{filter}(\Omega)$
S (kVA)	V_{low} (V)[a]	R_{pu} (%)	Z_{pu} (%)	
9750	208	0.93	5.3	0.59
7500	208	0.93	5.3	0.77
2500	600	0.52	5.75	1.29
1500	480	0.72	5.9	2.99
1000	600	0.73	4.7	4.53
500	600	0.84	4.36	10.39
450	480	0.89	4.28	12.29
300	208	0.88	4.3	18.18
225	600	1.03	3.88	28.56
150	208	1.19	3.32	49.51
75	208	1.13	3.22	93.96

a: The nominal line-to-line voltage of transformer (LL-rms). The primary-side voltage is 25kV (LL-rms) for all of the listed transformers.

On the other hand, the system model is also used to estimate the system equivalent ZS impedance at the 9th and 15th harmonic frequencies at the proposed filter location (F_1 in Figure 3.7). The obtained minimum values during the day are 56.84Ω and 41.6Ω for the 9th and 15th harmonic orders, respectively. Because of these values, the transformer size of 225 kVA is adopted as the minimum transformer size to be used in the ZS filter design procedure. As Table 3.2 shows, this transformer size provides a 28.56 Ω filter impedance, which is smaller than the minimum value of the system impedance at 9th and 15th harmonics.

The introduced iterative process (Figure 3.6) was employed to determine the final filter design. Table 3.3 presents the component sizes of the designed filter package. Two filters at both the F1 and F2 locations (in Figure 3.7) were required to fulfill the mitigation objective of a 75% decrease in the interference level. In addition, a single-tuned version of the ZS filter with the same transformer size (450kVA) and tuned to the 9th harmonic was also designed and modeled in the simulations for a comparative study. As Table 3.3 shows, the capacitor sizes required for the double-tuned filter were larger than those of the single-tuned one, but the values are still practical and not too large if compared with those of the conventional filter designs. Figure 3.3 shows the ZS impedance of the designed filter configurations for different harmonic frequencies.

Table 3.3 Designed Components Size for the Single and Double-Tuned Filters

Transformer Size	The Single-Tuned	The Double-Tuned		
450 kVA	C	C_1	C_2	L_2
	44.20 kvar [a]	30.05 kvar	105.66 kvar	37.80 µH

a: The kvar value is calculated by assuming the transformer secondary-side voltage (480V) as the rating value of capacitor.

In order to establish a sound understanding of the discussed ZS filters performance, the HLF simulation results for the following cases are also presented and discussed in this section.

- Case I: normal system condition before installing any filter.
- Case II: one single-tuned version of the designed ZS filter (with 450kVA transformer) is installed in location F1.

- Case III: two single-tuned version of the designed ZS filter (with 450kVA transformer in Table 3.3) are installed in the locations F1 and F2.
- Case IV: one double-tuned version of the designed ZS filter (with 450kVA transformer in Table 3.3) is installed in location F1.
- Case V: one double-tuned version of the designed ZS filter but with a larger transformer size of 1000kVA is installed in location F1.
- Case VI: two double-tuned versions of the designed ZS filter (with 450kVA transformer in Table 3.3) are installed in the locations F1 and F2 (This case presents the recommended filter set to completely fulfill the mitigation objective).

In order to quantify the mitigation efficiency of each filter case, the following three indices were adopted and are shown in Figure 3.8 through Figure 3.10.

- IDD (Individual Demand Distortion) of the dominant sequence harmonic currents calculated at the "Monitoring Location" shown in Figure 3.7.
- The frequency spectrum of the total induced voltage on the parallel conductor representing telephone line.
- The C-message weighted values of the induced noise voltages ($CMWV_h$ and $CMWV_{total}$, which were used for defining the mitigation objective).

The daily 95% percentile value of each index during the day is calculated and presented for each case (for the details of daily 95% percentile value, refer to Section 2.4).

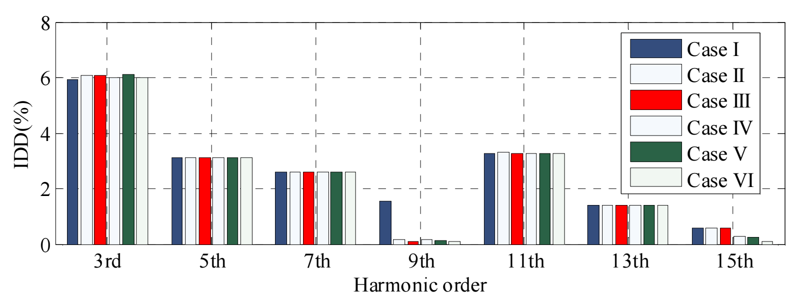


Figure 3.8 IDD of the dominant sequence of harmonic current components (daily 95% percentile value)

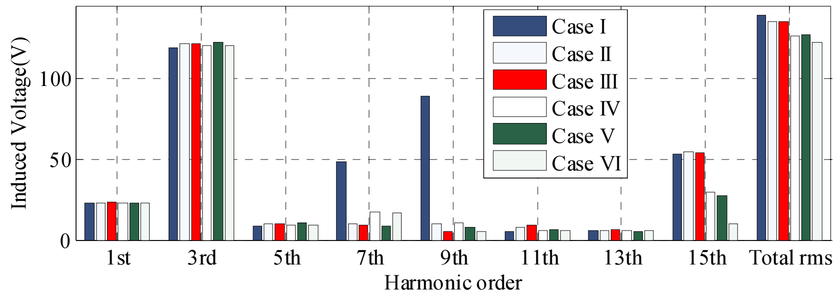


Figure 3.9 The harmonic spectrum of induced voltage on the parallel conductor (daily 95% percentile value)

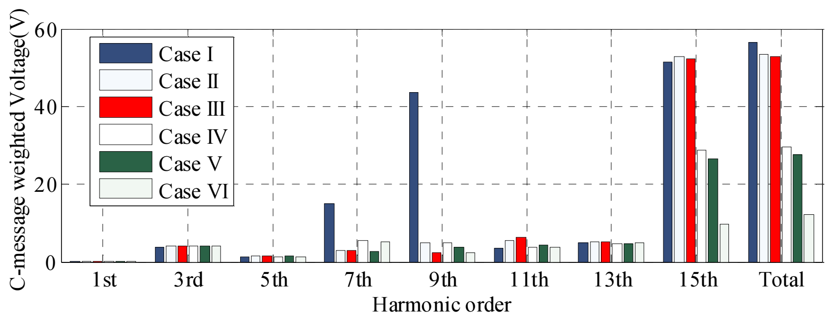


Figure 3.10 C-message weighted voltage components induced on the parallel conductor (daily 95% percentile value)

The following are the key observations from the simulation results:

- The results imply that the final designed filter set (case VI) effectively removed both the 9th and 15th harmonic components in either the power-line current (Figure 3.8) or the induced voltage on the parallel conductor (Figure 3.9). By lowering the total CMWV from 56.5V to 12V, the goal of a 75% decrease in interference level was achieved (Figure 3.10).
- The double-tuned ZS filters were found to be effective in mitigating both the 9th and 15th harmonics. Although the single-tuned versions could suppress the 9th harmonic, they were unable to mitigate the 15th harmonic. The 15th harmonic component was observed to increase in the single-tuned filter cases (II & III) and to cause a mitigation failure (See Figure 3.9 and Figure 3.10). This phenomenon is likely due to a parallel resonance between the filter and the system at the 15th harmonic frequency. At this harmonic frequency, the filter is inductive and the system is capacitive because of the shunt capacitance of the underground cables. Such observations once again confirm the need to use the proposed double-tuned ZS filter to mitigate a telephone interference problem.

- One single filter at location F1 was observed to be sufficient for effectively mitigating the 9th harmonic. However, the single location filter scenarios (cases IV & V) could not decrease the 15th harmonic by more than 40%. Specifically, case V even with a considerably larger transformer (1000kVA), did not lead to a further reduction of the 15th harmonic. Nonetheless, a single designed filter (case IV) mitigated almost 48% of the interference level, as shown in Figure 3.10. However, to achieve the mitigation objective of a 75% decrease in the noise level, two of the designed double-tuned filter packages were required at both locations F1 and F2.
- As we expected, Figure 3.8 shows that, the ZS filters had no effect on the positive/negative sequence harmonic components. For all the filter scenarios, the non-triplen harmonic values were not changed from the case without any filter.

3.4.5 Filter Loading Assessment Results

The procedure described in the Appendix B was employed to evaluate the loading of the transformer inside the designed double-tuned ZS filters. The harmonic currents flowing inside the transformers were obtained from the simulations and are shown in Figure 3.11, which shows that the 9th and 15th harmonic currents, which the filters were tuned to, were the dominant components.

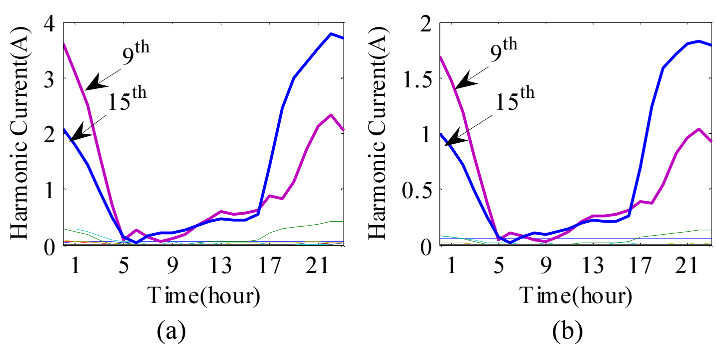


Figure 3.11 Daily profile of harmonic currents flowing inside the transformer (primary side) of the designed ZS filters (a) at location ‘F1’ (b) at location ‘F2’.

An analysis was conducted for both dry-type and liquid-filled transformers. As given in Table 3.4, conservative values for P_{EC-R}(pu) and P_{OSL-R}(pu) were adopted based on the transformer size (450kVA) and the data presented in Table B.1. P_{OSL-R}(pu) was also calculated by using equation (B.8) in the Appendix. The TLL index was calculated for both filters' transformers and is presented in Figure 3.12.

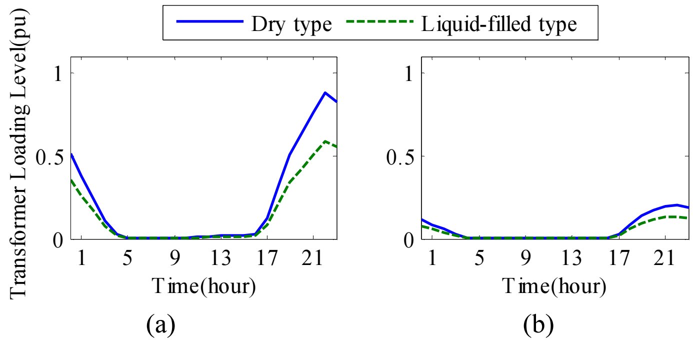


Figure 3.12 Estimated daily profile of the transformer loading level (TLL) for the designed ZS filters (a) at location 'F1' (b) at location 'F2'

The results illustrate that the transformers loading level was under the eligible maximum (1pu) for the whole day; therefore, the designed filters could operate safely without overloading their transformers.

Table 3.4 The adopted values of $P_{EC\text{-}R}$ and $P_{OSL\text{-}R}$ for the loading assessment

Transformer type	Dry type	Liquid-filled type
$P_{EC\text{-}R}$(pu)	0.08	0.05
$P_{OSL\text{-}R}$(pu)	0.04	0.1

3.5 Conclusions

This chapter presented a novel and effective filter to mitigate ZS harmonics in the power systems. The design and construction issues of the filters are fully investigated. The main findings and contributions of this work can be summarized as follows.

- The proposed filter can trap two harmonics simultaneously. It becomes a very attractive method to mitigate telephone interference problems.
- The filter can be constructed using regular service transformers and low voltage LC components. As a result, it is a very cost-effective filter. Installing a filter is as sample as adding a customer to the distribution system.
- A practical design procedure has been developed for the filter. This chapter also presented a method for loading assessment of the filter transformer.
- The proposed filter package and its design method have been tested through computer simulation studies. The results have shown that the filter is quite

effective to trap zero sequence harmonics and is an attractive solution to the telephone interference problem.

Chapter 4

Design of Medium-Voltage Passive Harmonic Filters

The shunt connected passive harmonic filters are a popular choice for the medium- and high-voltage applications in power systems [3],[8]-[11],[14]. This chapter discusses the option of installing Medium-Voltage (MV) filters to achieve a system-wide harmonic mitigation in residential distribution power systems. The proposed ZS filters in Chapter 3 are also included to develop an effective MV filter package. An iterative design procedure is introduced. It helps to simplify addressing the complex problem of designing such filters to mitigate distributed harmonic sources.

The chapter is organized as follows. Section 4.1 describes the adopted passive MV filter topologies. The key considerations required for designing the MV passive filters are reviewed in section 4.2. A general and practical design procedure is proposed in section 4.3. This procedure serves as a practical guideline for designing MV passive filters to mitigate the harmonics of a residential feeder. The proposed method is employed in section 4.4 to design MV filters for both the studied feeders in order to accomplish the mitigation goals defined in this thesis. The final design specifications for the feeders are tabulated in section 4.5. Section 4.6 presents a summary of the contents of this chapter.

4.1 MV Passive Harmonic Filter Package

One of the first important steps in designing a passive harmonic filter is to select the proper topology. Most of the filter topology studies such as [8],[12] have focused on the industrial harmonic sources. The results of these investigations as well as the common industry practice recommend the conventional single-tuned filters as the preferred topologies based on the economic and design issues. However, as discussed before, there is also considerable amount of ZS harmonics such as 3^{rd}, 9^{th} and 15^{th} in a residential distribution feeder. Therefore, the proposed double-tuned ZS filter introduced in Chapter 3 is also included in the suggested MV filter package to mitigate 3^{rd} and 9^{th} harmonics as well. Using the ZS filter instead of the single-tuned filters for eliminating the ZS harmonics has the following advantages:

1) The ZS filter will not adversely affect the reactive power profile and other non-ZS harmonics of the system.

2) Compared to the alternative choice of two single-tuned filters tuned to the ZS harmonics, the double-tuned ZS filter can be a much simpler and less expensive option (The economic analysis in the consequent chapter will demonstrate this fact).

Figure 4.1 shows the selected MV filter package for this chapter studies.

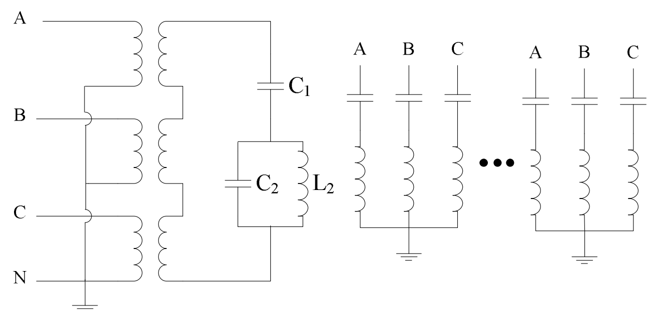


Figure 4.1 The MV level passive filter package consisting of a double-tuned ZS filter and the conventional single-tuned filter branches.

4.2 Design Considerations

Several constraints and issues have to be considered when designing a passive harmonic filter. This section discusses the key design issues thereby developing a general design guideline.

4.2.1 System Reactive Power Profile

Traditionally, the capacitors of harmonic filters were sized according to the reactive power requirements of the system [8],[12]. However, the distribution feeders serving residential loads generally do not require a planned reactive power compensation. Such systems usually include several underground cable sections so that their shunt capacitances collectively lead to a considerable source of reactive power.

For example, Figure 4.2 and Figure 4.3 show the estimated daily profile of real/reactive power associated with the real and ideal feeders monitored in substation obtained from simulation results. The reactive power consumption of both feeders is negligible and it is even negative in some hours for the actual feeder (Figure 4.2) which is due to the shunt capacitance of its underground cables.

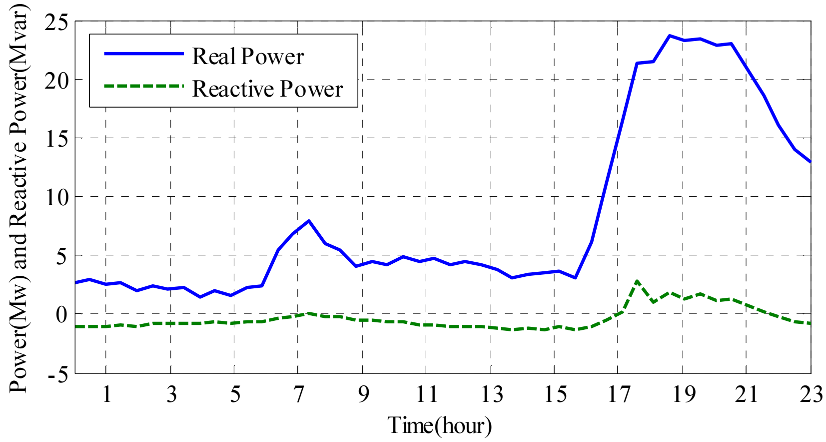


Figure 4.2 Daily profile of real/reactive power profile of the actual feeder.

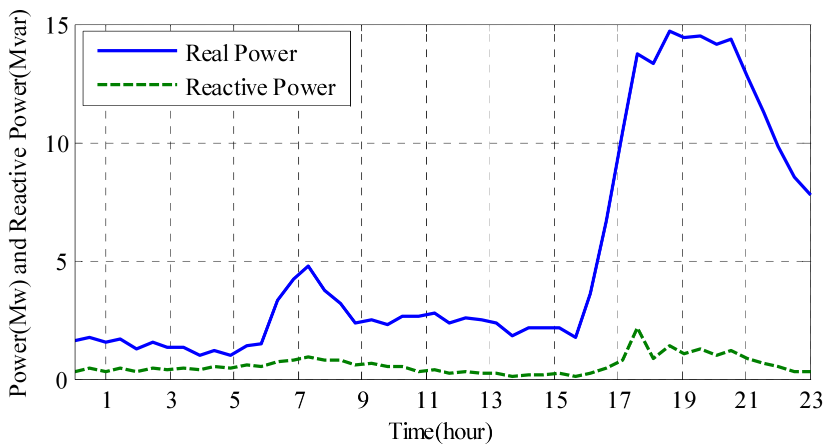


Figure 4.3 Daily profile of real/reactive power profile of the ideal feeder.

Therefore, the filters will be designed with the minimum capacitor sizes for these systems not only to avoid occurrence of any overvoltage along the feeder (because of extra reactive power) but also to decrease the component costs. However, after the design is finalized, the voltage profile of the feeder must be checked. In case of observing overvoltage in the system, the sizes of filter capacitors shall be decreased.

It must be also noted that the above concerns are just for single-tuned branches, and not for the ZS filter part which does not affect the reactive power profile of the system.

4.2.2 Filter Components Loading

A harmonic filter is susceptible to failures and breakdowns if its components are exposed to excessive harmonic currents and voltages. According to IEEE standards [3],[37], the voltage and current waveform during operation of filter capacitors are required not to exceed the following limits.

a) 110% of rated rms voltage.
b) 120% of rated peak voltage (i.e. rated rms voltage multiplied by square root of two).
c) 135% of nominal rms current based on rated kvar and voltage.
d) 135% of rated kvar.

During the design procedure, loading condition of all the filter capacitors have to be analyzed according to the above standard limits. If the operation current and voltage of a capacitor is observed to exceed the limits in simulations, its size must be increased. However, for the capacitors inside the ZS filter, both of their kvar and rated voltage have to be increased to avoid changing their capacitance.

The loading level of the transformer inside the ZS filter can be also assessed by the procedure developed in Chapter 3. Again, if its loading analysis illustrates an overloading condition, a larger size of transformer must be chosen.

4.2.3 Filter Placement

In the traditional harmonic filter applications, filters have been installed at the PCC of the large and known harmonic-generating load and therefore placement has not been a major filter design issue. However, in the residential distribution systems harmonic sources are not concentrated in single points and can be dispersed all along the feeder. As discussed in Chapter 1, several algorithms and strategies have been developed for allocation and placement of passive filters in a distribution system [15]-[17]. Such algorithms are too complex and need several computational efforts. Besides, since most of them are developed on the basis of oversimplified harmonic models, they can not be employed for the simulation platform of this thesis. Therefore, this thesis tackles such complex problem of filter placement for distributed sources with a simplified and practical iterative approach as described below.

1) The possible locations for the passive filters are identified in each feeder.
2) The filter design procedure starts with a minimum size package.
3) The filter package performance is then assessed by running the HLF simulations for the different locations. If the mitigation objective is achieved by installing the filter in

one of the locations, then the filter design is finalized and the location with the highest elimination of harmonics is chosen. However, if none of the locations can bring the expected mitigation efficiency, the filter package design will be improved and the whole process will be repeated for the new package again.

4) In case one filter package fails to obtain the mitigation goals, the design procedure can be continued with installing two harmonic filters in two locations.

4.3 Overall Design Procedure

The overall passive harmonic filter design procedure is established in this section based on the discussions in section 4.2. Figure 4.4 illustrates an overall view of the proposed methodology in which the placement and loading assessment considerations are combined into the proposed iterative procedure.

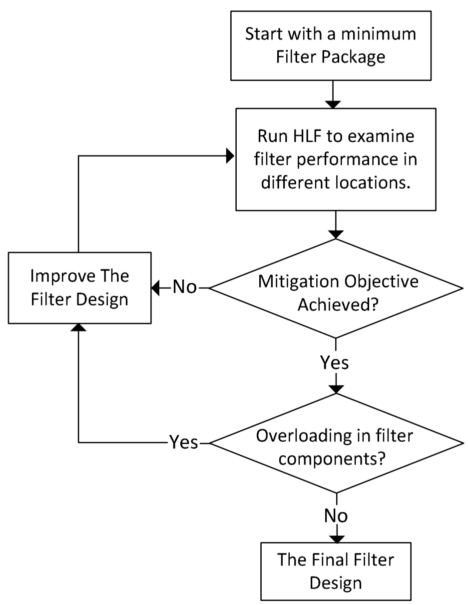


Figure 4.4 The proposed iterative design procedure in a quick view.

Figure 4.5 shows every details of the design process where the filter improvement block in Figure 4.4 is also expanded. As shown in the flowchart, the whole procedure can be explained as below:

- The first step in improving the filter package is increasing capacitor size of single-tuned branches. The inductors are also sized accordingly (For further details of designing single-tuned branches, refer to Appendix C.1). The capacitor size can be increased up to their maximum limit (which is chosen by the designer in the beginning of process).

- If the capacitors sizes reach their maximum limit and filter package still needs to be improved, the second step will be taken that is to enlarge the ZS filter transformer. Then, the other components of the ZS filter can be designed accordingly based on the guidelines developed in Chapter 3.
- If the larger transformer sizes of ZS filter also fail to achieve the essential filtering improvements, the designer can consider the addition of a new single-tuned branch to the filter package. However, in the proposed design procedure, maximum number of single-tuned branches is considered to be three.
- In case a filter package even including three single-tuned branches beside the ZS filter is still unable to gain the mitigation objective, the designer has to choose the option of installing two filter packages in two different locations of the feeder.
- Setting the harmonic mitigation objective was fully discussed in Chapter 2. In summary, the goal is to decrease both the average voltage THD over the feeder and harmonic current TDD in substation by 75% (the daily 95% percentile values are considered).

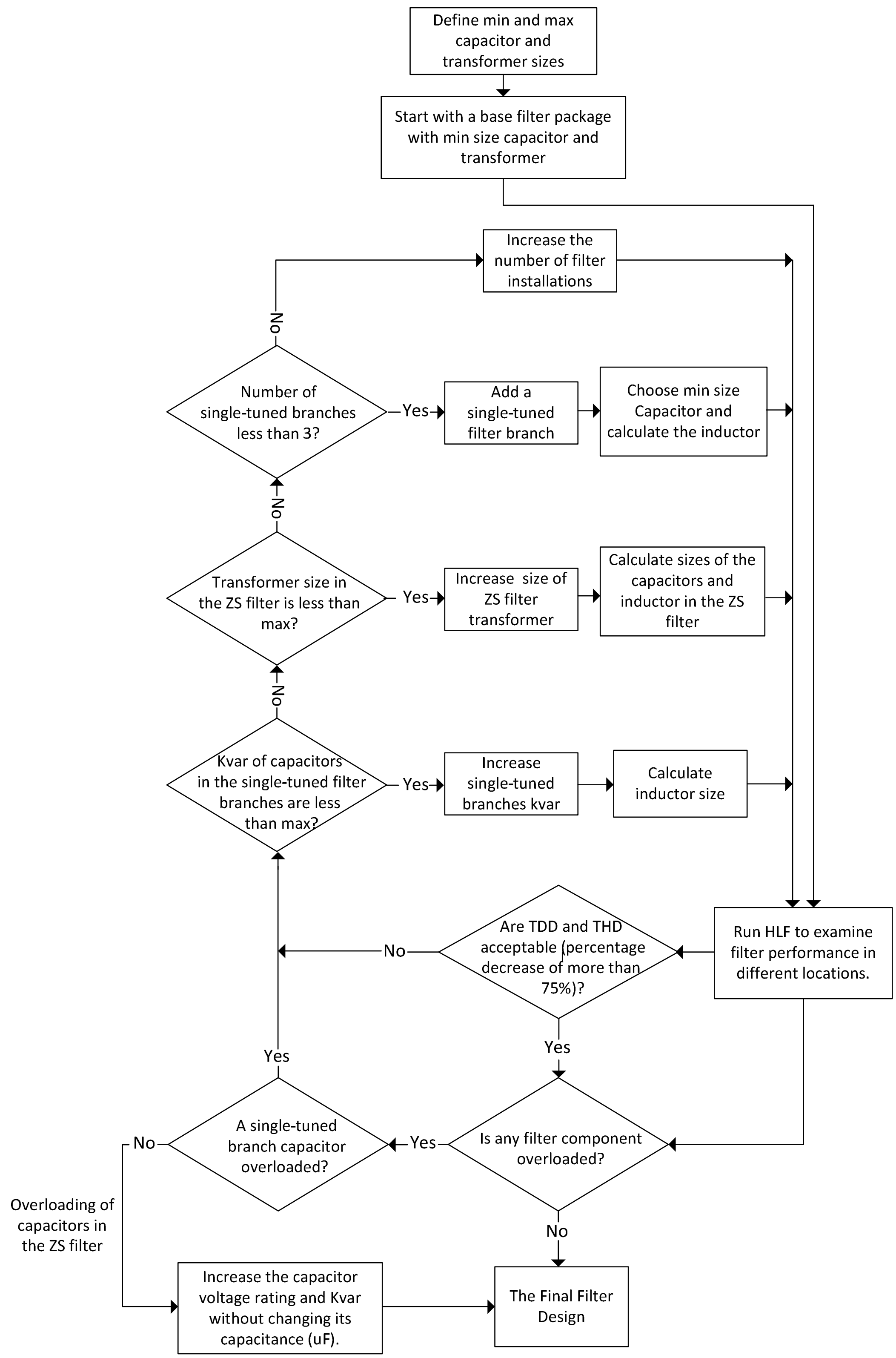


Figure 4.5 Detailed flowchart of the proposed design procedure for the MV passive filter.

4.4 Iterative Design Results

The proposed procedure is employed to design the passive MV filters for both of the real and ideal feeder. The iterative route taken to obtain the final proper design for each of the systems is presented in this section.

Table 4.1 lists the different sizes of transformers used for design of ZS filter. The standard capacitor sizes of 150,300,450,600,900 and 1200 kvar are also adopted in this design [37].

Table 4.1 List of transformers used for the filter design.

Transformer				$Z_{filter}(\Omega)$
S (kVA)	V_{low} (V)[a]	R_{pu} (%)	Z_{pu} (%)	
300	208	0.88	4.3	18.18
500	600	0.84	4.36	10.39
1000	600	0.73	4.7	4.53
2500	600	0.52	5.75	1.29

a: The nominal secondary-side voltage of transformer (LL-rms).
The primary-side voltage is 25kV for all of the listed transformers.

Regarding the filter location(s), two potential locations are chosen for the actual feeder labeled as 'MV I' and 'MV II' in Figure 4.12. For the ideal feeder, four possible locations are selected along the feeder with the distances of 3, 7, 10 and 13km from the substation, respectively.

For selection of the tuning frequencies, the harmonic distortion spectrum of the feeders shown in Figure 4.6 and Figure 4.7 must be considered. For both of the feeders, the ZS filter will be tuned to 3^{rd} and 9^{th} which are the dominant ZS components. Among the other harmonic orders, 5^{th} and 11^{th} are the dominant ones so that they are chosen as the tuning frequencies for the first two single-tuned branches. The next branch, if necessary, will be tuned to 7^{th} (for the actual feeder, one branch will be tuned to 13^{th} rather than 11^{th} due to its special system impedance. More details will be provided in section 4.4.2).

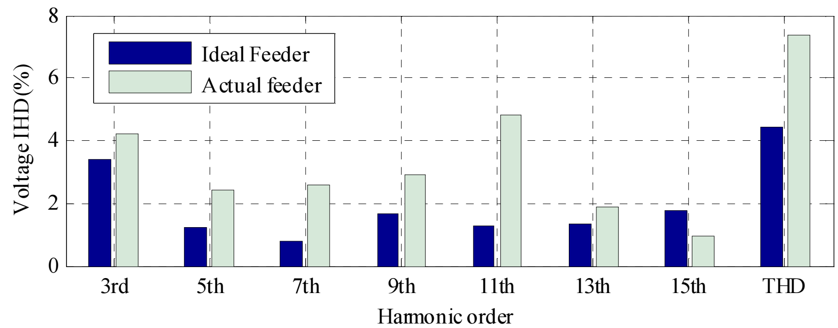


Figure 4.6. Votage IHD of both feeders average over feeder before filter installation (daily 95% percentile value).

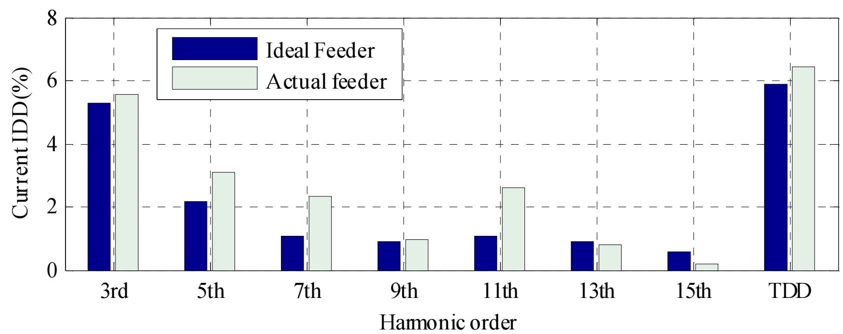


Figure 4.7 Current IDD of both feeders at the substation before filter installation (daily 95% percentile value).

Sections 4.4.1 and 4.4.2 present the design procedure and results for the ideal and actual feeders, respectively.

4.4.1 For Ideal Feeder

Table 4.2 lists the cases which are iteratively generated to find the final MV passive filter design for the ideal feeder. As seen in the table, each case has been examined in all the four locations. The results show that two single-tuned branches beside the ZS filter can not be sufficient to achieve the mitigation objective and a third branch is also essential. For example, in cases no. 17 to 19, although maximum size of transformers and capacitors are used, the percentage decrease of voltage THD is still less than the defined goal of 75%.

By addition of a 7^{th} single-tuned branch, the filter performance is improved. Finally, for case no. 50 (which is highlighted in the table) the aimed decrease in THD and TDD is obtained. The filter components are also not overloaded in this case. The filter location of this final design is 7km from substation, which is almost in the middle of the feeder.

Figure 4.8 and Figure 4.9 show the system and the designed filter impedance obtained by performing frequency scan on HLF models. Table 4.3 also gives the detail of loading assessment of the designed filter components. All components are showing acceptable loading level according to IEEE standards. The daily voltage profile of the feeder is also plotted in Figure 4.10 and Figure 4.11 for the middle and the end point, respectively. As the voltage profile shows, the designed filter not only has not caused any overvoltage problem, but also has improved the voltage level during the peak hours. Therefore, the performance of the designed package is also validated with regard to the system reactive power requirements.

Table 4.2 The results of iterative filter design procedure for ideal feeder.

Case No.	ZS filter	Single tuned filter branches						Filter Location	Filter effectiveness		Loading assessment	
	Transformer size (kVA)	#1		#2		#3		Distance from substation (km)	Percentage decrease in TDD	Percentage decrease in THD	Single tuned filters	The ZS filter
		h_{tuned}	Capacitor (kvar)	h_{tuned}	Capacitor (kvar)	h_{tuned}	Capacitor (kvar)					
1	300	4.9	300	10.9	150	-	-	3	36.56	26.81	×	×
2	300	4.9	300	10.9	150	-	-	7	51.48	44.84	×	×
3	300	4.9	300	10.9	150	-	-	10	53.99	51.11	×	×
4	300	4.9	300	10.9	150	-	-	13	51.73	52.01	×	×
5	300	4.9	450	10.9	300	-	-	3	37.31	29.10	✓	×
6	300	4.9	450	10.9	300	-	-	7	53.09	48.81	✓	×
7	300	4.9	450	10.9	300	-	-	10	55.80	55.74	✓	×
8	300	4.9	450	10.9	300	-	-	13	53.42	56.45	✓	×
9	300	4.9	900	10.9	600	-	-	3	37.24	31.56	✓	×
10	300	4.9	900	10.9	600	-	-	7	54.99	53.20	✓	×
11	300	4.9	900	10.9	600	-	-	10	58.33	60.71	✓	×
12	300	4.9	900	10.9	600	-	-	13	55.83	61.07	✓	×
13	2500	4.9	600	10.9	450	-	-	3	75.79	49.02	✓	✓
14	2500	4.9	600	10.9	450	-	-	7	74.83	67.48	✓	✓
15	2500	4.9	600	10.9	450	-	-	10	69.36	71.38	✓	✓
16	2500	4.9	600	10.9	450	-	-	13	60.70	67.28	✓	✓
17	2500	4.9	1200	10.9	900	-	-	3	77.63	51.94	✓	✓
18	2500	4.9	1200	10.9	900	-	-	7	75.67	71.02	✓	✓
19	2500	4.9	1200	10.9	900	-	-	10	70.59	73.51	✓	✓
20	2500	4.9	1200	10.9	900	-	-	13	62.15	68.77	✓	✓
21	300	4.9	300	10.9	150	6.9	150	3	36.65	27.36	×	×
22	300	4.9	300	10.9	150	6.9	150	7	52.02	45.97	×	×
23	300	4.9	300	10.9	150	6.9	150	10	54.63	52.50	×	×
24	300	4.9	300	10.9	150	6.9	150	13	52.38	53.42	×	×
25	300	4.9	600	10.9	450	6.9	450	3	37.18	31.13	✓	×
26	300	4.9	600	10.9	450	6.9	450	7	54.90	52.73	✓	×
27	300	4.9	600	10.9	450	6.9	450	10	58.17	60.38	✓	×
28	300	4.9	600	10.9	450	6.9	450	13	55.70	60.85	✓	×
29	300	4.9	1200	10.9	900	6.9	900	3	35.96	33.28	✓	×
30	300	4.9	1200	10.9	900	6.9	900	7	57.66	56.72	✓	×
31	300	4.9	1200	10.9	900	6.9	900	10	62.14	64.57	✓	×
32	300	4.9	1200	10.9	900	6.9	900	13	59.92	65.02	✓	×
33	1000	4.9	600	10.9	450	6.9	450	3	73.99	47.83	✓	✓
34	1000	4.9	600	10.9	450	6.9	450	7	75.66	67.77	✓	✓
35	1000	4.9	600	10.9	450	6.9	450	10	69.56	72.19	✓	✓

Table 4.2 (continued).

Case No.	ZS filter	Single tuned filter branches						Filter Location	Filter effectiveness		Loading assessment	
	Transformer size (kVA)	#1		#2		#3		Distance from substation (km)	Percentage decrease in TDD	Percentage decrease in THD	Single tuned filters	The ZS filter
		h_{tuned}	Capacitor (kvar)	h_{tuned}	Capacitor (kvar)	h_{tuned}	Capacitor (kvar)					
36	1000	4.9	600	10.9	450	6.9	450	13	61.14	68.77	✓	✓
37	1000	4.9	1200	10.9	900	6.9	900	3	77.21	51.46	✓	✓
38	1000	4.9	1200	10.9	900	6.9	900	7	78.84	73.04	✓	✓
39	1000	4.9	1200	10.9	900	6.9	900	10	71.95	77.47	✓	✓
40	1000	4.9	1200	10.9	900	6.9	900	13	63.35	73.04	✓	✓
41	2500	4.9	450	10.9	300	6.9	300	3	80.07	48.73	✓	✓
42	2500	4.9	450	10.9	300	6.9	300	7	76.83	67.14	✓	✓
43	2500	4.9	450	10.9	300	6.9	300	10	69.45	70.98	✓	✓
44	2500	4.9	450	10.9	300	6.9	300	13	60.60	67.48	✓	✓
45	2500	4.9	900	10.9	600	6.9	600	3	86.00	52.60	✓	✓
46	2500	4.9	900	10.9	600	6.9	600	7	80.24	72.80	✓	✓
47	2500	4.9	900	10.9	600	6.9	600	10	71.73	76.67	✓	✓
48	2500	4.9	900	10.9	600	6.9	600	13	62.50	72.09	✓	✓
49	2500	4.9	1200	10.9	900	6.9	900	3	88.25	54.51	✓	✓
50	2500	4.9	1200	10.9	900	6.9	900	7	81.57	75.51	✓	✓
51	2500	4.9	1200	10.9	900	6.9	900	10	72.79	79.31	✓	✓
52	2500	4.9	1200	10.9	900	6.9	900	13	63.54	74.15	✓	✓

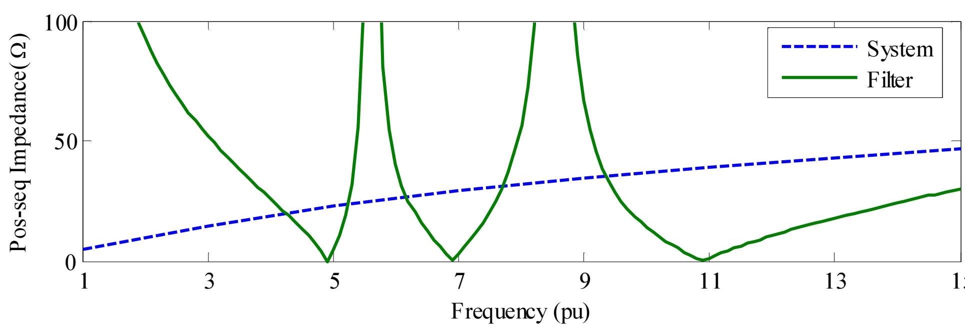


Figure 4.8 Positive-sequence frequency scans of the designed filter and system impedance for ideal feeder.

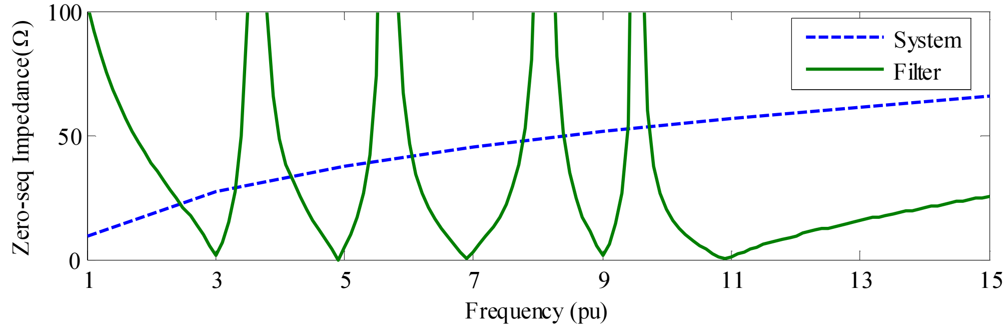


Figure 4.9 Zero-sequence frequency scans of the designed filter and system impedance for ideal feeder.

Table 4.3 Loading analysis of the designed filter for the ideal feeder.

Filter component			Operation value	Rated value	Ratio of operation to rated value (%)	IEEE standard limit (%)	Is under limit?
ZS filter	C_1	Peak voltage(V)	140.5	848.5	16.6	120	✓
		RMS voltage(V)	101.0	600	16.8	110	✓
		RMS current(A)	760.0	1497.2	50.8	135	✓
		kvar	76.5	898.3	8.5	135	✓
	C_2	Peak voltage(V)	2.4	848.5	0.3	120	✓
		RMS voltage(V)	1.6	600	0.3	110	✓
		RMS current(A)	6.9	842.2	0.8	135	✓
		kvar	0.0	505.3	0.0	135	✓
Single-tuned filter branches	C_{5th}	Peak voltage(V)	21575.0	20365	105.9	120	✓
		RMS voltage(V)	15358.0	14400	106.7	110	✓
		RMS current(A)	30.4	27.8	109.4	135	✓
		kvar	1368.5	1200	114.0	135	✓
	C_{11th}	Peak voltage(V)	21410.0	20365	105.1	120	✓
		RMS voltage(V)	14832.0	14400	103.0	110	✓
		RMS current(A)	21.7	20.8	104.0	135	✓
		kvar	950.2	900	105.6	135	✓
	C_{7th}	Peak voltage(V)	21188.0	20365	104.0	120	✓
		RMS voltage(V)	15024.0	14400	104.3	110	✓
		RMS current(A)	21.9	20.8	105.0	135	✓
		kvar	975.3	900	108.4	135	✓

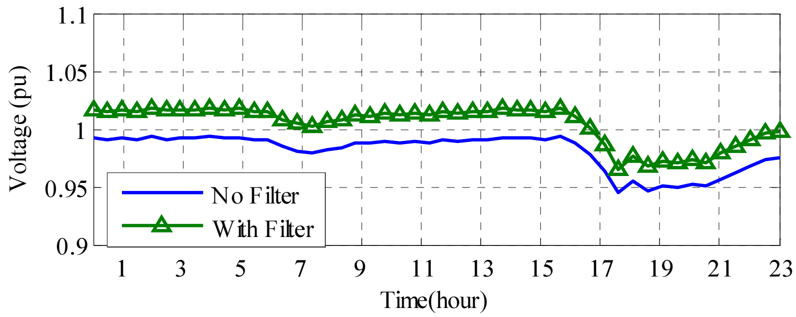


Figure 4.10 Daily voltage profile at the middle of the ideal feeder.

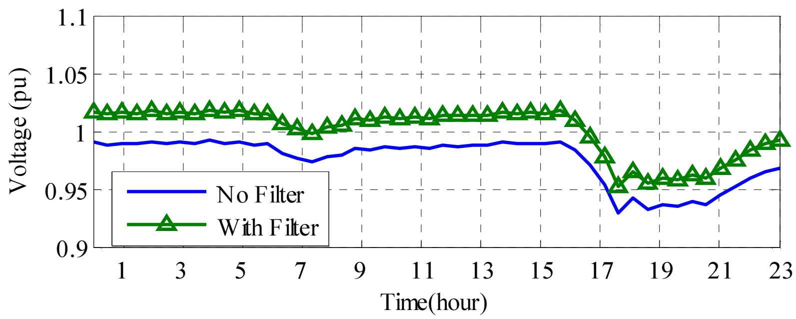


Figure 4.11 Daily voltage profile at the end of the ideal feeder

4.4.2 For Actual feeder

The iterative process of filter design for the actual feeder is presented in Table 4.4. The first filter case is consisting of the ZS filter and two single-tuned branches tuned to 5th and 13th harmonic. Differently from the designed filter for the ideal feeder, one branch is tuned to 13th rather than 11th. The reason is that the system is observed to be capacitive in high order harmonics (See Figure 4.13) and a filter tuned to 11th will be inductive at both 11th and 13th harmonics thereby increasing the risk of a parallel resonance between system and the filter in such harmonic orders.

The first twelve cases in the table show that a filter with just two single-tuned branches can not exhibit the anticipated performance. From cases number 13 to 21, another single-tuned branch tuned to 7th harmonic is also added. These cases have been just examined for the 'MV II' location since the results of first twelve cases reveal that this location performs better rather than the 'MV I' (Filter locations in the actual feeder are labeled in Figure 4.12). However, even with three single-tuned branches and selecting the largest transformer and capacitor size, the aimed 75% decrease in current TDD is still not achieved. Therefore, from case no. 22, two filter packages are considered to be installed at both locations. Case no. 33 shows the final design. In this case, one of the capacitors in the ZS filter of the 'MV II' location is overloaded. To address this issue, this capacitor voltage and kvar are increased according to the proposed design guideline. Details of loading analysis of the final designed filters are given in Table 4.5 and Table 4.6.

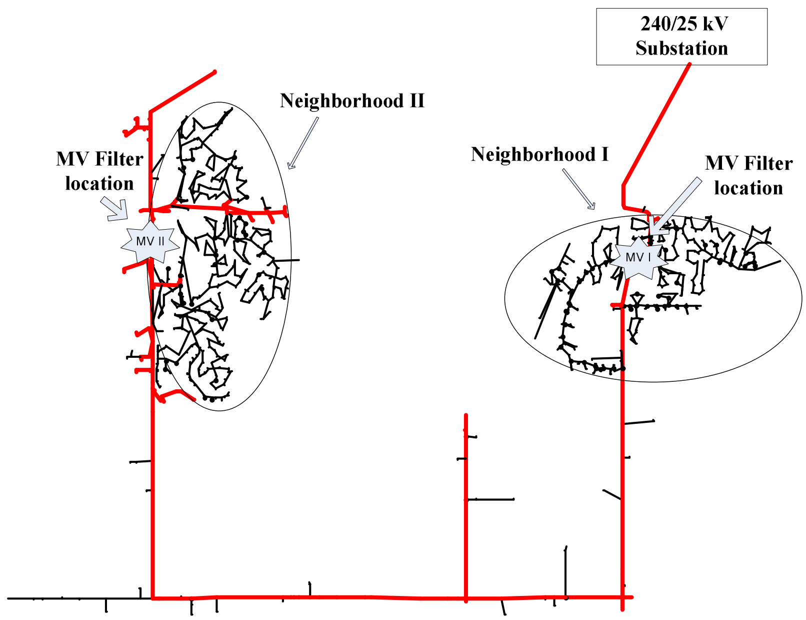


Figure 4.12 The MV filters locations in the actual feeder

The voltage profile of the system for both neighborhoods is also evaluated with and without the filter in Figure 4.15 and Figure 4.16. Similarly to the ideal feeder case, the filter is found to improve the voltage level at the peak hours. Although for the other times of the day the filter is boosting it to higher values than 1pu, the voltage is still kept within a 5% limit from the nominal value, which is the steady-state voltage limit commonly adopted by distribution companies.

Table 4.4 The results of iterative filter design procedure for actual feeder.

Case No.	ZS filter	Single tuned filter branches						Filter Location(s)	Filter(s) effectiveness		Loading assessment	
	Transformer size (kVA)	#1		#2		#3			Percentage decrease in TDD	Percentage decrease in THD	Single tuned filters	The ZS filter
		h_{tuned}	Capacitor (kvar)	h_{tuned}	Capacitor (kvar)	h_{tuned}	Capacitor (kvar)					
1	300	4.9	300	12.9	150	-	-	II*	52.32	51.45	×	×
2	300	4.9	300	12.9	150	-	-	I*	20.94	2.68	×	×
3	300	4.9	900	12.9	600	-	-	II	55.98	60.22	✓	×
4	300	4.9	900	12.9	600	-	-	I	22.85	22.10	×	×
5	300	4.9	1200	12.9	900	-	-	II	52.48	55.83	✓	×
6	300	4.9	1200	12.9	900	-	-	I	22.83	22.59	×	×
7	500	4.9	300	12.9	150	-	-	II	54.82	51.65	×	×
8	500	4.9	300	12.9	150	-	-	I	30.77	0.29	×	×
9	500	4.9	900	12.9	600	-	-	II	58.26	61.83	✓	×
10	500	4.9	900	12.9	600	-	-	I	34.09	18.07	×	×
11	500	4.9	1200	12.9	900	-	-	II	54.29	57.01	✓	×
12	500	4.9	1200	12.9	900	-	-	I	34.82	18.35	×	×
13	300	4.9	600	12.9	450	6.9	450	II	58.02	67.89	×	×
14	300	4.9	900	12.9	600	6.9	600	II	60.00	70.88	✓	×
15	300	4.9	1200	12.9	900	6.9	900	II	62.36	73.43	✓	×
16	1000	4.9	600	12.9	450	6.9	450	II	66.43	75.82	×	✓
17	1000	4.9	900	12.9	600	6.9	600	II	67.85	79.85	✓	✓
18	1000	4.9	1200	12.9	900	6.9	900	II	69.00	83.57	✓	✓
19	2500	4.9	600	12.9	450	6.9	450	II	67.16	77.46	×	✓
20	2500	4.9	900	12.9	600	6.9	600	II	68.43	81.27	✓	✓
21	2500	4.9	1200	12.9	900	6.9	900	II	69.47	85.13	✓	✓
22	1000	4.9	600	12.9	450	-	-	I & II*	59.77	59.49	✓	✓
23	1000	4.9	900	12.9	600	-	-	I & II	64.61	64.51	✓	✓
24	1000	4.9	1200	12.9	900	-	-	I & II	56.95	56.72	✓	✓
25	2500	4.9	600	12.9	450	-	-	I & II	59.98	59.64	✓	✓
26	2500	4.9	900	12.9	600	-	-	I & II	64.95	64.38	✓	✓
27	2500	4.9	1200	12.9	900	-	-	I & II	57.40	56.77	✓	✓
28	300	4.9	450	12.9	300	6.9	300	I & II	64.15	67.01	×	×
29	300	4.9	600	12.9	450	6.9	450	I & II	65.57	72.92	✓	×
30	300	4.9	900	12.9	600	6.9	600	I & II	66.69	75.27	✓	×
31	500	4.9	450	12.9	300	6.9	300	I & II	72.56	71.15	×	×
32	500	4.9	600	12.9	450	6.9	450	I & II	74.08	78.31	✓	×
33	500	4.9	900	12.9	600	6.9	600	I & II	75.11	81.28	✓	×**

* I and II stand for the locations in neighborhood I and neighborhood II, while I & II stands for two filter installations at both locations.

** Overloading of the ZS filter capacitors will be fixed by increasing those capacitors rated voltage and kvar.

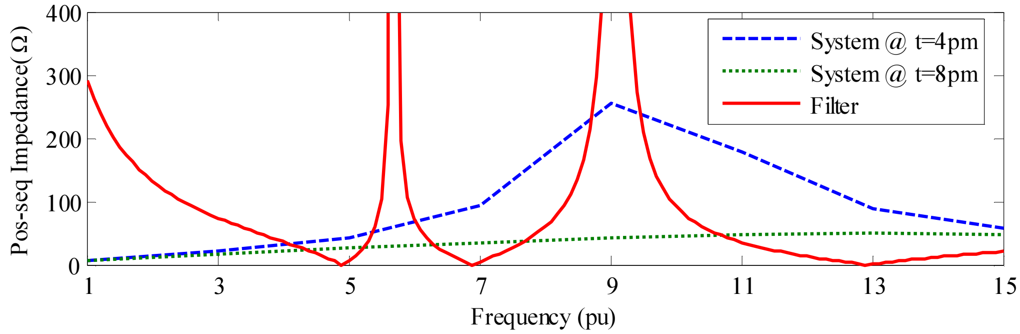


Figure 4.13 Positive-sequence frequency scans of the designed filter and system impedance for actual feeder.

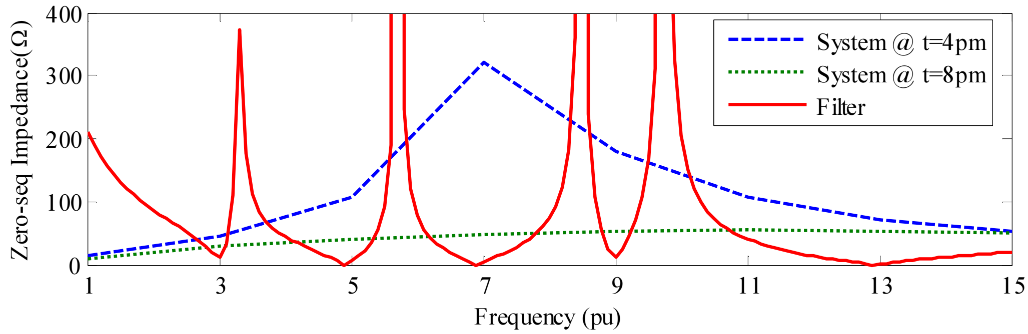


Figure 4.14 Zero-sequence frequency scans of the designed filter and system impedance for actual feeder.

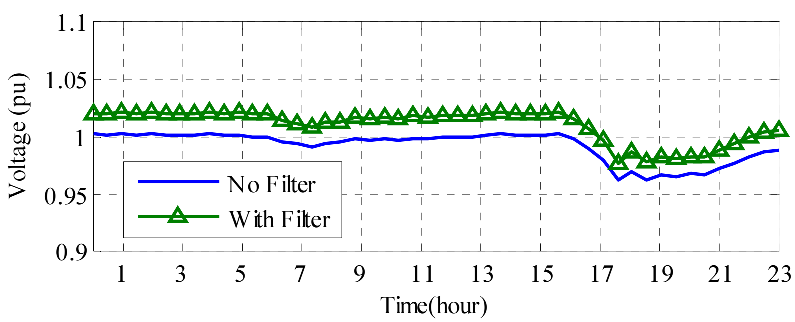


Figure 4.15 Daily voltage profile at Neighbourhood I.

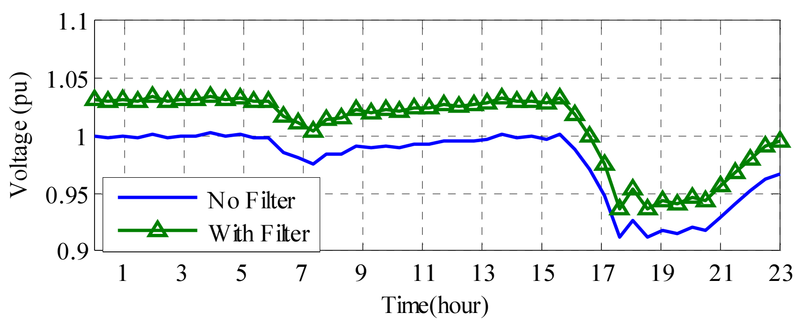


Figure 4.16 Daily voltage profile at Neighbourhood II.

Table 4.5 Loading analysis of the designed filter for the actual feeder at neighborhood I.

Filter component			Operation value	Rated value	Ratio of operation to rated value (%)	IEEE standard limit (%)	Is under limit?
ZS filter	C_1	Peak voltage(V)	209.4	848.5	24.7	120	✓
		RMS voltage(V)	153.2	600	25.5	110	✓
		RMS current(A)	310.3	400.8	77.4	135	✓
		kvar	47.3	240.5	19.7	135	✓
	C_2	Peak voltage(V)	51.8	848.5	6.1	120	✓
		RMS voltage(V)	34.3	600	5.7	110	✓
		RMS current(A)	39.1	225.4	17.3	135	✓
		kvar	1.3	135.3	1	135	✓
Single-tuned filter branches	C_{5th}	Peak voltage(V)	21602	20365	106.1	120	✓
		RMS voltage(V)	15370	14400	106.7	110	✓
		RMS current(A)	22.7	20.8	108.9	135	✓
		kvar	1026.1	900	114	135	✓
	C_{13th}	Peak voltage(V)	21393	20365	105.1	120	✓
		RMS voltage(V)	14819	14400	102.9	110	✓
		RMS current(A)	14.6	13.9	105	135	✓
		kvar	631.9	600	105.3	135	✓
	C_{7th}	Peak voltage(V)	21195	20365	104.1	120	✓
		RMS voltage(V)	15046	14400	104.5	110	✓
		RMS current(A)	14.6	13.9	105.4	135	✓
		kvar	651.5	600	108.6	135	✓

Table 4.6 Loading analysis of the designed filter for the actual feeder at neighborhood II.

Filter component			Operation value	Rated value	Ratio of operation to rated value (%)	IEEE standard limit (%)	Is under limit?
ZS filter	C_1^*	Peak voltage(V)	574.4	1414.2	40.6	120	✓
		RMS voltage(V)	413.6	1000	41.4	110	✓
		RMS current(A)	833.8	668	124.8	135	✓
		kvar	343.7	668	51.5	135	✓
	C_2	Peak voltage(V)	138.2	848.5	16.3	120	✓
		RMS voltage(V)	92.6	600	15.4	110	✓
		RMS current(A)	105.1	225.4	46.6	135	✓
		kvar	9.7	135.3	7.2	135	✓
Single-tuned filter branches	C_{5th}	Peak voltage(V)	21782	20365	107	120	✓
		RMS voltage(V)	15608	14400	108.4	110	✓
		RMS current(A)	24.3	20.8	116.9	135	✓
		kvar	1074.1	900	119.3	135	✓
	C_{13th}	Peak voltage(V)	22401	20365	110	120	✓
		RMS voltage(V)	15029	14400	104.4	110	✓
		RMS current(A)	16.7	13.9	120.1	135	✓
		kvar	656.2	600	109.4	135	✓
	C_{7th}	Peak voltage(V)	21850	20365	107.3	120	✓
		RMS voltage(V)	15259	14400	106	110	✓
		RMS current(A)	15.3	13.9	110.4	135	✓
		kvar	671.7	600	112	135	✓

* The rated voltage and kvar of this capacitor has been increased from 600V to 1000V and 240.5 to 668 respectively to avoid overloading (The capacitance is not altered).

4.5 Final Design Specifications

Table 4.7 presents the final components sizes of the designed MV filters for both of the real and ideal feeders. The sizes of capacitors, transformers and inductors as specified in the table are reasonable when compared to the common industrial filter design practices such as [39].

Table 4.7 Specification of designed MV passive filters for the system-wide harmonic mitigation.

<table>
<tr><th>Filter Design</th><th colspan="4">Ideal Feeder</th><th colspan="4">Actual feeder</th></tr>
<tr><td rowspan="6">Double-tuned ZS filter (3^{rd} and 9^{th})</td><td colspan="2">Transformer size</td><td colspan="2">2500kVA</td><td colspan="2">Transformer size</td><td colspan="2">500kVA</td></tr>
<tr><td colspan="2" rowspan="2">C_1</td><td>kvar</td><td>898.3</td><td colspan="2" rowspan="2">C_1</td><td>kvar*</td><td>240.47</td></tr>
<tr><td>Vrated</td><td>600V</td><td>Vrated*</td><td>600V</td></tr>
<tr><td colspan="2" rowspan="2">C_2</td><td>kvar</td><td>505.29</td><td colspan="2" rowspan="2">C_2</td><td>kvar</td><td>135.26</td></tr>
<tr><td>Vrated</td><td>600V</td><td>Vrated</td><td>600V</td></tr>
<tr><td colspan="2">L_2(mH)</td><td colspan="2">0.0419</td><td colspan="2">L_2(mH)</td><td colspan="2">0.157</td></tr>
<tr><td rowspan="6">Single tuned filter branches</td><td rowspan="2">5th</td><td rowspan="2">h_{tuned}=4.9</td><td>L(mH)</td><td>57.54</td><td rowspan="2">5th</td><td rowspan="2">h_{tuned}=4.9</td><td>L(mH)</td><td>76.72</td></tr>
<tr><td>C(kvar)</td><td>1200</td><td>C(kvar)</td><td>900</td></tr>
<tr><td rowspan="2">7th</td><td rowspan="2">h_{tuned}=6.9</td><td>L(mH)</td><td>38.69</td><td rowspan="2">7th</td><td rowspan="2">h_{tuned}=6.9</td><td>L(mH)</td><td>58.04</td></tr>
<tr><td>C(kvar)</td><td>900</td><td>C(kvar)</td><td>600</td></tr>
<tr><td rowspan="2">11th</td><td rowspan="2">h_{tuned}=10.9</td><td>L(mH)</td><td>15.504</td><td rowspan="2">13th</td><td rowspan="2">h_{tuned}=12.9</td><td>L(mH)</td><td>16.60</td></tr>
<tr><td>C(kvar)</td><td>900</td><td>C(kvar)</td><td>600</td></tr>
<tr><td>Filter Location(s)</td><td colspan="4">One filter at 7km from substation (~middle of feeder)</td><td colspan="4">Two filters at locations MV 1 (Neighborhood I) and MV 2 (Neighborhood II)</td></tr>
</table>

* For the filter package installed at Neighborhood II of the actual feeder, the voltage rating and kvar of C_1 (in the ZS filter) must be increased to 1000V and 668kvar to avoid overloading.

4.6 Summary

This chapter studied the option of installing centralized MV passive filters in the primary feeder of a distribution system to mitigate the harmonics from residential sources. The main issues and required considerations to obtain an effective design were identified and addressed by proposing a proper comprehensive guideline. The filters were sized for both of the feeders to accomplish the harmonic elimination objective established in Chapter 2.

Through this chapter studies, it was revealed that MV passive filters can not have a unique design for different systems. For example, the number of the filter installations, sizing of the components and even the tuned frequencies in the final design specs were found to be different for the two feeders.

In contrast to the complex filter design methods available in the literature, the proposed iterative technique is simple and practical. No time-consuming optimization algorithms are required by this approach.

Chapter 5

Proposed Scheme for Low-Voltage Distributed Active Filters

The literature on the topic of distributed active filters has been limited to the installations in the primary feeder [40],[41]. A few studies such as [42] tried to apply passive filters for the low-voltage customers to mitigate the dominant harmonic orders (3^{rd}, 5^{th} and 7^{th}), but the result were unsatisfactory, and all the design issues were not considered. This chapter proposes a novel harmonic mitigation method that installs low-voltage distributed active filters in a distribution system. As shown in Figure 5.1, unlike the conventional MV filters, the distributed filters are installed in the 120V voltage level of the secondary systems either directly connected to the low-voltage side of the transformer or installed at one of the customer houses. This chapter presents the initial feasibility studies on the distributed active filters idea to identify the main challenges for both its implementation and performance. Theories and measures are developed to support the proposed filter scheme design, configuration and placement. The simulation tools introduced in Chapter 2 are also used to evaluate the harmonic filters' effectiveness.

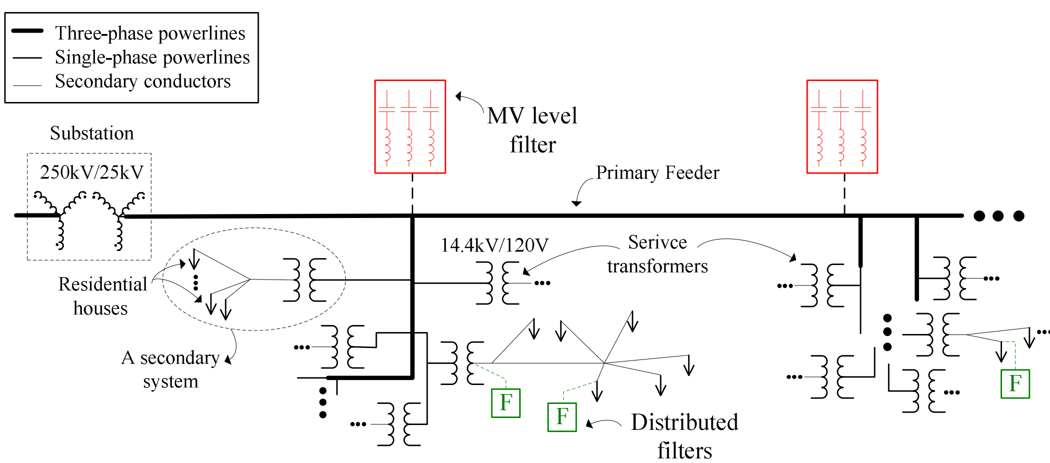


Figure 5.1 A generic residential distribution feeder illustrating different possible filter schemes

This chapter is organized as follows. Section 5.1 discusses the selection of the filter type (active or passive) and topology. Moreover, the operation principle and advantages of the chosen virtual-impedance active filters are explained in this section. Section 5.2

investigates the installment issues for a distributed filter scheme. Theoretical analyses are performed to study the possible filter configurations and placement options. Section 5.3 presents the results of the secondary system simulation studies where different filter installation options are assessed for a typical North American secondary distribution system. In addition, the overall harmonic mitigation effectiveness of the proposed distributed filters scheme is evaluated by using primary system simulations in Section 5.4. Both of the actual and ideal feeders are studied with some supporting sensitivity analyses to achieve a better understanding of the overall performance of the filters in suppressing the distribution system harmonics. Section 5.5 determines the final specification of the distributed filters schemes for both studied feeders in accordance with the defined mitigation objectives presented in Chapter 2. Finally, the main findings of this chapter are summarized in section 5.6.

5.1 Filter Type and Topology Selection

Section 5.1.1 explains why the active filters are preferred to their passive counterparts for the proposed distributed scheme. In addition, section 5.1.2 also discusses the reason behind selecting the virtual-impedance active filters instead of the other conventional types of active filter.

5.1.1 Active versus Passive Filters

When it concerns the distributed filter schemes, the active filters are usually preferred over the passive ones. In fact, the virtual-impedance type of active filters is selected for the proposed mitigation method (The reason of choosing this type of active filters will be discussed in the next section). This type of active filters sinks the harmonic currents by exhibiting a low resistive impedance at all of the harmonic frequencies while appearing as an open-circuit for the fundamental frequency component [40]-[41],[43]-[44]. Such active harmonic filters will at least have the following advantages over the passive counterparts when applied for the distributed scheme:

- Multiple branches of passive filters are needed to mitigate all harmonic orders (3^{rd}, 5^{th}, 7^{th}, etc.), while it can be all done by a single active device. Overall, the size of the active filter will be considerably less than its passive counterpart for this application.

- Since the virtual-impedance active filters appear as resistive impedances to the system, they will not cause harmonic amplification due to a parallel resonance.

- The typical secondary system impedance values are quite low so that very low filter impedances are also needed. In contrast to the passive filters, such active filters establish their equivalent impedance virtually through a power electronics circuit and its control system. While for the passive counterparts, the required low filter impedance has to be established physically where it already includes the series resistance of their capacitor and inductors as well as the residual impedance due to the components detuning.

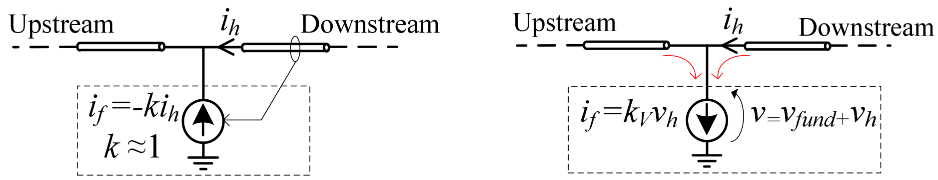
In addition, since the filters are supposed for a low voltage application, the price of active filter power-electronic devices will also become reasonable compared to their passive counterparts.

5.1.2 Virtual-impedance Active Filter

Shunt active filters can be generally classified into two groups based on their control principle as below[19],

1. The traditional active filters (with a current-detection based control): It appears as a controlled current source injecting a compensating harmonic current into the system to cancel the harmonic currents flowing from the downstream side (Figure 5.2 (a)).

2. The virtual-impedance active filters (with a voltage-detection based control): This type also behaves as a controlled current source in the circuit but instead of injecting the compensating current, it sinks a current proportional to the harmonic part of the filter voltage (v_h in Figure 5.2 (b)) so that a virtual resistive impedance is established to absorb the harmonics from both upstream and downstream sides of the system (Figure 5.2 (b)). For the fundamental frequency, the filter acts as an open circuit (The equivalent circuit of such filters is depicted in Figure 5.4(b)) [40]-[41],[43]-[44].



(a) (b)

Figure 5.2 Simplified schematic of a shunt active filter with (a) current-detection based control (traditional type) (b) voltage-detection based control (virtual-impedance).

The virtual-impedance active filter (second type) is selected for the proposed distributed filter scheme because of the following advantages over the traditional type,

- Unlike the current-detection based type, the virtual-impedance filter can be also installed at one of the houses since of its ability to attract the harmonics from the other customers' houses.
- Whether the filter being installed at service transformer or one of the houses, with the virtual-impedance type, a portion of the harmonics from the other parts of system (associated with other service transformers) will be also mitigated. This fact will be verified by the simulation results that will be later presented in section 5.4.1.
- As shown in Figure 5.2 (a), the traditional active filters require measuring of the downstream power-line current. The virtual-impedance filter does not require such current sensors.

The only remaining issue with the virtual-impedance active filters is the fact that they have to establish a lower impedance than the system's one to achieve an effective harmonic suppression. Figure 5.3 shows an impedance frequency scan of a typical secondary system measured at a house (This frequency scan is obtained by both simulation and analytical analysis. For more details of the system refer to Figure 5.11).

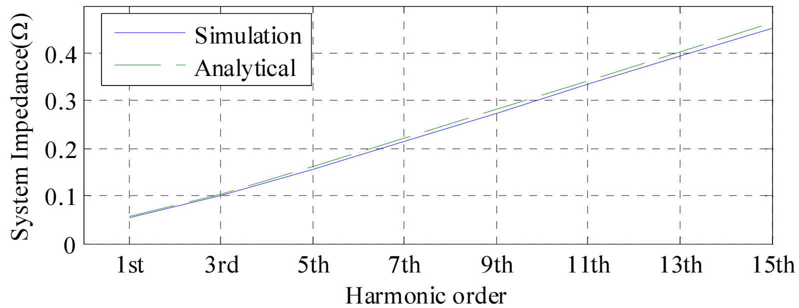


Figure 5.3 Frequency scan at a house of a typical secondary feeder (House #3 in Figure 5.11)

Figure 5.3 shows that the system impedance is quite low. Therefore, the ability of establishing low virtual impedance values must be considered in the design of such active filters (In the consequent sections of this chapter, the impedance values required for an effective mitigation will be studied). Traditionally, it has not been a concern for the design of the virtual-impedance active filters, since all the previous studies have considered them only for the primary-level systems (MV) where the system impedance is not too low. Moreover, too low filter impedances have been always deliberately avoided to prevent filter overheating [40],[41].

Figure 5.4(a) shows a very simplified schematic of the circuit and control diagram of a single-phase virtual-impedance active filter [43]. In the steady-state condition, the filter current (i_f in Figure 5.4(a)) will approximately equals the reference current ($i_{f,ref}$ in Figure 5.4 (a)). So that,

$$i_f = i_{f,ref} \Rightarrow i_f = K_V v_h \qquad (5.1)$$

where K_V is the control loop gain factor as shown in Figure 5.4(a). From (5.1), the equivalent harmonic impedance of the filter can be calculated (Figure 5.4(b)):

$$Z_f(h) = v_h / i_f \Rightarrow Z_f(h) = 1/K_V \qquad (5.2)$$

As a result, the gain factor in the control loop (K_V) determines the obtained virtual impedance (Z_f). The higher this gain factor, the lower filter impedance is achieved (For example to obtain Z_f=0.02Ω, K_V must be at least 50). However, too high values of K_V may cause some stability, etc. issues for the filter converter control mechanisms. The possible issues and their solutions are supposed to be studied in the next level of this research project devoted to the design and implementation of the proposed virtual-impedance active filters.

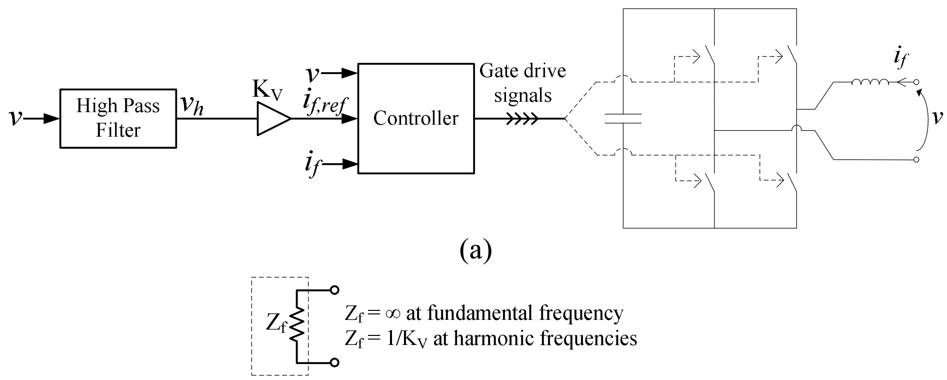


Figure 5.4 The single-phase virtual-impedance active filter (a) Circuit schematic and control diagram (b) Equivalent system

5.2 Filter Installment Issues

This section investigates the available options and essential consideration of installing the distributed filters in a North American distribution system. Section 5.2.1 studies the option of installing the filters directly between the two phases to save in number of filters. Different available locations to place the filter within the system are also discussed in Section 5.2.2.

5.2.1 Double- phase Connection

The North American secondary distribution systems have a double-phase circuit structure. Each appliance in a house is either connected to one of the phases and neutral (120V) or directly between the two phases (240V) [45]. With such double-phase configuration, two options will be possible for equipping the secondary system with these filters. The first option is to connect two separated filters each of them between one phase and neutral (Figure 5.5(b)). The other option is to connect a single filter directly between phases A and B (Figure 5.5(c)). Intuitively, the first choice is certainly effective; however, evaluating the performance of the second option needs a deeper analysis.

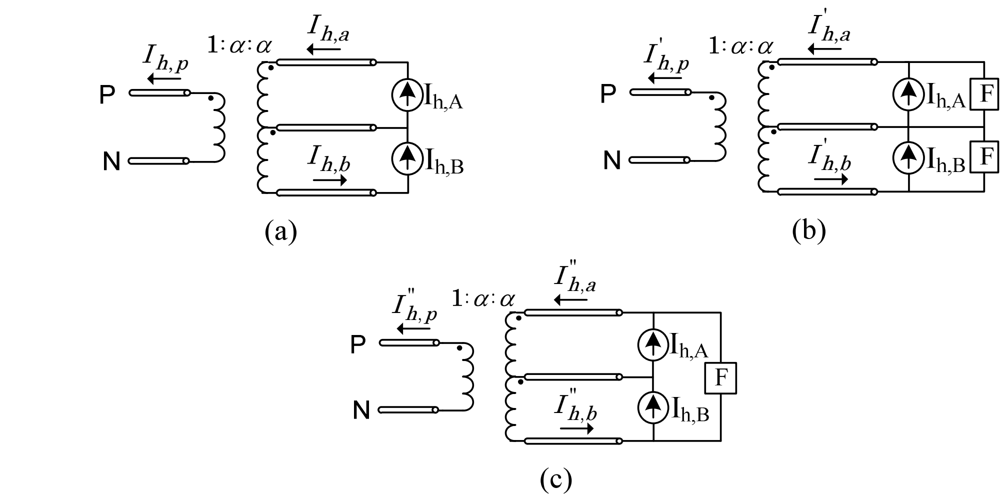


Figure 5.5 Different possible filter installment options: (b) Two single-phase connected filters (c) One double-phase connected filter.

Figure 5.6 shows the equivalent circuits used to analytically evaluate and compare the effectiveness of the aforementioned options. In the figure, Z_s and Z_p are the secondary- and primary-winding impedances respectively (All the impedance values are transferred to the secondary side). The secondary to primary voltage ratio of the service transformer is shown by α. Z_f, Z_l and $Z_{eq,pr}$ are the filter, secondary power-line and primary system equivalent impedance values, respectively. The current sources of $I_{h,A}$ and $I_{h,B}$ are representing the harmonic currents generated by the nonlinear loads in phases A and B. The harmonic currents penetrating into the primary system respectively for the two cases are respectively labeled as $I'_{h,p}$ and $I''_{h,p}$.

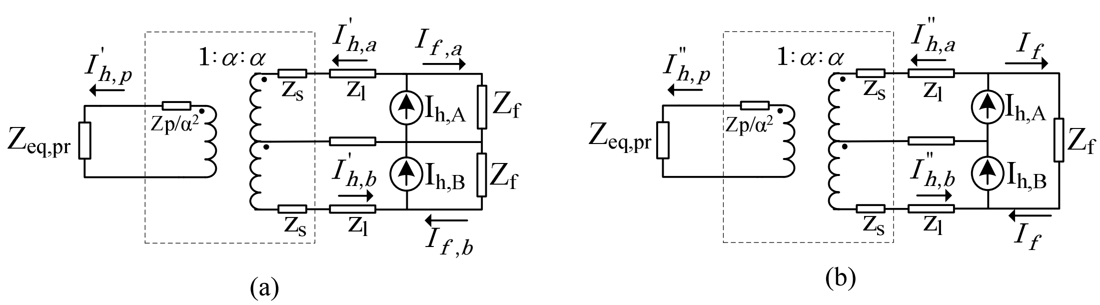


Figure 5.6 Equivalent circuit of system with (a) two single-phase filter (b) one double-phase filter.

When there is no filter in the system, the harmonic current penetrating into the primary system ($I_{h,p}$ in Figure 5.5(a)) is,

$$I_{h,p} = \alpha\ (I_{h,a} + I_{h,b}) = \alpha\ (I_{h,A} + I_{h,B}) \tag{5.3}$$

For the case of two single-phase filters connected to each phase (Figure 5.6(a)), one has the following four equations according to Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL):

$$\begin{cases} I'_{h,p} = \alpha\ (I'_{h,a} + I'_{h,b}) \\ I'_{h,a} + I_{f,a} = I_{h,A} \\ I'_{h,b} + I_{f,b} = I_{h,B} \\ (\alpha^2 Z_{eq,pr} + Z_p) I'_{h,p} / \alpha + (Z_s + Z_l) I'_{h,a} = Z_f I_{f,a} \\ (\alpha^2 Z_{eq,pr} + Z_p) I'_{h,p} / \alpha + (Z_s + Z_l) I'_{h,b} = Z_f I_{f,b} \end{cases} \tag{5.4}$$

Solving the above set of equations,

$$I'_{h,p} = \frac{Z_f}{Z_f + Z'_{eq}} \alpha\ (I_{h,A} + I_{h,B}), \tag{5.5}$$

where

$$Z'_{eq} = 2\alpha^2 Z_{eq,pr} + 2Z_p + Z_s + Z_l \tag{5.6}$$

In a typical service transformer, the relationship between the winding impedances are as below [45],

$$\begin{cases} Z_T = R_T + jX_T \\ Z_p = 0.5R_T + j0.8X_T\ , \\ Z_s = R_T + j0.4X_T \end{cases} \tag{5.7}$$

where Z_T is the full-winding nameplate impedance of the transformer. Substituting (5.7) into (5.6), Z'_{eq} can be simplified as below,

$$Z'_{eq} = 2\alpha^2 Z_{eq,pr} + 2Z_T + Z_l\ . \tag{5.8}$$

By combining equations (5.3) and (5.5), the following expression can be obtained to determine the filters effectiveness:

$$\frac{I_{h,p}^{with\ Sph\ filter}}{I_{h,p}^{No\ filter}} = \frac{Z_f}{Z_f + Z'_{eq}} \tag{5.9}$$

As intuitively expected, when the filter impedance is lower enough than the system equivalent impedance ($Z_f \ll Z'_{eq}$) , the right side of (5.9) converges to zero implying that filter eliminates the harmonics before flowing to the primary system.

For a double-phase connected filter directly between phase A and B, KVL and KCL principles apply the following set of equations:

$$\begin{cases} I''_{h,p} = \alpha\ (I''_{h,a} + I''_{h,b}) \\ I''_{h,a} + I_f = I_{h,A} \\ I''_{h,b} + I_f = I_{h,B} \\ 2(\alpha^2 Z_{eq,pr} + Z_p) I''_{h,p} / \alpha + (Z_s + Z_l)(I''_{h,a} + I''_{h,b}) = Z_f I_f \end{cases} \tag{5.10}$$

Solving the above set of equations leads to

$$I''_{h,p} = \frac{Z_f}{Z_f + Z''_{eq}} \alpha\ (I_{h,A} + I_{h,B}), \tag{5.11}$$

where

$$Z''_{eq} = 4\alpha^2 Z_{eq,pr} + 4Z_p + 2Z_s + 2Z_l \overset{(7)}{==} 4\alpha^2 Z_{eq,pr} + 4Z_T + 2Z_l\,. \tag{5.12}$$

Furthermore, by dividing (5.11) over (5.5), the final equation for evaluating the performance of a double-phase connected filter can be further simplified as below,

$$\frac{I_{h,p}^{with\ Dph\ filter}}{I_{h,p}^{No\ filter}} = \frac{Z_f}{Z_f + Z_{eq}^{Dph}}, \tag{5.13}$$

where $Z_{eq}^{Dph} = 4\alpha^2 Z_{eq,pr} + 4Z_T + 2Z_l\,.$ (5.14)

The equation (5.13) demonstrates that the double-phase connected filter is also able to eliminate the harmonic penetration into the primary system with a similar theoretical principle to the single-phase connected filters. Comparing (5.8) and (5.14) also reveals that the equivalent system impedance for the double-phase connection is even higher than the single-phase connected ones; therefore, even a more effective harmonic mitigation can be achieved with the same filter impedance value!

Due to the obvious advantage of saving in number of filter devices, the double-phase connection is chosen for the distributed filtering scheme and will be used in all of this thesis studies. Simulation studies will be also provided in section 5.3.1 to verify the effectiveness of the double-phase configuration compared to the single-phase ones.

5.2.2 Filter Location Options

As depicted in Figure 5.7, each filter can be either installed at the supplying service transformer or at one of the customer houses. In the previous section, (5.11) and (5.12) were derived for assessing the double-phase connected filter performance. When the filter is attached to the service transformer, there will be no line impedance (Z_l) in (5.12) and the equivalent system impedance will be as below,

$$Z_{sys} = 4\alpha^2 Z_{eq,pr} + 4Z_T \tag{5.15}$$

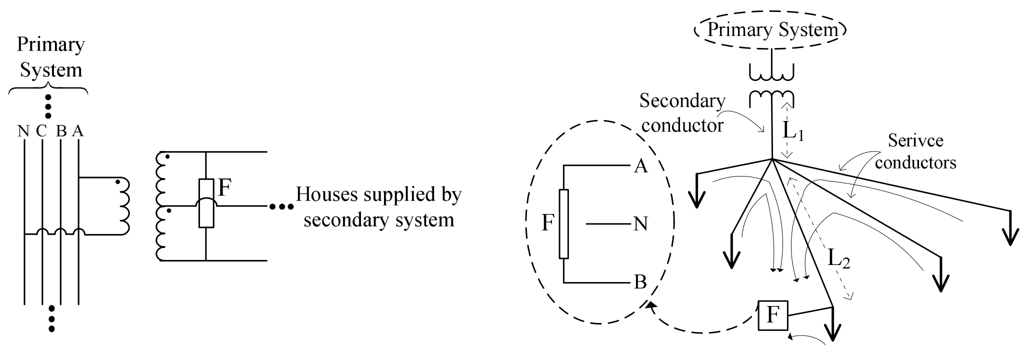


Figure 5.7 The two options for filter location: (a) at service transformer (b) at one of the houses.

The simplified circuit shown in Figure 5.8 is used for analyzing the case when the filter is installed in a house. $I'_{h,A}$ and $I'_{h,B}$ are the current sources representing the harmonic currents generated by the house which filter is installed at. The harmonic currents injected by the other houses are modeled as $I_{h,A}$ and $I_{h,B}$. Z_{Ls} and Z_{Lb} are the impedances of secondary and the service conductor of the house with the filter, respectively. In this simplified circuit, the impedances of other service conductors and linear home appliances are ignored since of their negligible effect on the harmonic flow.

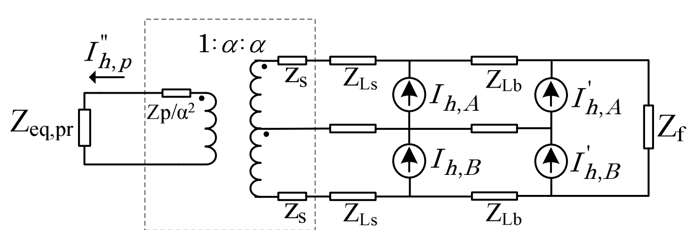


Figure 5.8 The equivalent circuit of system when installing filter at one of the houses.

By ignoring the harmonic currents produced by the house with filter ($I'_{h,A}$ and $I'_{h,B}$), the equivalent circuit can be even more simplified as shown in Figure 5.9. As depicted in the figure, the equivalent filter branch impedance includes the service conductor impedance as well as the filter impedance.

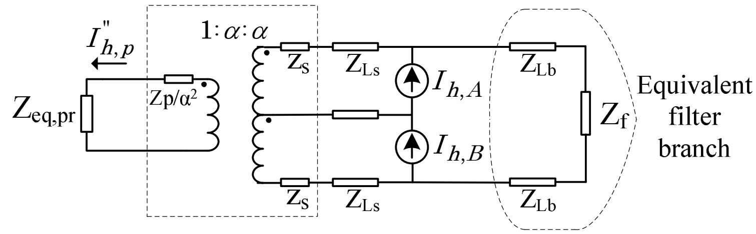


Figure 5.9 The equivalent filter branch when installing filter at one of the houses, simplified with ignoring the harmonic currents generated inside that house.

Based on this simplified equivalent circuit (Figure 5.9), one can use a similar equation to (5.11) to assess the filter effectiveness as below,

$$\frac{I_{h,p}^{Filtered}}{I_{h,p}^{No\ filter}} = \frac{Z_{eq,F}}{Z_{eq,F} + Z_{sys}}, \tag{5.16}$$

where the equivalent system impedance is

$$Z_{sys} = 4\alpha^2 Z_{eq,pr} + 4Z_T + 2Z_{Ls}, \tag{5.17}$$

And the equivalent filtering impedance (The impedance of equivalent filter branch shown in Figure 5.9) is,

$$Z_{eq,F} = Z_F + 2Z_{Lb} \tag{5.18}$$

In conclusion, although placing the filter in a house leads to a higher equivalent filtering impedance compared to service transformer placement; however, the system equivalent impedance will be also higher. Anyways, the closest house to the service transformer must be equipped with the filter to achieve the most effective harmonic suppression (the closest house will bring the lowest service conductor impedance (Z_{L2}) leading to lowest filtering impedance ($Z_{f,eq}$)).

The above analyses also reveal that with any of the location options, just one filter is enough for each secondary system to achieve an effective harmonic mitigation. Simulation results will be also provided in section 5.3.2 to evaluate and compare different filter location options. Table 5.1 compares the two location options in summary.

Table 5.1 Comparison of the two filter location options

	Filter location	
	At the service transformer	At the closest house
Effective harmonic mitigation	✓	✓
Providing higher equivalent system impedance		✓
Providing lower equivalent filtering impedance	✓	

5.3 Simulation Studies on Secondary System

This section conducts the simulation studies on the secondary level of distribution systems in support of the theoretical discussions presented in this chapter so far. The studies are mainly aimed to answer the following questions regarding a distributed active filter scheme for a North American distribution system:

1. How is the filters effectiveness when they are directly connected between the two phases?
2. Is a single filter really enough for each secondary system? If so, what are the optimum locations for installing the filters?
3. What is the impact of the secondary system configuration?
4. How much the filter impedance value affects the harmonics elimination?

As depicted in Figure 5.10, three types of configurations can be found for a secondary distribution system in North America: cascade, parallel or a combination of parallel and cascade. The last two configurations are more common compared to the first one.

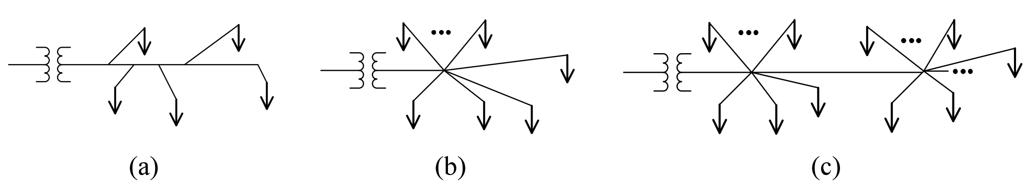


Figure 5.10 Different configurations of a secondary distribution system (a) cascade (b) parallel (c) combination of parallel and cascade.

In order to avoid too much complexity in the simulations, the parallel configuration is chosen for most of the simulations as the typical system. Consisting of a service transformer supplying five residential houses as shown in Figure 5.11, the typical system is sufficient for most of the studies such as comparing different filter configurations, filter installation at the transformer, required filter impedance, etc. Additionally, section 5.3.2.1 will also study the systems with a more generalized configuration to verify the conclusions obtained via the typical system regarding the optimum house for filter placement.

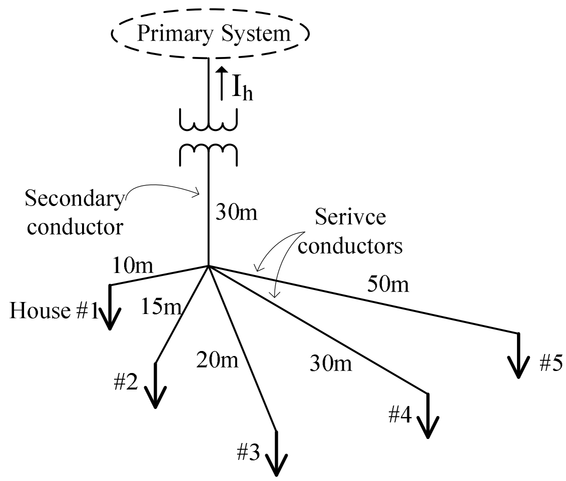


Figure 5.11 The typical secondary system chosen for simulation studies.

Table 5.2 gives the parameters of the typical system used in the simulations. Figure 5.12 and Figure 5.13 show the circuits for performing the load flow and harmonic load flow simulations of the system by employing an in-house HLF program [29]. At harmonic frequencies, linear loads in a house are represented as impedances (Z_{ha} , Z_{hb} and Z_{hab} in Figure 5.12) ,while, nonlinear loads are modeled as harmonic current sources(I_{ha} and I_{hb} in Figure 5.13). The modeling method to obtain the equivalent harmonic current sources and impedances of each house is based on the similar bottom-up approach as described in Chapter 2. Since the models are time-varying, the results are obtained for different hours during a day.

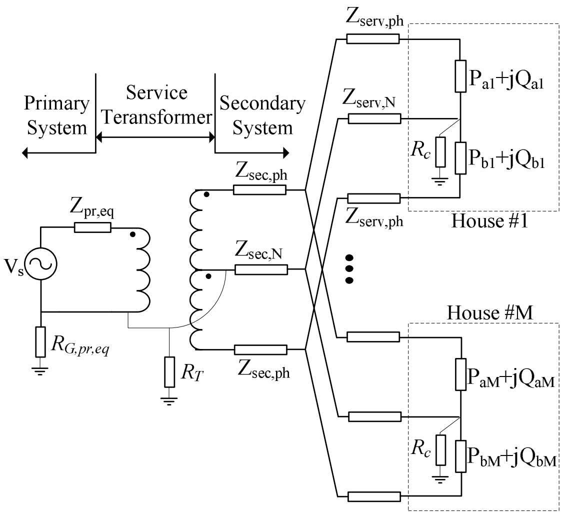


Figure 5.12 The model circuit of the secondary system at fundamental frequency for harmonic load flow simulations

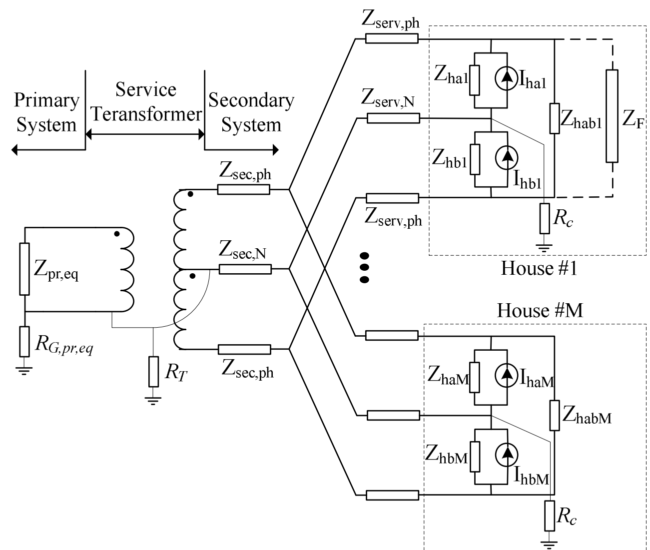


Figure 5.13 The model circuit of the secondary system at harmonic frequencies for harmonic load flow simulations

The virtual-impedance active filters are modeled as an open circuit in the fundamental frequency and as a constant resistive impedance at the harmonic frequencies (Z_f in Figure 5.13). A relatively small impedance is selected for all of the simulations (Z_f=0.01Ω). Different values of filter impedance will be also studied by a sensitivity study in section 5.3.3.

The simulation results are presented in the consequent sections. The index of interest for all of the studies is the harmonic distortion (IDD and TDD) of the current collectively flowing to the primary system through the service transformer (I_h in Figure 5.11). The reduction of such index can exhibit the effectiveness of different filtering scenarios. Section 5.3.1 presents the results for verifying performance of the double-phase connected filter. Some case study results are shown in section 5.3.2 to evaluate different filter placement options. Finally, a sensitivity study is conducted in section 5.3.3 to investigate the impact of different filter impedance values.

Table 5.2 Simulation system parameters

System parameter		Value
Primary system	Grounding resistance ($R_{G,pr,eq}$) [a]	0.4560+0.2963j Ω
	Primary equivalent impedance ($Z_{pr,eq}$) [b]	0.4806+2.5833j Ω
	Primary voltage source (V_s)	14.4kV
Service transformer	Voltage ratio	14.4kV/120V/120V
	kVA rating	37.5 kVA
	Impedance	2% pu
	Resistance	1.293% pu
	Grounding resistance (R_T)	12 Ω
Secondary system	Secondary conductor phase Impedance ($Z_{sec,ph}$)	0.21+0.094j Ω/km
	Secondary conductor neutral Impedance ($Z_{sec,N}$)	0.55+0.365j Ω/km
	Service conductor phase Impedance ($Z_{serv,ph}$)	0.34+0.137j Ω/km
	Service conductor neutral Impedance ($Z_{serv,N}$)	0.55+0.365j Ω/km
	House grounding resistance(R_C)	1 Ω
	Each house daily average power	1kW
Filter virtual impedance	at fundamental frequency	∞
	at harmonics	0.01 Ω

[a] This impedance is obtained as the equivalent of an MGN distribution system grounding resistance value. For more details, refer to [7].

[b] This value is in fact varied depending where the service transformer is connected to the feeder. To avoid complexity, a typical value of substation impedance is used here [28] (Please note that this impedance have a very negligible effect on the studies , since when transferred to secondary side of the transformer, it will be so much smaller than other secondary system components impedance).

5.3.1 Double-phase versus Single-phase Connection

The two different options for installing the filter in a secondary system with the double-phase scheme (as discussed in section 5.2.1) are investigated by selecting the following case studies.

1. The typical secondary system (Figure 5.11) normal operation without any filter.
2. Two single filters are installed separately one to phase A and the other to phase B at house #3 of the system (Figure 5.11).
3. One double-phase filter connected directly between phase A and B of the same house.

The daily profile of current TDD and average value of IDD associated with the harmonic current penetrating to primary system for all the cases are shown in Figure 5.14. The results once again confirm the effectiveness of double-phase connection as anticipated by the theoretical discussions in section 5.2.1.

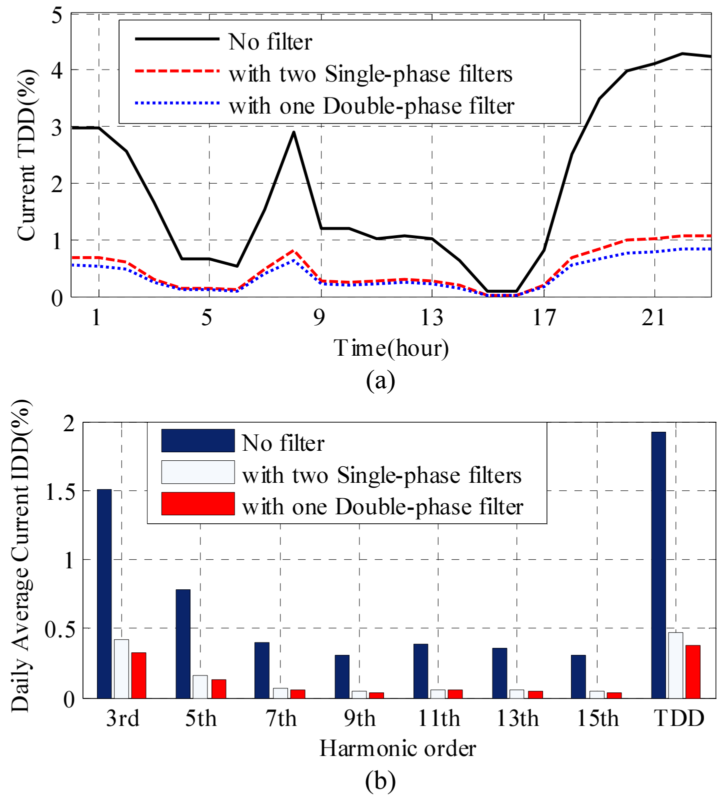


Figure 5.14 Comparison of single-phase and double-phase filter configurations in mitigation of harmonic currents penetrating the primary system (a) Daily profile of Current TDD (b) Daily average value IDD.

5.3.2 Filter Placement in the Secondary System

This section studies different filter placement options in a secondary system. The first step is to compare filter installation at the service transformer and the houses in the typical system (with the parallel configuration as in Figure 5.11). Then, additional analytical and simulation results are provided in 5.3.2.2 by considering a more generalized system configuration.

5.3.2.1. In the Typical System

The following cases are studied,

1. The typical secondary system (Figure 5.11) normal operation without any filter.
2. A double-phase filter is installed at the service transformer.
3. A double-phase filter is installed at house #1.

…

7. A double-phase filter is installed at house #5.

Figure 5.15 and Figure 5.16 present the simulation results. Between different house cases, the filter brings the most effective harmonic mitigation when installed in the closest one to the service transformer. (Theoretically speaking, the closest house case causes the highest harmonic reduction by having the lowest equivalent filtering impedance as discussed in section 5.2.2). The service transformer seems to be the most effective location; however, installing the filter in the closest house is also observed to be quite competitive with the transformer option.

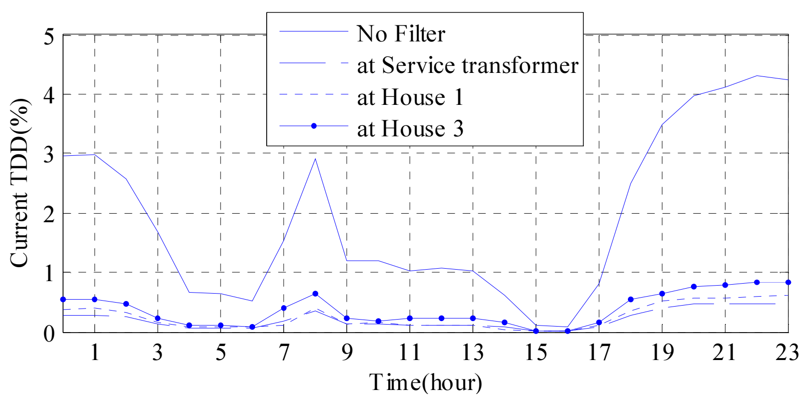


Figure 5.15 Harmonic current daily profile for different filter locations.

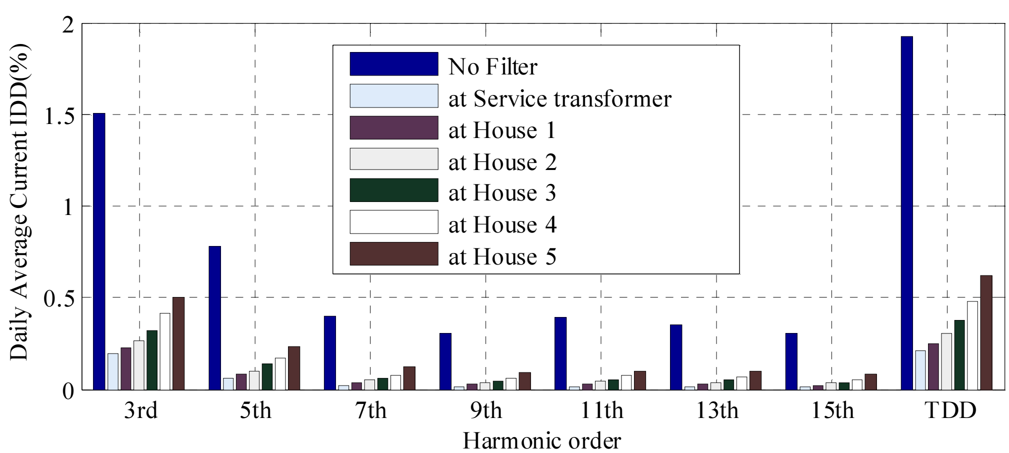


Figure 5.16 Daily average harmonic current IDD for different filter locations.

5.3.2.2 In a Generalized Configuration

Studies in the previous section revealed that the closest house to the service transformer is the most effective one among the other houses to locate the filter in a parallel configured secondary system. This section considers a more generalized system as depicted in Figure 5.17. There are two groups of houses supplied by the transformer. Apparently, the house with the shortest service conductor is the best option inside each group (Location A in the first group and location B in the second one). In this section, analytical estimations and simulation studies are performed to identify which of these two options (Locations A and B) is the most effective filter location.

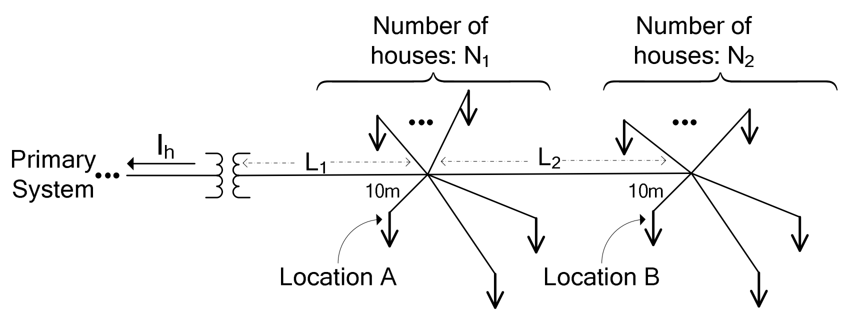


Figure 5.17 A generalized secondary distribution system with a combined parallel-cascade configuration.

In order to cover most of the common North American secondary systems, several cases including different combinations of house numbers in each group and typical minimum and maximum of secondary conductor lengths are considered as follows.

1. Distribution of house numbers in each group: {N_1=7 & N_2=3, N_1=5 & N_2=5, N_1=3 & N_2=7},
2. First secondary conductor length: L_1= {10m, 30m},
3. Second secondary conductor length: L_2= {20m, 60m}.

The service conductor length of the houses with filter (which are the ones with shortest service conductors) is considered 10m for all the cases. Lengths of the service conductors of other houses will have negligible effect on harmonic flow results so that are just randomly selected for each case. The filter effectiveness at both locations A and B is assessed by measuring the harmonic reduction percentage. Table 5.3 shows the results. Analytical studies are only presented for the 3rd harmonic, where associated simulation results are also presented both for 3rd harmonic and all the harmonics (TDD). Appendix D.1 describes the details of the analytical estimation procedure.

Table 5.3 The harmonic reduction percentage for comparing filter locations A and B including several cases with different length of lines and number of houses.

Secondary system configuration parameters					$\frac{IDD_{3rd}^{Filtered}}{IDD_{3rd}^{NoFilter}}(\%)$				$\frac{TDD_{I}^{Filtered}}{TDD_{I}^{NoFilter}}(\%)$	
					Analytical Estimation		Simulation Result		Simulation Result	
Case No.	N_1	N_2	L_1 (m)	L_2 (m)	Filter Location		Filter Location		Filter Location	
					A	B	A	B	A	B
1	7	3	10	20	20.0	26.0	18.5	20.5	16.2	18.4
2	7	3	10	60	20.0	34.8	18.5	23.2	16.2	21.2
3	7	3	30	20	17.5	23.0	16.2	18.2	14.2	16.3
4	7	3	30	60	17.5	31.5	16.2	21.0	14.2	19.3
5	5	5	10	20	20.0	23.5	18.5	21.9	16.2	19.9
6	5	5	10	60	20.0	28.7	18.5	28.0	16.2	26.1
7	5	5	30	20	17.5	20.8	16.2	19.5	14.3	17.8
8	5	5	30	60	17.5	26.0	16.2	25.4	14.3	23.8
9	3	7	10	20	20.0	21.0	18.5	25.0	16.3	22.8
10	3	7	10	60	20.0	22.6	18.5	35.6	16.3	33.2
11	3	7	30	20	17.5	18.6	16.2	22.2	14.3	20.3
12	3	7	30	60	17.5	20.5	16.2	32.3	14.3	30.2

The results of all the cases show that the filter is always more effective at location A compared to location B. In conclusion, when installing the filter at one of the houses of a secondary distribution system, the most effective mitigation is achieved by placing the filter in the closest house to the service transformer disregard of the system configuration.

Interestingly, the results also verify the fact that most of the system configuration parameters such as number of houses and all the conductor lengths (except of the first secondary conductor and the service conductor of the house with filter) do not affect the filtering performance considerably, when the filter is located in the closest house to service transformer (location A). For example, the simulation results of cases 3, 4, 7, 8, 11 and 12 with the similar secondary lengths (L_1) of 30m and service conductor lengths of 10m are quite similar.

5.3.3 Sensitivity Study of Filter Impedance

As discussed in section 5.1.2, the secondary system low impedance is one of the main challenging issues for a distributed filter scheme. In the studies presented in previous sections, a low enough filter impedance was chosen to guarantee filter ability in sinking the harmonic. Hereby, the influence of filter impedance is studied by using a range of filter impedances. To quantify the effectiveness of filter in suppression of harmonics, the percentage decrease value of TDD associated with the current flowing to the primary system is used.

As shown in Figure 5.18, the results illustrate that a quite low filter impedance is essential to achieve a considerable reduction in the harmonics flowing to the primary system.

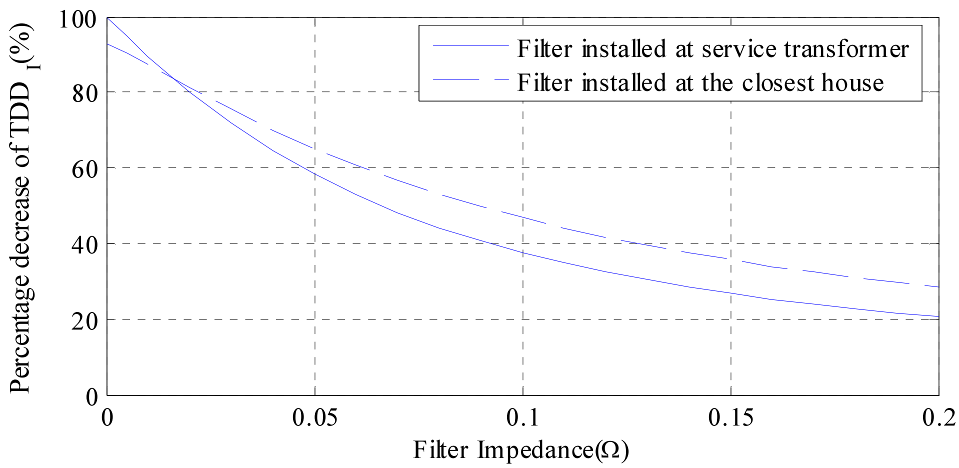


Figure 5.18 Percentage decrease of daily average current TDD obtained with different filter impedance values.

5.4 Simulation Studies on Primary System

In the previous sections, the distributed filter scheme was thoroughly examined in the secondary system. Issues regarding filter configuration and placement were investigated to effectively eliminate harmonics injected from the secondary system to the primary distribution feeder. In the present section, several simulation studies are conducted with the objective of establishing a comprehensive understanding of such filter scheme effectiveness in mitigation of the whole system harmonics. Different feeder types and conditions are included in the studies to answer the following important questions:

1. Is it essential to equip all of the service transformers in a feeder with the distributed filters to achieve an effective harmonic suppression? If not, how does this mitigation scheme improve with increasing the number of installed filters?
2. How the feeder configuration and the distribution of loads affect the distributed filters performance?
3. What is the required filters impedance range to reach a reasonable system-wide harmonic mitigation?

The studies are conducted on both the real and ideal feeders introduced in Chapter 2. Each of the secondary systems supplied by the feeder is modeled when equipped with the distributed filters. System modeling and simulation techniques are explained in details in in Chapter 2 and Appendix A. Indices of interest are also adopted according to Chapter 2. The simulation results accompanied with the related discussions are presented in sections 5.4.1 through 5.4.3.

5.4.1 Base Results

This section presents the initial results of equipping the real and ideal feeders with the distributed filters. The simulations are performed for different percentages of secondary systems equipped with such filters. The both filter location options are included for each feeder study: in one case, the filters are directly attached to the service transformers, while the nearest houses to the service transformers are chosen as the filters locations for the other case (For more details regarding filter placement options refer to sections 5.2.2 and 5.3.2). The filter impedance value of Z_f=.01Ω is chosen for these basic studies. The other impedance values will be examined by the sensitivity study performed in section 5.4.3.

As shown through Figure 5.19 and Figure 5.20, the base results confirm that for both filter locations and for both feeders the distributed filters can be significantly effective in suppression of feeder harmonics. Even with only 30% of the system equipped with the filters, a noticeable reduction of the harmonic indices is observed.

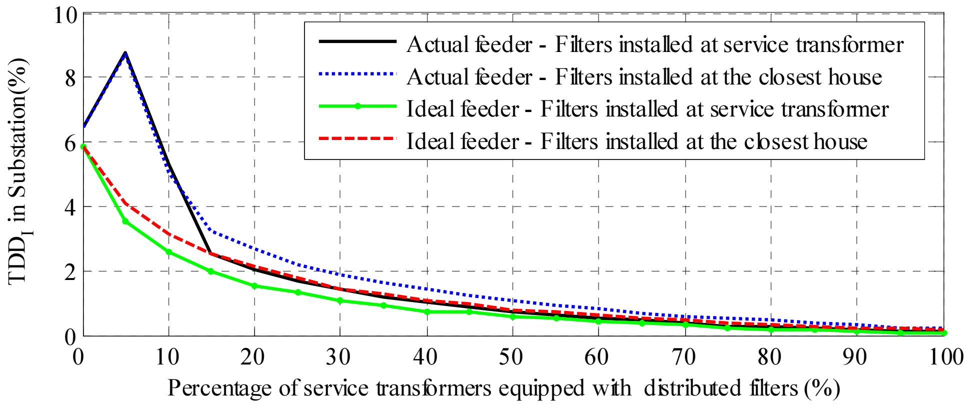


Figure 5.19 Current TDD in substation (daily 95% percentile value) versus percentage of service transformers equipped with distributed filters.

At low percentages of filters installation, the actual feeder exhibits a different behavior from the ideal feeder. Especially for voltage THD as shown in Figure 5.20, that with lower percentages than 10%, THD is even somehow increased inside the actual feeder. As introduced in Chapter 2, the actual feeder (differently from the ideal one) have several sections of underground cable with significant shunt capacitive admittance values and this phenomenon is due to the existence of these shunt capacitances in the system (For more explanations refer to Appendix D.2). To verify this scenario, an additional simulation case is also conducted by removing the shunt capacitance of underground cables inside the actual feeder. This extra case is added to Figure 5.21 and Figure 5.22, where the percentage decrease of TDD_I and THD_V are plotted. The results also demonstrate that the major cause of the difference between the real and ideal feeders at low filtering percentages is the shunt capacitance of underground cables.

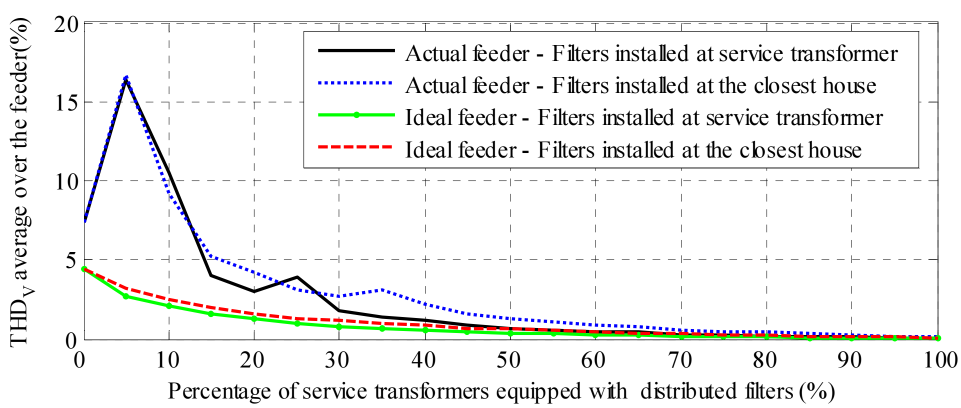


Figure 5.20 Voltage THD (daily 95% percentile value) average along feeder versus percentage of service transformers equipped with distributed filters.

In addition, a very attractive illustration of the Figure 5.21 and Figure 5.22 is highlighted by the dashed red lines added to the plots. For those linear dashed lines, the percentage decrease of TDD_I (or THD_V) is exactly equal to the filtering percentage. Comparing the obtained results with such dashed lines indicates that the percentage harmonic decrease achieved by the distributed filters in the both feeders can be much higher than the filtering percentage. It is due to the fact that each filter not only eliminates the harmonics generated inside its own secondary system, but also contributes to the system-wide harmonic mitigation by attracting the harmonics flowing from the other service transformers of the feeder. Such ability of sinking harmonics from both downstream and upstream sides of the system is one of most important merits of the chosen virtual-impedance active filters compared to their traditional counterparts with the current-detection based control as discussed in section 5.1.2. If the traditional active filters were chosen for the distributed filter scheme, then the harmonic reduction percentage could have only been reaching as high as the red dashed lines in the figures.

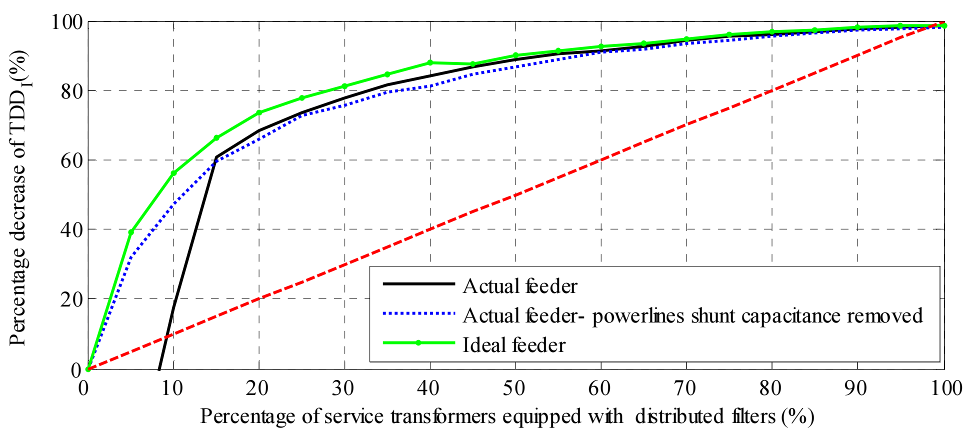


Figure 5.21 Percentage decrease of substation current TDD versus percentage of secondary systems equipped with the distributed filters installed in service transformer.

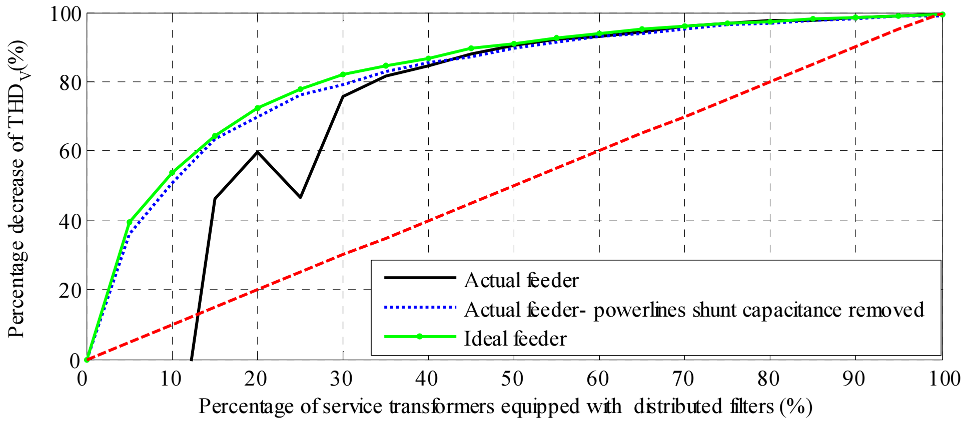


Figure 5.22 Percentage decrease of feeder average voltage THD versus percentage of secondary systems equipped with the distributed filters installed in service transformer.

5.4.2 Sensitivity Study of Feeder Parameters

This section presents the sensitivity study to assess the influence of the feeder characteristics and loads distribution on the distributed filters performance. Simulation results for the following cases are compared in Figure 5.23.

I. The ideal feeder normal condition without any changes.

II. The ideal feeder with the power-line sections length decreased from 1000m to 500m.

III. The ideal feeder with the power-line sections length increased from 1000m to 2000m.

IV. The ideal feeder with reducing the number of supplied service transformers from 450 to 225.

V. The ideal feeder when all the feeder conductors are converted from overhead lines to underground cables.

VI. The ideal feeder where all of the service transformers are moved to end of the feeder.

VII. The ideal feeder where all of the service transformers are moved to the middle of the feeder.

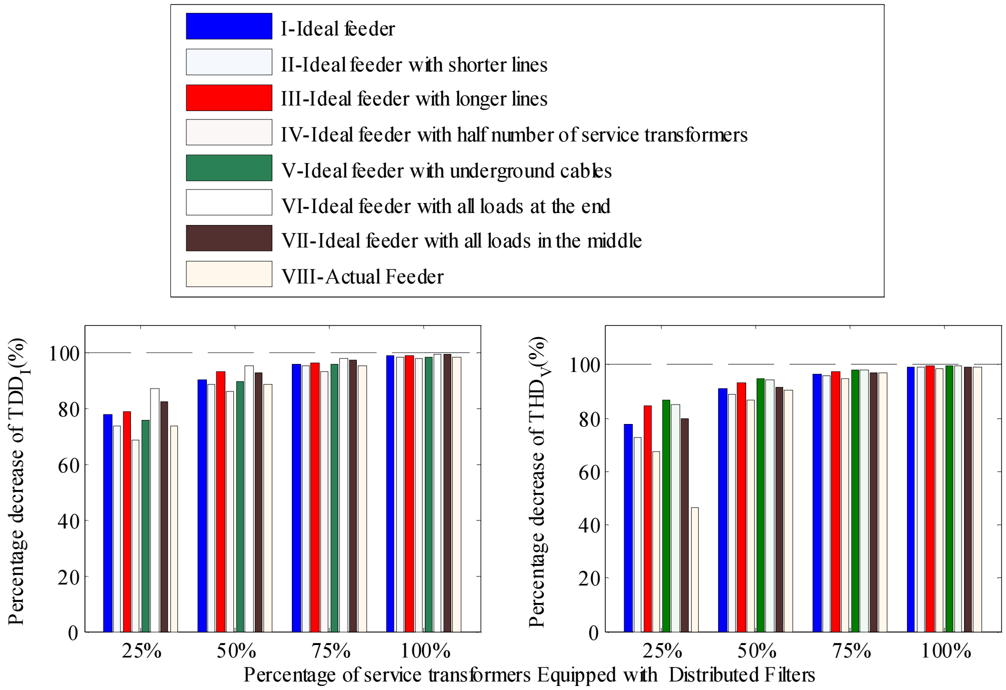
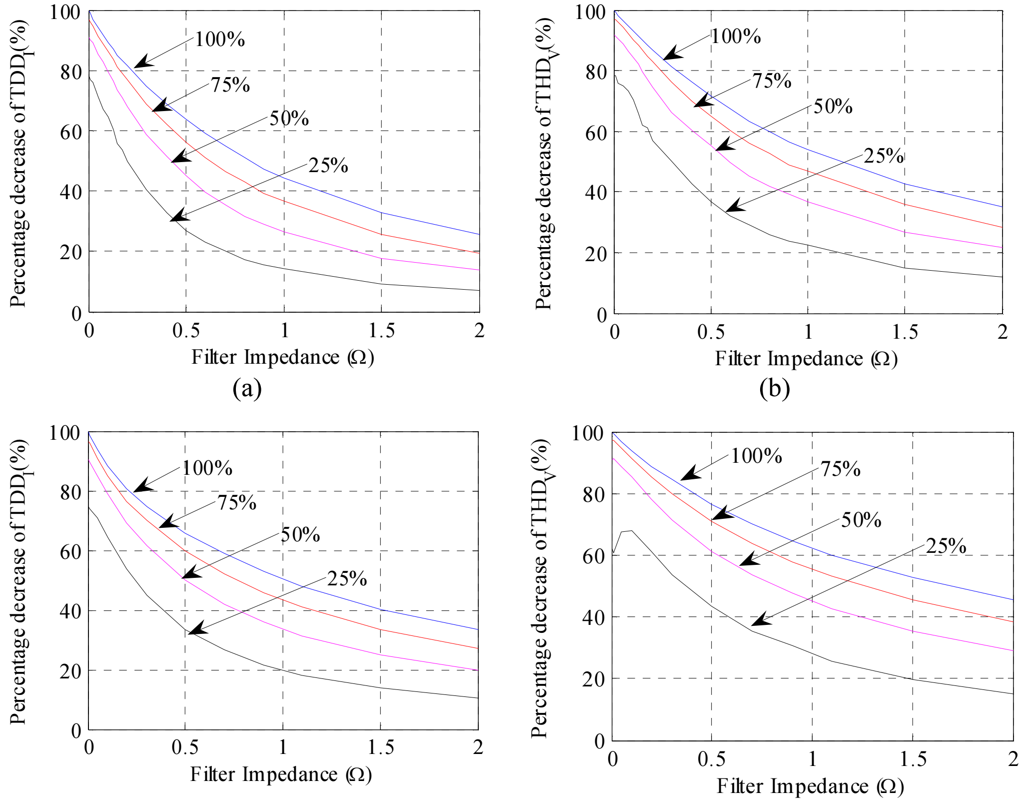


Figure 5.23 Percentage decrease values of current TDD and voltage THD versus percentage of service transformers equipped with distributed filters for different feeder characteristics.

No significant difference among the different cases is observed especially as the percentage of filtered secondary systems increases. Promisingly, the results illustrate that for any feeder with only equipping 25% of service transformers with the distributed filters, at least 50% of harmonics pollution can be mitigated.

5.4.3 Sensitivity Study of Filter Impedance

In all of the results shown in the previous sections, the filters impedances were chosen to be Z_f=0.01Ω. This section presents the results to study the sensitivity of distributed filters effectiveness to their impedance value. Simulations are including a range of filter impedances from 0.001 to 2Ω installed on both of the real and ideal feeder. The results are all shown in Figure 5.24 where the filters are connected directly to service transformers. The results of the other case associated with installation of filters at the closest house are similar and can be found in Appendix D.3.



(a) (b) (c) (d)

Figure 5.24 Percentage decrease of current TDD and voltage THD versus filter impedance including four different percentages of service transformers equipped with virtual-impedance distributed filters (a) (b) Ideal feeder (c)(d) Actual feeder (The filters are installed directly at service transformers for all the cases).

Comparing the above results with the ones presented in section 5.3.3, the distributed filters performance in mitigating the harmonics in the primary system is found to be less sensitive to filter impedance compared to the secondary system study (see Figure 5.18). Indeed, a wider range of impedances can bring an effective harmonic mitigation. For example, according to Figure 5.18 at least an impedance value of 0.1Ω is required for the filter to eliminate 40% of harmonics generated in its own secondary system; however, the results presented here, reveal that equipping 50% of service transformers by filters of around 0.5 Ω impedances can mitigate at least 40% of the feeder harmonic indices.

This significant difference between the primary and secondary system studies is once again demonstrating the effectiveness of virtual-impedance distributed active filters reflected in the primary system of distribution system. As mentioned in the previous sections, such filters not only suppress harmonic currents generated by their own secondary system, but also sink the harmonics flowing from other service transformers in the system.

5.5 Final Design Specifications

According to the conducted studies presented in this chapter, the final design specifications of distributed active filters for both of the real and ideal feeders are derived. The system-wide harmonic mitigation objective defined in Chapter 2 is adopted as the design criteria.

Two key variables must be determined to finalize the design of distributed active filters. The first is the number of the required filters and the second is the maximum permissible equivalent impedance for each device. In order to specify these two variables, the results of the previous section studies which presented the mitigation performance obtained by different number of filters and impedance values can be interpolated. Shown in Table 5.4 are the maximum allowable impedance values necessary to achieve the mitigation objective for the different cases. As the results show, the more number of installed filters, the higher value the filters impedances are permitted to be. For most of the cases, at least 35% of secondary systems must be equipped with the filters; otherwise, the defined mitigation goal is not achieved.

Table 5.4 The maximum allowable filter impedance values for different percentage of secondary systems equipped with filters to accomplish the system-wide harmonic mitigation objective in both of the real and ideal feeders.

		Maximum allowable filter impedance (Ω)									
Percentage of secondary systems equipped with filters		10%	20%	25%	30%	35%	40%	50%	70%	90%	100%
Ideal Feeder	At service transformer	-	-	0.02	0.055	0.08	0.1	0.135	0.205	0.265	0.295
	At the closest house	-	-	-	-	0.045	0.07	0.115	0.195	0.265	0.295
Actual feeder	At service transformer	-	-	-	-	0.06	0.08	0.11	0.17	0.225	0.25
	At the closest house	-	-	-	-	-	0.025	0.09	0.165	0.23	0.26

In order to save in the number of filters, installation percentages of less than 40% are selected for the final design specifications. The final design characteristics for the two feeders are given in Table 5.5. The average loading of each device is also estimated on the basis of substation harmonic currents and number of filters (The detailed process for this loading estimation can be found in the appendix D.4).

Table 5.5 The final design specifications of distributed active filters for a system-wide harmonic mitigation in both the real and ideal feeders

		Ideal Feeder		Actual feeder	
Filter placement option		At service transformer	At the closest house	At service transformer	At the closest house
Maximum allowable filter impedance $Z_f(\Omega)$		0.08	0.045	0.06	0.025
Percentage of secondary systems equipped with filters		35%	35%	35%	40%
Total number of required filters [a]		158	158	177	202
Average loading of each filter (A) [b]	From Simulation	23.55	23.55	36.3	31.8
	From Measurements	-	-	16.6	14.5
Filters nominal voltage	240V (Connected between phase A and B of the secondary system. See Figure 5.7)				

[a] The real and ideal feeders have 504 and 450 service transformers (secondary systems) respectively.
[b] The maximum daily value is shown.

5.6 Summary

The followings are summary of the main findings in this chapter.

- The studies confirmed the effectiveness of a distributed virtual-impedance active filter scheme for harmonic mitigation in a distribution system. The results showed that harmonic filters of such scheme contributes to the overall mitigation by eliminating the harmonics generated by the secondary system where they are installed as well as well as sinking the harmonics from all over the system. It was observed that equipping roughly 35% of the system transformers with such filters can lead to the aimed 75% reduction of feeder overall distortion indices.

- Because of the generally low system impedance at the secondary distribution systems, low impedance values of the virtual-impedance active filters are required to guarantee their effective performance. For instance, to mitigate 75% of harmonics pollution of a feeder with equipping half of its transformers with such distributed filters, an equivalent filter impedance of 0.06 Ω is needed. Ideally, such filters are able to set up any virtual impedance value as low as desired by increasing a gain factor in their control loop. However, some control operation or stability issues may appear in the practical implementation. The possible issues can be studied in future steps of the distributed filters research.

- Analytical and simulation studies revealed that the filters can be still very effective when connected directly between phases A and B of the North American type secondary distribution systems, so that one filter can be saved per each secondary system compared to the case of using two filters separately for each phase.

- The studies also confirmed that only one filter will be enough for each secondary system. The two choices of direct connection to the service transformer or installation at the nearest house supplied by the transformer were found as the most effective placement options for the distributed filters. The latter one has the advantage of a little higher equivalent system impedance; while for the first choice, the equivalent filtering impedance will not include the service conductor impedance.

- Conducting some sensitivity analyses, the feeder characteristics such as main trunk configuration, conductor type and loads distribution, etc. were not found to affect the distributed filters performance significantly.

Chapter 6

Comparison of Centralized and Distributed Filter Schemes

Two different methods to mitigate harmonics in the modern residential distribution systems are studied in this thesis. Chapter 4 and Chapter 5 investigate the centralized and distributed filter schemes, respectively. As Table 6.1 shows, the proper filter type for each scheme is also identified in the two chapters. Passive filters are not appropriate for the distributed scheme because of the low system impedance in the secondary distribution systems (and also because of the other issues discussed in Chapter 5). As well, active filters are not a popular choice for the centralized option because of their high cost and insufficient reliability for Medium-Voltage (MV) applications. Therefore, the two feasible system-wide harmonic mitigation options studied in this thesis are as follows:

- **Centralized filter scheme:** Installing MV passive harmonic filters in the primary feeder,
- **Distributed filter scheme:** Installing distributed active filters in low-voltage secondary systems.

In chapters 4 and 5, the final design specifications are also developed for both the above schemes to accomplish the mitigation objectives defined in Chapter 2. In this chapter, these two strategies are thoroughly compared on the basis of performance, technical and economic issues.

Table 6.1 The proper filter type for the distributed and centralized schemes

Harmonic Filter Type	Centralized Filters at Primary Feeder (Medium-Voltage)	Distributed Filters at Secondary System (120V Voltage)
Passive Filters	✓	×
Active Filters	×	✓

This chapter is organized as follows. Section 6.1 compares the performance of the two methods in terms of eliminating the system harmonic distortions. The different technical issues and challenges associated with the two schemes are discussed in section 6.2. The total implementation costs are estimated and compared for both methods in section 6.3.

6.1 Mitigation Performance

Figure 6.1 through Figure 6.4 shows the harmonic distortions of both feeders when the designed filter schemes are implemented. Both schemes of distributed filters and the MV filter have achieved the mitigation goal of 75% decrease in current TDD and voltage THD indices. For the individual harmonic orders, also, both schemes are observed to be effective in suppression of all the harmonic orders. In overall, both options are found capable to meet requirements of a system-wide harmonic elimination.

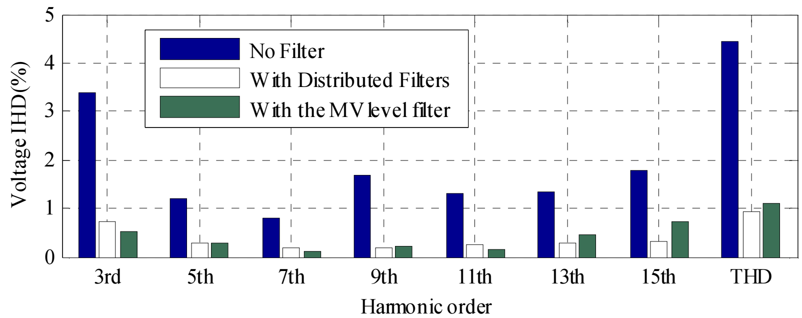


Figure 6.1 Daily maximum voltage IHD average over the feeder for the MV and distributed filters cases in the ideal feeder.

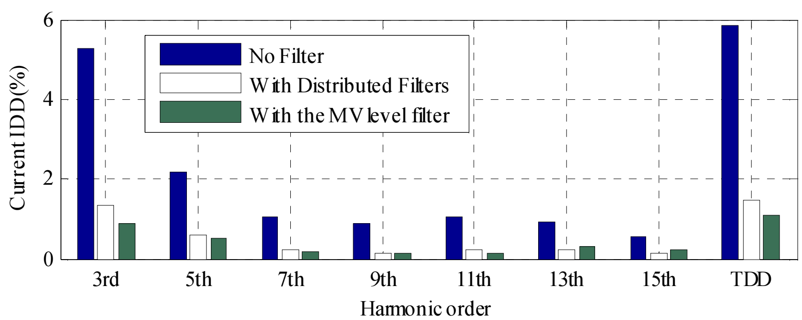


Figure 6.2 Daily maximum current IDD in substation for the MV and distributed filters cases in the ideal feeder.

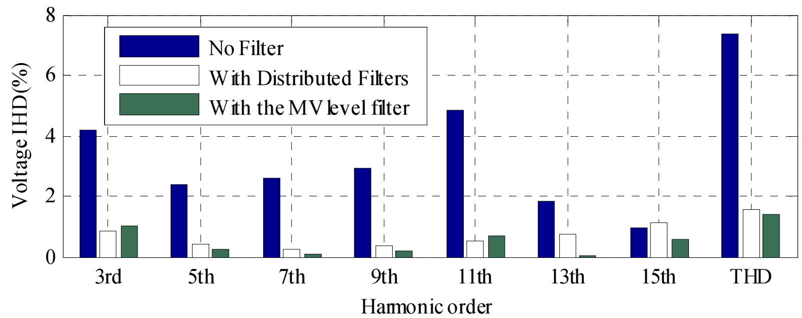


Figure 6.3 Daily maximum voltage IHD average over the feeder for the MV and distributed filters cases in the actual feeder.

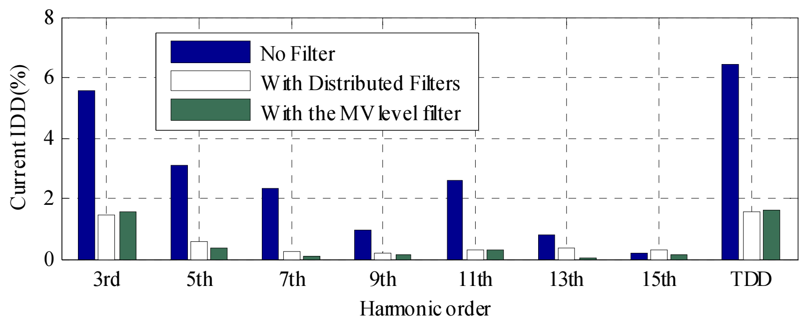


Figure 6.4 Daily maximum current IDD in substation for the MV and distributed filters cases in the actual feeder.

6.2 Technical Aspects Comparison

The two harmonic mitigation schemes can be also compared on the basis of technical and design aspects as follows [3],[9],[12],[14].

- **Design complexity:** As shown in Chapter 4, the design of centralized MV filters is not a simple process and requires consideration of several factors and constraints. The real implementation of such filters needs even a more complex process including design of a proper protection scheme, insulation and mechanical adjustments. In addition, MV filter design can not have a unique design for different feeders. As seen in Chapter 4 , most of specifications of final designed filter packages such as the number of filter installations, tuning frequencies and components sizing were different between the two feeders. In contrast to the MV filters, the distributed active filters can have a unique design for different feeders. Sensitivity studies performed in Chapter 5 showed that the impact of feeder characteristics and conditions on performance of such filters is negligible. In fact, once the prototype of these active filters is designed and manufactured, several of them could be installed in different residential feeders and there is no need to conduct a study or to carry a design for each individual system. The more number of installed filters, the more effective the system-wide harmonic mitigation will be.

- **Parallel resonance with system:** The MV filters are always prone to establish a parallel resonance with the system leading to severe harmonic amplifications. Although, a careful design can avoid this negative impact, such issues can emerge later because of filter detuning due to its components aging and possible changes in the system conditions. The distributed active filters never lead to this type of problems. Studies in Chapter 5 showed that for the actual feeder and for the low percentages of filtering, some unexpected harmonic amplifications may be observed for this scheme, but the impact was insignificant and just limited to filter installation percentages less than 10%.

- **System reactive power and voltage profile consideration:** While this issue must be considered in the design of MV passive filters, the distributed active filter does not affect the fundamental frequency load flow at all.

- **Changing of System conditions:** In case of a feeder reconfiguration, system extension or addition of loads, the performance of MV filters can be significantly affected. On the other hand, as one of the advantages of distributed filters, their operation is not dependent on the primary feeder conditions and can maintain an effective operation regardless of the changes in the primary system. In fact, as discussed in Chapter 5, the equivalent impedance of the primary feeder, when transferred to the secondary system, is very negligible and does not affect the performance of distributed filters significantly.

- **Reliability:** Overall, the distributed active filters provide a more reliable harmonic mitigation scheme. Outage of a single filter branch in a centralized MV filter may cause loss of mitigation performance or overloading of other branches. However, outage of one or two devices in the distributed scheme does not have a significant impact on the overall mitigation effectiveness.

- The only challenging issue about the proposed distributed active filters is the requirements imposed on it to exhibit a low impedance. As discussed in Chapter 5, the control loop of such filters can be adjusted to comply with such impedance requirements. However, some issues may arise regarding the operation and control of the converter inside the device. Once the necessary power-electronic studies on this topic are conducted and a real prototype of the device is implemented, there will be no concern regarding this issue for using a distributed active filter scheme for system-wide harmonic mitigation.

The above technical discussions to compare the two schemes can be summarized in Table 6.2.

Table 6.2 Technical comparison between the two harmonic filter schemes.

	Centralized MV passive filters	Distributed active filters
Less complex design		✓
Unique design for every systems		✓
Avoiding parallel resonance		✓
Unnecessity of system reactive power and voltage profile considerations		✓
Performance in changed system conditions		✓
Reliability		✓
Unnecessity of further research for prototype design	✓	

6.3 Economic Analysis

This section analyzes and compares the overall costs of the two studied filter schemes. For estimating the cost of MV filters, the data from [9],[39] is used. Since the data belongs to the year of 1999, an annual inflation rate of 2.5% is also considered to obtain an up-to-date cost estimation. Table 6.3 and Table 6.4 show the approximate expenses associated with an MV filter component and installation, respectively.

The price of transformers is also assumed as given in Table 6.5 based on the data provided by a utility company in Edmonton, Canada.

Table 6.3 Cost of capacitors and inductors for a MV filter.

Capacitor (25kV)	\$40 per kvar
Inductor (25kV)	~\$2800 per phase for 10mH<L<30mH
	~\$3400 per phase for 30mH<L<50mH
	~\$3800 per phase for 50mH<L<80mH

Table 6.4 Estimated costs for each MV filter installation.

Switching Device	$34,000
Overvoltage Protection	$7,000
Civil	$7,000
Engineering & Design	$28,000
Labor Cost [a]	$28,800
Real State	$100,000
Total Installation Cost	$204,800

[a] Labor cost is based on: 3 persons * 8 hour/day * 60 days * $20/hour.

Table 6.5 Estimated price of transformers (for the ZS filters).

	Transformer size (kVA)	Transformer price
Filter of actual feeder	500	$21,600
Filter of ideal feeder	2500	$30,000

By the above set of information, the overall cost of designed MV filter packages is estimated as presented in details in Table 6.6. The price of the low-voltage capacitors of the ZS filters are excluded in expense estimation of MV filters.

Table 6.6 Overall estimated cost for components and installations of designed MV filter packages.

		For actual feeder	For ideal feeder
Components Cost	Single-tuned Branches	$115,200	$150,000
	ZS Filter	$21,600	$30,000
Installation Cost		$204,800	$204,800
Total Cost Per Each Filter Package		$341,600	$384,800
Total Cost		$683,200	$384,800

For the distributed active filters, however, the price estimation can be challenging since there is no low-voltage single-phase virtual-impedance active filter in the present market. However, the price of available conventional low-voltage single-phase active filters ranges from $50 to $200. For this economic analysis, each active filter device price is assumed $500 as a conservative estimate. Once one of such filters with a final design in compliance with requirements specified for the proposed distributed filters (as described in Chapter 5) is manufactured, the accurate price will be exactly known. An average installation expense of $1500 per each device is also assumed. Hence, the total cost of each active device filter will be $2000. The overall cost of the distributed active filters scheme can be simply obtained by multiplying price of each device by the total number of required devices (See Table 5.5 for the final specification of the distributed active filters).

Finally, Table 6.7 gives the total estimated costs for comparing the two harmonic filter schemes. For both the feeders, the distributed active filter scheme is found to be the more economic option by being less expensive than its counterpart.

Table 6.7 Comparison of total mitigation costs by the MV filters and the distributed active filters.

Total harmonic mitigation cost	MV filters	Distributed active filters
For actual feeder	\$683,200	\$354,000
For ideal feeder	\$384,800	\$316,000

6.4 Summary

This chapter presented a comprehensive comparison between the centralized passive filter and the distributed active filter schemes. Despite the fact that both strategies can accomplish an effective system-wide harmonic mitigation, the investigations revealed that the distributed active filter can be a very promising option considering both economic and technical aspects.

Chapter 7

Conclusions and Future Work

7.1 Thesis Conclusions and Contributions

This thesis discussed the mitigation of harmonics in residential distribution systems. The existing mitigation measures are not always effective in managing the new harmonic situation, which includes several small and dispersed harmonic sources. An extensive set of studies was conducted to propose and assess different methods to effectively mitigate the harmonics injected by the residential loads in a distribution system. All the discussed mitigation strategies were evaluated by performing simulation studies on a generic feeder and a real distribution system serving residential customers in Edmonton, Canada. The key conclusions and contributions of this thesis can be summarized as follows.

- A novel double-tuned version of transformer-based filters was proposed to mitigate the Zero-Sequence (ZS) harmonics in a residential power system. The double-tuned feature was revealed to be very effective for solving ZS harmonic-caused problems such as telephone interference. Effective guidelines and methods were developed for loading assessment and the sizing of the filters' components. These filters' application issues specific to mitigating telephone interference problems were also investigated.

- An effective passive harmonic filter package including the proposed ZS filters was introduced to accomplish a system-wide harmonic suppression. A simple design guideline was developed by taking into account the essential considerations for applying MV passive filters to mitigate the residential harmonic sources of a dispersed and random nature.

- As a novel system-wide harmonic mitigation strategy, the concept of low-voltage distributed filters was also introduced in this thesis. The scheme was based on installing low-voltage virtual-impedance active filters in the secondary levels of the residential distribution systems. This scheme's design, installation and performance issues were thoroughly investigated by both developing essential theoretical principles and performing different simulation studies. Our method was found to be very promising for harmonic elimination in the modern residential feeders. The results revealed that an acceptable widespread harmonic suppression was obtained by equipping only 35% of the feeder's service transformers with filters.

- The thesis also performed a comprehensive comparison of the centralized and distributed filtering options. The studies revealed that passive filters were the proper type for the centralized scheme, while the virtual-impedance active filters were a better choice for the distributed scheme. Both the technical and economic aspects were considered to compare these two methods. Compared to the centralized option, the proposed distributed active filter strategy exhibited several merits such as being more economical and reliable and allowing for a unique design for different feeders. As a result, this novel scheme is a very promising and effective solution to the increasing harmonic problems in residential feeders.

7.2 Suggestions for Future Work

The author's suggestions for continuing the studies on harmonic mitigation in residential power distribution systems are as follows.

- As discussed in Chapter 2, a comprehensive standard which specifically addresses the harmonic mitigation requirements in residential distribution systems has not been developed yet. The appropriate standards and limits must be precisely determined by the utilities by compromising between the mitigation costs and the severity of the problems caused by the harmonics.

- In Chapter 3, the proposed ZS filters' application for telephone interference problems was thoroughly studied. Such filters can be also employed to mitigate other problems caused by ZS harmonics, such as neutral current/voltage rise. If necessary, a triplen-tuned version of such filters could be developed to trap all the 3^{rd}, 9^{th} and 15^{th} harmonics.

- As explained in Chapter 5, in order to guarantee the effectiveness of distributed active filters, they must be able to exhibit a low enough harmonic impedance.

However, if the equivalent impedance of such devices be lowered too much, some control and operational problems may occur in their converters. The possible issues and the related concerns need to be fully investigated in the continuation of this research. Additionally, the simple power-electronic structure of these devices could be expanded to provide some smart applications in addition to harmonic mitigation. Therefore, the devices could be applied to serve as a part of future smart grid technologies as well.

- A conservative cost estimate was made for the distributed filters scheme in Chapter 6 (including both the device and installation prices). After the active filters have been developed and manufactured, their actual price might be lower than our estimate. When an industrial prototype of these devices has been implemented, a more precise estimation of the total cost can be obtained.

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Appendix

Appendix A Aggregated harmonic model of secondary systems

This section of appendix explains how the equivalent aggregated harmonic models of the secondary systems are established. The procedure is similar as in [28], however, the proposed distributed active filters are also included in the models. Section A.1 describes the modeling procedure where the distributed filters are included as well. Next, the developed aggregated model will be verified by simulations for a typical secondary system in section A.2.

A.1 Modeling procedure

In order to cover all the studies of this thesis, the aggregated model must be derived for three scenarios (Figure A.1): 1) the service transformer is supplying the houses without any filter 2) when a filter is attached to the service transformer and 3) the case when filter is installed at one of the houses. As the first step, the equivalent circuits for the three scenarios are established as shown in Figure A.2 (a)-(c). In the equivalent circuits, the conductors connecting the houses other than the house with filter are ignored since of their negligible effect on the harmonic flows. However, for the third scenario, the secondary conductor and service conductor of the filter house do have the impact on harmonic flow and are included as shown in Figure A.2 (c). When generating the aggregated models for the whole feeder, lengths of these conductors (L_{sec} and L_{serv} in Figure A.1) for each secondary system are randomly chosen from typical ranges as the followings,

L_{sec}: 20m-60m,

L_{serv}: 5m-25m.

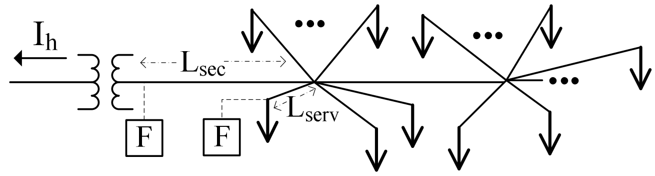

Figure A.1 A general secondary system with (or without) the distributed filters installed at either the service transformer or the closest house.

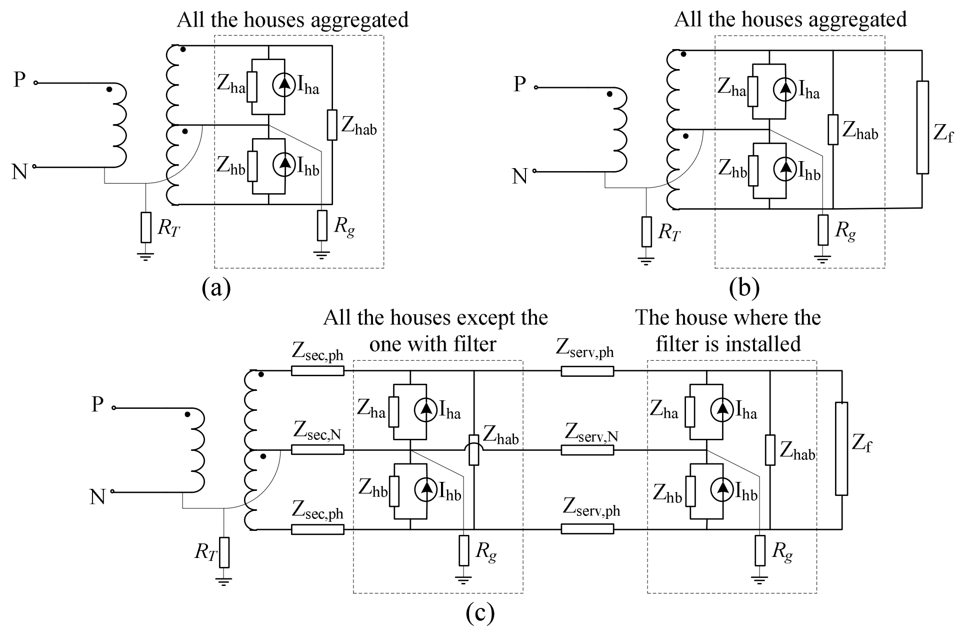

Figure A.2 Equivalent circuit of the system (a) without any filter (b) with a filter installed at the service transformer (c) with a filter installed at the closest house

Once the equivalent circuits are established, their Y and I matrix can be developed and reduced to obtain the final simplified models. The equivalent reduced Y and I matrices will only include nodes P and N where the secondary system is connected to the primary feeder through the service transformer (The procedure is thoroughly described in [28] for the first scenario). Finally, each of developed simplified models for each secondary system looks like the circuit shown in Figure A.3.

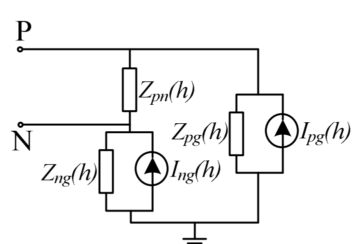

Figure A.3 The developed aggregated harmonic model of a secondary distribution system

A.2 Aggregated model verification

The developed simplified model for all the three scenarios (No filter, filter at service transformer and filter at the closest house) is verified by performing two sets of harmonic load flows on a typical secondary system. The first scenario is obtained by using the comprehensive simulation circuit explained in section 5.3 and the other scenario is performed by employing the developed model as shown in Figure A.4.

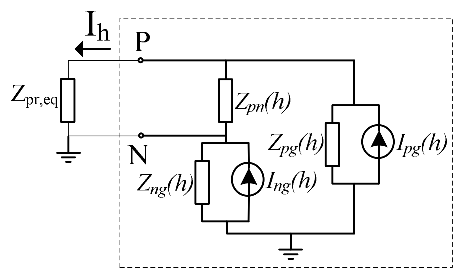

Figure A.4 Circuit for verification of the developed aggregated model

The results of the two harmonic flow studies (model versus detailed simulation) are shown and compared through Figure A.5 and Figure A.6 by plotting the harmonic current distortion profile of the current entering the primary side (I_h in Figure A.1 and Figure A.4).

The results obtained by the model and the simulation match very well, so that the developed models are quite effective in representing the service transformers and their supplied residential loads for studying both the distributed filters and also other mitigation schemes in a primary distribution system.

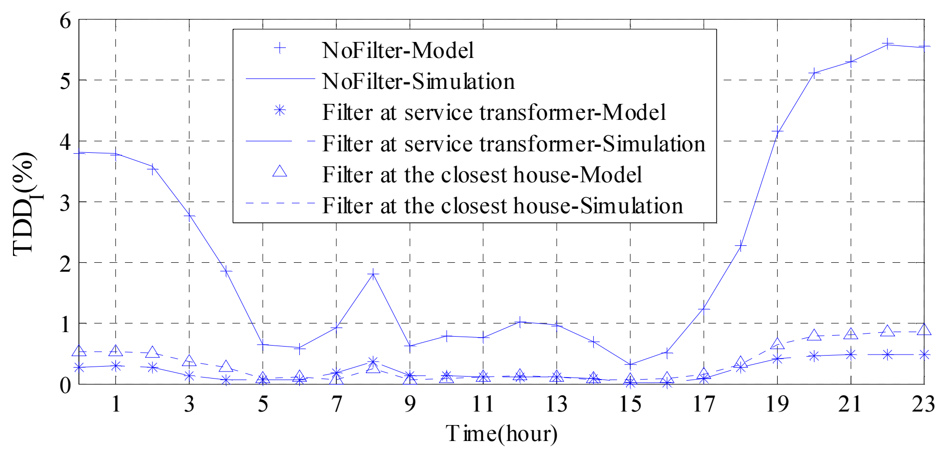

Figure A.5 Current TDD daily profile of the different cases obtained by the simplified model and detailed simulation

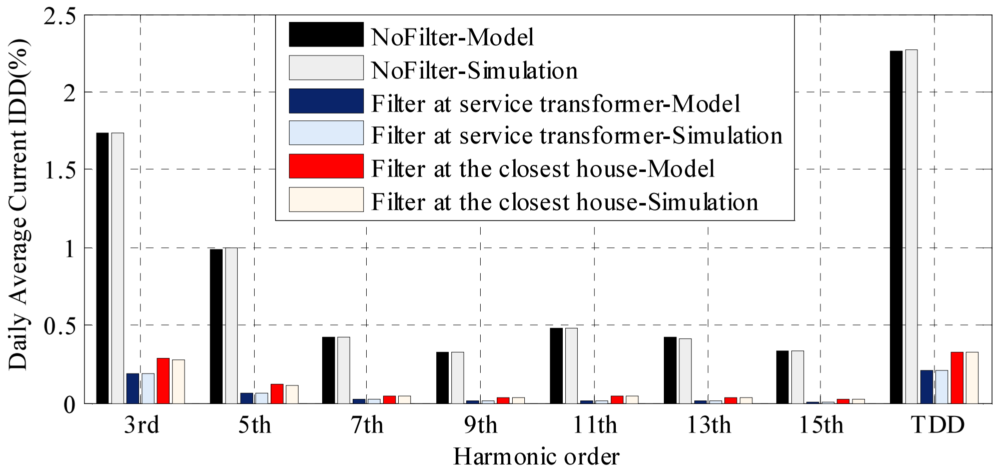

Figure A.6 Daily average current IDD of the different cases obtained by the simplified model and detailed simulation

Appendix B Loading Assessment of the ZS Filter Transformer

In general, the literature presents two categories of methods for the loading evaluation of transformers exposed to high harmonic currents:

• One approach is to calculate the k-factor index based on the harmonic content of the operation current. Next, a specialized k-factor type transformer able to operate under such a harmonic level is selected for that application [46]-[48].

• The other method is to calculate the maximum allowed current based on the harmonic content flowing in the transformer and to operate it under a decreased load to avoid overheating [1],[48].

However, the intention of assessing the loading of the transformer inside a ZS filter is neither to use a specialized transformer (k-factor) nor to decrease the transformer current. In fact, the main objective is to verify that the transformer of a selected size is not overheated by the harmonics flowing inside the filter. For this thesis, the proper transformer loading assessment method for the design of ZS filters is developed based on the same theories behind the k-factor and transformer derating methods in the IEEE std. ([48]).

To assess the loading condition of the ZS filter transformer, an index called the 'Transformer Loading Level (TLL)' can be defined as follows:

$$TLL(pu) = \frac{P_{TLL}}{P_{TLL-rated}}, \tag{B.1}$$

where P_{TLL} represents the transformer total load loss during filter operation, and the transformer maximum permissible loading capacity is represented by $P_{TLL\text{-}rated}$, which is the transformer load loss under a rated sinusoidal current. Therefore, as long as TLL does not exceed 1pu, the transformer of the ZS filter operates safely without overheating.

According to [48], the total load loss consists of the copper power loss (P_C) and the winding eddy current power loss (P_{EC}) and other stray loss (P_{OSL}) parts as follows:

$$P_{TLL} = P_C + P_{EC} + P_{OSL} . \tag{B.2}$$

By considering the copper power loss at the rated condition as the base value ($P_{C\text{-}rated}$(pu)=1), each of these power losses can be calculated from the transformer harmonic currents as follows[48]:

$$P_C(pu) = \frac{RI_{rms}^{\ 2}}{RI_{rated}^{\ 2}} = \left(\frac{I_{rms}}{I_{rated}}\right)^2 \tag{B.3}$$

$$P_{EC}(pu) = P_{EC-R}(pu)\sum_{h=1}^{\infty} h^2 (\frac{I_h}{I_{rated}})^2 \tag{B.4}$$

$$P_{OSL}(pu) = P_{OSL-R}(pu)\sum_{h=1}^{\infty} h^{0.8} (\frac{I_h}{I_{rated}})^2 \tag{B.5}$$

Consequently, one can obtain $P_{TLL\text{-}rated}$ as

$$P_{TLL-rated} = 1 + P_{EC-R}(pu) + P_{OSL-R}(pu) \tag{B.6}$$

Finally, the equation for deriving TLL can be written as

$$TLL(pu) = \frac{P_C(pu) + P_{EC}(pu) + P_{OSL}(pu)}{1 + P_{EC-R}(pu) + P_{OSL-R}(pu)}, \tag{B.7}$$

where P_C(pu), P_{EC}(pu) and P_{OSL}(pu) can be determined from the harmonic currents flowing inside the filter by using (B.3)-(B.5).

The index calculation also requires the P_{EC-R}(pu) ('Eddy current loss factor') and P_{OSL-R}(pu) ('Other stray loss factor') values, which are, in fact, constant coefficients dependent mainly on the transformer design, size and structure.

According to the recommendation of IEEE standard, P_{OSL-R}(pu) can be obtained from P_{EC-R}(pu) by following a simple rule of thumb [48]:

$$P_{OSL-R}(pu) = \alpha P_{EC-R}(pu)\,, \tag{B.8}$$

where α is approximately 2 for a liquid-filled transformer and 0.5 for a dry-type transformer. According to this estimation, the only unknown in the TLL definition is P_{EC-R}(pu). In general, no practical and simple method to obtain this value from the transformer nameplate is available [48], [49]. The typical values of the eddy current loss factor for some different types of transformers are shown in Table B.1 [49].

Table B.1 Typical values of 'Eddy current loss factor' (PEC-R) [49]

Equipment		P_{EC-R}(%)
Dry Type Transformers	≤1000 kVA	3-8
	≥1500 kVA	12-20
Oil-Filled Type Transformers	≤2500 kVA	1
	2500~5000 kVA	1-5
	> 5000 kVA	9-15

For the loading assessment analysis in this thesis, a conservative value of P_{EC-R}(pu) was chosen according to the above table.

Appendix C MV passive harmonic filter design details

C.1 Design of single-tuned filter branches

Figure C.1 shows schematic of a conventional single-tuned filter branch. As discussed in Chapter 4, this filter is a part of the proposed filter package and its capacitors are sized according to the iterative design procedure.

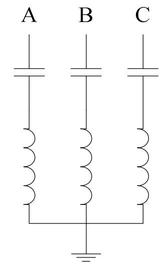

Figure C.1. A conventional single-tuned filter branch.

Once the capacitor size is known, the inductor size can be calculated by the following equation.

$$L = \frac{1}{C h_t^2 (2\pi f_0)^2} \quad \text{(C . 1)}$$

where f_0 is the power frequency (f_0=60Hz in North America) and h_t the tuned harmonic frequency. Based on the general practice, the filter is not tuned to exact harmonic frequencies but to a slightly lower frequency to avoid the following issues [3].

a) Capacitors with metalized film construction lose capacitance as they age which may result in slight increases in tuning frequency when used in harmonic filters. Therefore, a single-tuned filter tuned at below its rated frequency can still perform acceptable filtering even after the capacitor aging.

b) Tuning a harmonic filter too sharply to the harmonic frequency can unnecessarily stress the components and consequently increases prone of overloading.

c) The manufacturing tolerance of the inductors can cause a resulted tuning frequency higher than its designed nominal value.

d) Operation of capacitor fuses on failed capacitor elements or units can result in slightly boosting the tuning frequencies.

For example, in this thesis, single-tuned filters for 5^{th} and 7^{th} harmonics are tuned to 4.9 and 6.9 harmonic orders respectively.

Appendix D Distributed Active Filter Scheme Design Details

D.1 Analysis of a secondary system with generalized configuration

In section 5.3.2, analytical results were presented for a system with generalized configuration to assess different filter placement options. This section of appendix describes the analytical procedure used to estimate the filter effectiveness, when it is installed at locations A or B of the system (see Figure 5.17).

For location A, the system can be easily analyzed similarly as sections 5.2.1 and 5.2.2 of the report and by the means of equivalent circuit shown in Figure 5.9. The equations (5.16)-(5.18) will be modified as below for the current case,

$$\begin{cases} \dfrac{I_{h,p}^{Filtered}}{I_{h,p}^{No\ filter}} = \dfrac{Z_{eq,F}}{Z_{eq,F} + Z_{sys}} \\ Z_{sys} = 4\alpha^2 Z_{eq,pr} + 4Z_T + 2Z_{L1} \\ Z_{eq,F} = Z_F + 2Z_{Lb} \end{cases}, \tag{D . 1}$$

where Z_{L1} and Z_{Lb} are the impedances of the first secondary conductor and the filter house service conductor respectively. Other variables are still as the same as defined in the report.

However, a more sophisticated analysis is needed for the filter performance when it is installed in location B. The equivalent circuit shown in Figure D.1 is used to analyze this situation. In this circuit, Z_{L1} and Z_{L2} are the impedances of the first and second secondary conductors where Z_{Lb} represents the impedance of the service conductor connecting the house with filter. $I_{h,A1}$ and $I_{h,B1}$ represent the harmonic currents generated by the first group of houses and $I_{h,A2}$ and $I_{h,B2}$ are associated with the second groups of houses, respectively.

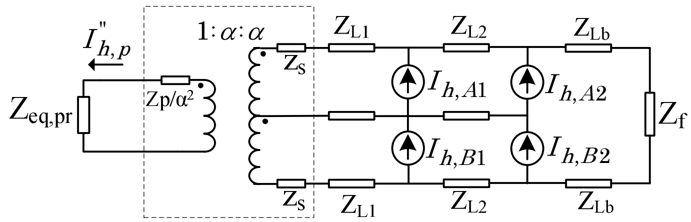

Figure D.1 The equivalent circuit for the case of placing the filter in location A of the generalized system shown in Figure 5.17.

According to the superposition principle and analyses conducted in sections 5.2.1 and 5.2.2, the primary harmonic current can be derived as below,

$$I_{h,p}^{Filtered} = \frac{Z_{eq,F} + 2Z_{L2}}{Z_{eq,F} + 2Z_{L2} + 2Z_{L1} + Z_{sys}} \alpha \left(I_{h,A1} + I_{h,B1}\right) + \frac{Z_{eq,F}}{Z_{eq,F} + 2Z_{L2} + 2Z_{L1} + Z_{sys}} \alpha \left(I_{h,A2} + I_{h,B2}\right) \tag{D . 2}$$

$$\text{where } \begin{cases} Z_{sys} = 4\alpha^2 Z_{eq,pr} + 4Z_T \\ Z_{eq,F} = Z_F + 2Z_{Lb} \end{cases} \tag{D . 3}$$

And when there is no filter in the system, one have the below equation similarly as (5.3),

$$I_{h,p}^{NoFilter} = \alpha \left(I_{h,A1} + I_{h,B1} + I_{h,A2} + I_{h,B2}\right) \tag{D . 4}$$

In order to simplify the derived equations, harmonic currents generated by each group of houses can be assumed proportional to the number of houses,

$$\begin{cases} I_{h,A1} \approx \dfrac{N_1}{N_2} I_{h,A2} \\ I_{h,B1} \approx \dfrac{N_1}{N_2} I_{h,B2} \end{cases} \tag{D . 5}$$

By dividing (D . 2) over (D . 4) and substituting (D . 5) into them,

$$\frac{I_{h,p}^{Filtered}}{I_{h,p}^{NoFilter}} \approx \frac{Z_{eq,F} + \dfrac{2N_1}{N_1 + N_2} Z_{L2}}{Z_{eq,F} + 2Z_{L2} + 2Z_{L1} + Z_{sys}} \tag{D . 6}$$

Finally, the above equation is employed to estimate the filter performance at location B and obtaining the analytical results (associated with generalized configuration) presented in section 5.3.2 of the thesis.

D.2 Impact of feeder shunt capacitance on distributed filters performance

By the results presented in section 5.4.1 of the thesis, shunt capacitance of underground cables inside the actual feeder were found to make the distributed filters somehow ineffective when the percentage of equipped transformers with the filters were lower than 10%. Theoretical explanation for such phenomenon is presented in this appendix.

Shunt capacitances can always cause abnormalities in system harmonic load flow by participating in parallel resonances with inductance of other system components. Figure D.2 shows a simplified system schematic to investigate any possible interaction of the distributed filters installed in secondary systems with primary power-lines shunt capacitance.

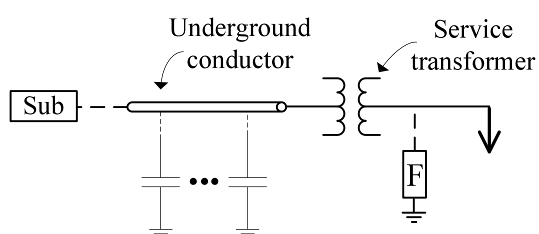

Figure D.2 A simplified schematic of feeder to analyze possible interactions of distributed filters and power-lines shunt capacitance.

The equivalent circuit for the case of no filter is shown in Figure D.3(a). As observed in the normal situation, because of the loads high impedance, there is no inductor branch in the system to establish a parallel resonance with the shunt capacitances. However, when a distributed filter is installed as shown in the circuit of Figure D.3(b), its low impedance bypasses the loads impedance providing a path for the transformer leakage inductance to establish a parallel resonance with the shunt capacitance of the underground cables.

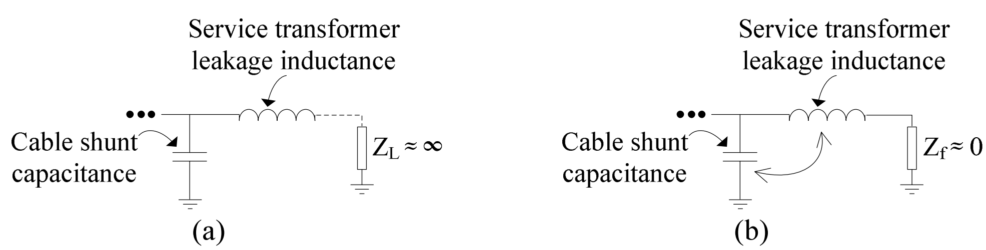

Figure D.3 The equivalent circuits showing how a parallel resonance may be established with installing the distributed filters.

Fortunately, based on the report results this phenomenon is unlikely to cause a significant problem for the proposed filter scheme and is only observed for the actual feeder (including long underground cables) and just in the low percentages of filters installation less than 10%.

D.3 Filter Impedance study for the closest house location

This appendix presents the primary system simulation results for the sensitivity of distributed filters to the filter impedance value, where the filters are installed in the closest house to their supplying transformer. As mentioned in section 5.4.3, the results do not differ from the case of direct connection to service transformers considerably.

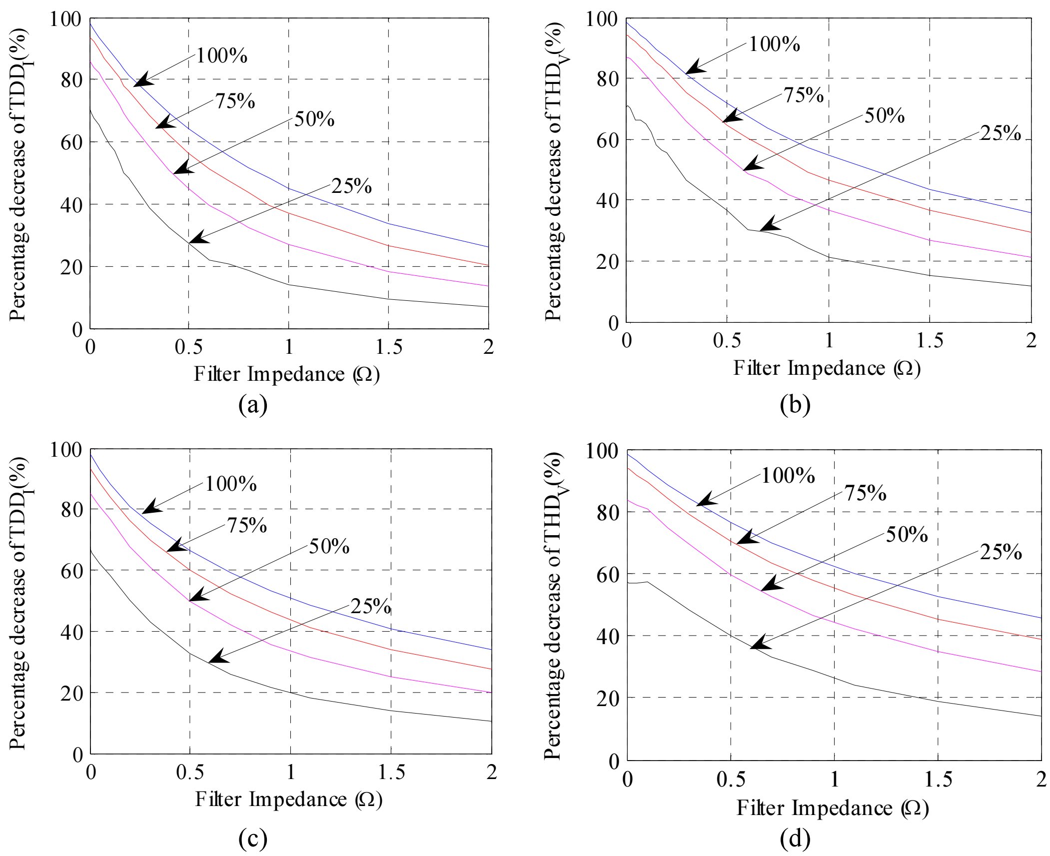

Figure D.4. Percentage decrease of current TDD and voltage THD versus filter impedance including four different percentages of service transformers equipped with virtual-impedance distributed filters (a) (b) Ideal feeder (c)(d) Actual feeder (The filters are installed at the closest house to the service transformers).

D.4 Loading Estimation of Distributed Active Filters

In this thesis, the loading of distributed filters are estimated on the basis of the feeder harmonic currents in substation. By a conservative approach, it is assumed that the distributed filters collectively sink the whole harmonic current of the feeder which in normal condition flows to the substation. The average harmonic current flowing inside each device can be derived by dividing the total current by the number of the devices. The service transformers voltage ratio needs to be considered too.

Therefore, the expression shown below is used to estimate the filters loading.

$$I_h^{Filter} = (I_{h-Sub}^{PhaseA} + I_{h-Sub}^{PhaseB} + I_{h-Sub}^{PhaseC}) \times \frac{14.4kV}{240V} \div N_F \, , \qquad \text{(D . 7)}$$

where N_f is the number of filter devices and I_h^{Filter} is the average current entering each filter. $I_{h\text{-}Sub}^{phaseX}$ is also the harmonic current of each phase at the feeder substation. For the actual feeder, the substation harmonic current is derived from both the simulation model and also some field measurements conducted in the feeder substation.