Analysis of Unbalanced Harmonic Propagation in Multiphase Power Systems

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9.1 Introduction

Harmonics related concerns were initially centered at a few large harmonic-producing devices until the early 1980s. Because these devices, such as HVDC and SVC, and their supply systems are well balanced among three phases, harmonic analysis based on positive sequence network representations was generally sufficient. The situation has changed significantly in recent years. More and more harmonic-producing loads are being connected to systems which are unbalanced. The effects of single phase harmonic-producing loads are also becoming important. The need to investigate harmonic propagation in unbalanced systems with unbalanced harmonic excitations has emerged.

Unbalanced harmonic analysis seeks to assess the propagation of harmonics in each phase of a power system. Sometimes, the harmonic currents in the neutral or ground conductors may also need to be calculated. In all cases, full phase representation of a network is required. As such, many unique component modeling and network solution issues must be addressed. Thanks to the pioneering work documented in references [1-4], methodologies for modeling and simulating unbalanced harmonic propagation have been established. The purpose of this paper is to summarize the progress achieved in this area. The key issues of multiphase harmonic power flow solutions are discussed. Sample cases are presented to illustrate the features of unbalanced harmonic analysis.

9.2 The Need for Multiphase Harmonic Analysis

In this paper, the term multiphase harmonic analysis is used to describe harmonic simulations which are based on a full phase representation of a system. The system and its loads can be balanced (a special case) or unbalanced. The term three-phase harmonic analysis is not used here because the full phase representation of a system often requires certain network components (such as transformers) be treated as multiphase components. Typical cases that require multiphase harmonic analysis are summarized as follows:

1. Utilization system harmonic analysis. Sample utilization systems are utility secondary distribution systems, commercial building distribution systems, and aircraft power systems. These systems may contain many single-phase harmonic sources. The networks are unbalanced as well. Sample needs of harmonic analysis are the assessment of harmonic currents in neutral conductors, the evaluation of harmonic mitigation devices and the de-rating of supply transformers.
2. Distribution system harmonic analysis. Most utility distribution systems are unbalanced in both network structures and connected loads. Even if the harmonic sources of interest are three-phase, unbalanced harmonic analysis is often required. The main interest of such analysis includes the determination of harmonic resonance conditions, the assessment of harmonic-telephone interference, and the verification of customer power quality levels.
3. Analysis of harmonic problems in balanced systems. For balanced systems, the majority of harmonic related problems can be investigated using the one-phase based methods. However, cases do arise that need unbalanced analysis. These typically relate to the generation of unbalanced harmonic currents from specific loads or operating conditions.
4. Special Cases. The nature of some harmonic caused problems may warrant multiphase harmonic analysis. For example, residual (zero sequence) harmonic currents which are of primary concern for telephone interference need to be determined using such analysis. The generation of non-characteristic harmonics is another example.

9.3 Modeling Considerations

9.3.1 Linear Components and Networks

Linear components are those components that do not produce harmonic voltages or currents. The generic model of linear components is a multiphase coupled [Z(h)] or [Y(h)] matrix, where h is the harmonic number.

Lines and Cables: The basic model is a per-unit length multiphase series [Z(h)] and shunt [C] matrices that include all phase and ground conductors of the component. A line model can then be constructed either as a lumped parameter π circuit (for short lines) or a distributed parameter π circuit (for long lines). Inclusion of ground conductors in the model helps to determine the neutral or grounding currents.

Transformers: The main difficulty in modeling transformers is the variety of transformer connections and the resultant phase shift effects. The phase shift effects must be simulated because they are an important means of harmonic mitigation. Experience shows that the best approach is to model transformers as coupled windings that have no pre-determined connection forms. The coupling is represented by a [Z(h)] or

[Y(h)] matrix with transformation ratios included [3]. A particular transformer connection is specified in the input data by renaming the winding terminal nodes in a way similar to the actual transformer connections (Figure 9.1). Thus any transformer configurations can be simulated. Although the model can include linear magnetizing branches, the effects of the branches are insignificant for most harmonic cases.

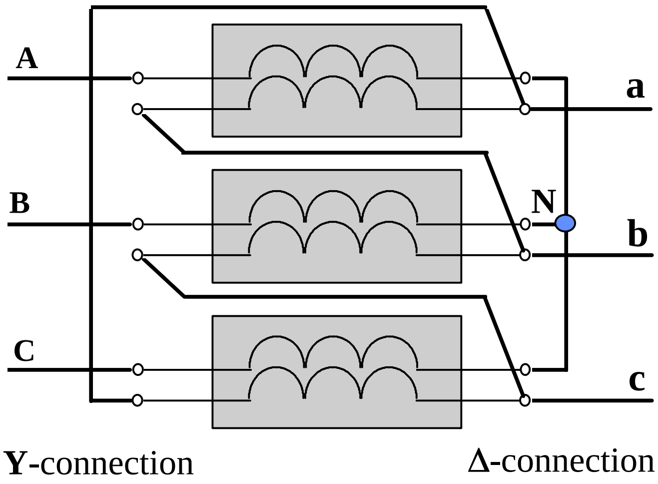

Figure 9.1. Transformer model example: connection of three two-winding transformers to form a Y-D three-phase transformer by node renaming

Rotating Machines: These include induction and synchronous machines. They can be modeled as a three-phase, balanced fundamental frequency voltage source behind a three-phase harmonic impedance matrix (Figure 9.2). Again, no motor connections such as Y or Δ are specified in the model. The voltage source is determined from the fundamental frequency load flow solution. The impedance matrix can be determined as

$$[Z_m(h)] = \frac{1}{3}\begin{bmatrix} Z_o + 2Z_n & Z_o - Z_n & Z_o - Z_n \\ Z_o - Z_n & Z_o + 2Z_n & Z_o - Z_n \\ Z_o - Z_n & Z_o - Z_n & Z_o + 2Z_n \end{bmatrix}$$

where $Z_n = R_n + jhX_n$ is the locked rotor (negative sequence) impedance of the machine when h=1. Z_o is highly dependent on the machine armature winding pitch design and typical values are not available.

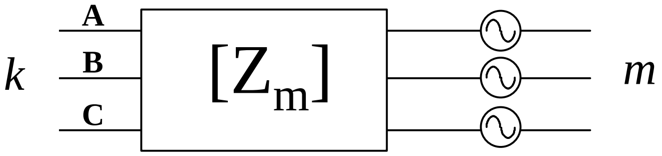

Figure 9.2. Model for three-phase rotating machines

General Loads: General loads refer to the aggregate form of various individual loads. Modeling of general loads must address three critical issues. The first issue is the load's response to harmonic excitations. The second is its response to unbalanced excitations. The third is that the load may contain harmonic currents. The first issue has not been fully solved. But some preliminary results, such as the CIGRE harmonic load model, are available [5]. Series R and L elements determined from 60Hz are used as harmonic load models in some cases as well. Reference [4] analyzed the second issue. The main idea is that if the load's responses to the positive and zero sequence harmonic excitations are known, a three-phase harmonic load model can be constructed using a coupled 3 by 3 [Z(h)] matrix as

$$[Z(h)] = \frac{1}{3}\begin{bmatrix} Z_o + 2Z_p & Z_o - Z_p & Z_o - Z_p \\ Z_o - Z_p & Z_o + 2Z_p & Z_o - Z_p \\ Z_o - Z_p & Z_o - Z_p & Z_o + 2Z_p \end{bmatrix}$$

where $Z_p(h)$ may be determined from the CIGRE load model. Few works are known that investigated the determination of $Z_o(h)$ data. Due to lack of data, it may be assumed that $Z_o(h)$ is about 1 to 5 times of $Z_p(h)$. The ratio of 1 corresponds to cases where the load has no mutual coupling. The ratio of 5 corresponds to cases where the load consists of a large percent of three-phase rotating loads or loads with ungrounded star points. The third issue is unsolved and needs considerable research. Present practice is to ignore the harmonic currents if they are small or to represent the entire load as three-phase harmonic current sources if they are significant. The current sources are typically determined from field measurements.

External Networks: Due to its multiphase modeling capability, the representation of external networks is easier in multiphase harmonic analysis than in the one-phase based analysis. The reason is that each interface between the external and study networks can be treated as one phase of a multiphase network equivalence (Figure 9.3). The data can be determined from frequency scanning of the external network one phase at a time across all interface phases. The results are a frequency dependent multiphase [Z(h)] or [Y(h)] matrix in series with multiphase fundamental frequency voltage sources. The voltage sources are the open circuit voltages of the external networks.

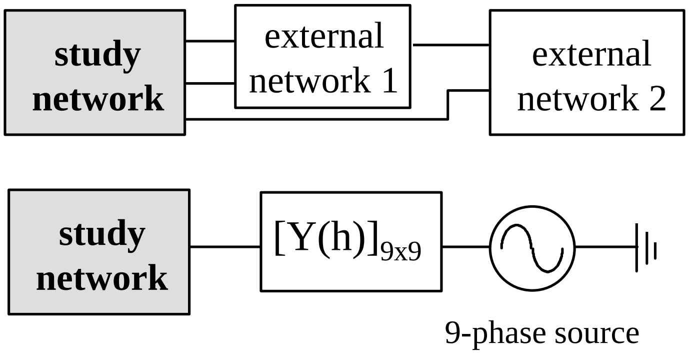

Figure 9.3. Example of external network equivalence. Since there are three three-phase lines connected to the study network, the equivalence is a 9 phase system

3.2 Nonlinear or Harmonic-Producing Components

There are no major differences between the multiphase or one-phase based harmonic analyses in terms of modeling nonlinear components. Previous chapters provide a good summary of the most important aspects of this subject. The purpose of this section is to highlight the unique characteristics of harmonic source representation under unbalanced conditions.

1) Single-phase harmonic sources connected in different phases of a system can only interact with each other through the system. Therefore, each source can be modeled separately. Models of such sources can take the forms of either harmonic current sources or detailed iteratively-improved device models.
2) A three-phase harmonic source, particularly the power electronics types, can have interactions among three phases that can influence the output of harmonic currents from each phase. Non-characteristic harmonics which wouldn't exist if the supply is balanced can be produced. A salient pole synchronous machine can become a harmonic source when unbalanced voltages are applied at the terminals as well. If the effects of non-characteristic harmonics need to be assessed, the sources must be modeled in detail. The models based on typical current spectra are no longer valid.
3) For those sources that have a nonlinear voltage-current relationship such as magnetizing branches of transformers, it is also a good practice to model them with a detailed model because "typical" harmonic spectra for such devices do not exist. For multiphase harmonic analysis, the placement of nonlinear magnetizing branches in an equivalent circuit depends on the transformer designs [3].

9.4 Simulation Methods

The unbalanced harmonic propagation in a power system can be simulated using a multiphase admittance matrix equation as follows:

$$[Y_h][\boldsymbol{V}_h] = [\boldsymbol{I}_h]$$

where each row of the $[Y_h]$ matrix represents one node of the system. The node can be any phase of a three-phase bus. It can also be a neutral connection point such as the star point of a Y-connected transformer. Complicated transformer connections are included in this matrix through the node-renaming mechanism [4]. The right hand side is the harmonic current sources representing the harmonic producing devices.

Floating sub-networks such as delta connected subsystems and ungrounded motors could be encountered in multiphase analysis. Because there is no reference voltage for such networks, part of the $[Y_h]$ matrix is singular. These structures can be accommodated by adding appropriate impedances to ground or by modifying factorization algorithms.

Once this matrix is established, the various network harmonic solution methods developed for the one-phase based representations can be extended to the multiphase frame. As described in previous chapters, four types of harmonic analysis are normally performed:

1. Frequency Scan Analysis: In these studies, the network frequency response seen at any phase of a bus can be determined. The positive, negative and zero sequence frequency responses seen at a bus can also be determined. In this case, three-phase harmonic currents, in positive, negative or zero sequences respectively, are injected into the study bus. Multiphase frequency scans are useful, for example, to determine harmonic resonance caused by single-phase capacitor banks. In general, frequency scans are difficult to use in the multiphase case because of the large number of nodes that must be considered.
2. Harmonic Analysis Using Simple Current Source Models: In these studies, the harmonic-producing devices are modeled as simple individual-phase current sources. The current source magnitudes and angles are determined, for example, from measured harmonic spectra. It must be emphasized that the phase angles of a three-phase harmonic current sources are seldom 120^o apart among three phases. Even with a slight unbalance at the fundamental frequency, the phase angle unbalance at harmonic frequencies can be significant. Therefore, the harmonic spectra should be determined for each phase.
3. Harmonic Analysis Considering Fundamental Frequency Power Flow Results: The main problem of current source based analysis is the lack of fundamental frequency load flow information. As a result, the magnitudes and phase angles of the current sources cannot be determined adequately. In this improved analysis, a multiphase power flow is first solved. The harmonic currents injected are determined using the power flow voltages and "typical" source spectra.
4. Harmonic Power Flow Solutions: In this analysis, the harmonic sources are also represented as current sources. However, their magnitudes and phases are updated using an iterative scheme based on detailed (voltage-dependent) harmonic source models. Inter-phase coupling of the harmonic-sources can be modeled with good accuracy. The harmonic iteration scheme solves the network one frequency at a time. The calculated nodal voltages are then used to update the current source model [4]. In theory, simultaneous solutions of all harmonic orders like those used in the HARMFLO program [6] can also be developed for the multiphase analysis, but the algorithm would be extremely complex.

Due to the availability and widespread use in other analyses, time-domain simulation tools such as the Alternative Transients Program(ATP) are also used for studying harmonic propagation in unbalanced systems. The key problem in such usage is to identify when steady state conditions have been achieved.

9.5 Case Study I

This study illustrates how uncharacteristic harmonics can arise and require a multiphase analysis in an apparently balanced system. A ±150 MVar static var compensator is to be installed at a substation of B.C. Hydro. The SVC is connected to a 138 kV bus and consists of one thyristor-switched capacitor (TSC) and three thyristor-switched reactors (TSR). It is commonly believed that the TSR-type SVC is harmonic free. A TSR is essentially a reactor in series with an anti-parallel thyristor pair. These thyristors are randomly selected. Each thyristor has a deviation of voltage drop about ±0.07 V when it is conducting. As a result, one stack of series-connected thyristors will have a slightly different total forward voltage drop than the anti-parallel one. This voltage difference is effectively a direct voltage across the TSR branch. Since the resistance of the TSR branches and the SVC transformer windings is generally very small, a small direct voltage can result in a relatively large direct current. This current will circulate through the secondary winding of the SVC transformer and can cause a DC-offset saturation of the transformer (Figure 9.4). As typical power transformers need little magnetizing current, a small amount of direct current is sufficient to cause significant saturation and harmonic generation.

Statistical analysis showed that the direct current injected into the SVC transformer has a normal distribution. At the confidence level of 95%, the expected direct current can be as high as 19.2 ampere. This is a very large DC current for regular power transformers. It is therefore considered necessary to analyze the resultant harmonics. The objective is to find the highest direct current level that can be tolerated from a harmonic distortion point of view [7].

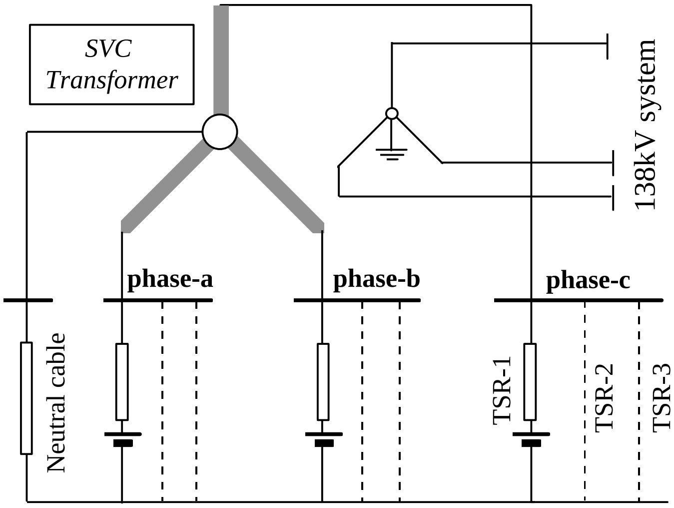

Figure 9.4. SVC system and the flow of TSR direct currents

9.5.1 Modeling of Harmonic Sources

The direct current into the SVC transformer is unbalanced. The worst case is that one phase serves as the return path for other two phases (Figure 9.4). This leads to the generation of unbalanced harmonics which contain positive, negative and zero sequence components. Moreover, because the transformer is saturated with a direct current offset, both even and odd harmonics are generated. The grounded primary allows the penetration of zero sequence harmonics into the supply system. They could interfere with telephone circuits.

In this investigation, the TSR branches are represented as impedances in series with DC voltage sources. The magnitudes and polarities of the DC sources were determined from the statistical analysis. A harmonic equivalent circuit is used to model the saturated transformer magnetizing branch. The harmonic iteration scheme is used to determine the harmonic currents generated [8]. Iterations are needed because the strong dependency of generated harmonic currents on supply voltage harmonics. Sample waveforms are shown in Figure 9.5.

9.5.2 Modeling of Supply System

The nature of the problem requires multiphase modeling of the supply system. A network model of the system near the SVC bus was developed (about 300 nodes). It facilitates the simulation of various network operating conditions. In the second approach, the supply system is modeled as a 60 Hz sinusoidal voltage source at the 138kV SVC bus. It effectively assumes that the supply system harmonic impedance is zero.

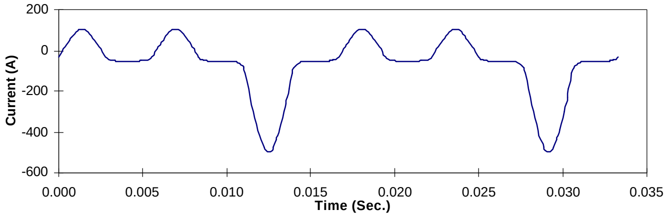

Figure 9.5. Harmonics from DC offset saturation of transformers

9.5.3 Sample Results

A number of possible SVC operation modes was analyzed. Table 9.1 provides harmonic current distortions (worst phase) under the condition that the SVC is operating in the fully inductive mode and with a 1.15pu 138 kV bus voltage. This mode has the largest DC current generation and the TSCs are not sinking harmonic currents from the transformer. Current distortions are listed in both ampere values and percentage values with respect to the nominal SVC current of 560 A. The spectra of the currents injected into the 138 kV system are shown in Figure 9.6. This figure indicates that only the lower order harmonics are of concern.

Table 9.1. Harmonic current distortion at the SVC bus.

Max. DC (A)	I2 (A)	I3 (A)	ITHD (A)	I2 (%)	I3 (%)	ITHD (%)
14	1.78	1.49	2.76	0.32	0.27	0.49
18	2.36	1.96	3.65	0.42	0.35	0.65
20	2.66	2.21	4.14	0.48	0.39	0.74
25	3.43	2.86	5.38	0.61	0.51	0.96
30	4.17	3.45	6.46	0.74	0.62	1.15
40	5.66	4.63	8.57	1.01	0.83	1.53
50	7.14	5.76	10.7	1.28	1.03	1.92

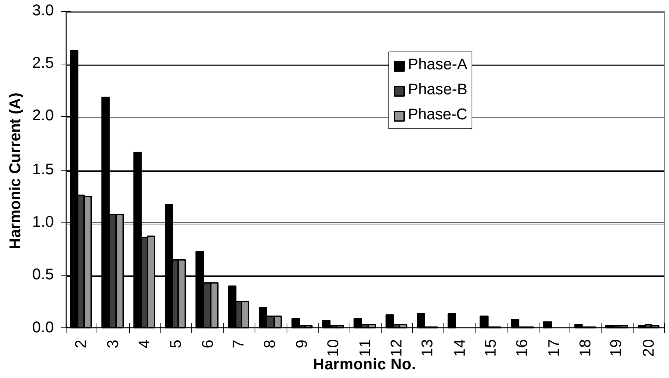

Figure 9.7. Harmonic currents injected into the supply system

9.6 Case Study II

Harmonics mitigation in a utilization system is investigated in this case. The system, shown in Figure 9.7, represents a simplified commercial building distribution system operated at a 120V level. The single phase loads contain harmonic sources such as switched mode power supplied devices (PC, printer etc.) and fluorescent lights. In order to reduce the neutral current and associated neutral voltage rise, a zero sequence current trapper would be connected to the receptacle panel. The current trapper, like a transformer, is made up of six coupled, equal turn ratio windings. The windings can be configured into either a zigzag form (Figure 9.8) or a delta-Y form. In the delta-Y configuration, the star point of the Y windings is connected to the neutral conductor. Both configurations are capable of trapping zero sequence fundamental frequency and harmonic currents. The objective of this study is to determine which configuration is more effective and what are the winding loading conditions.

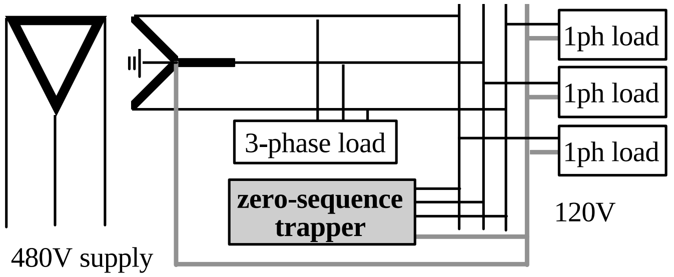

Figure 9.7. Simplified utilization system for case II

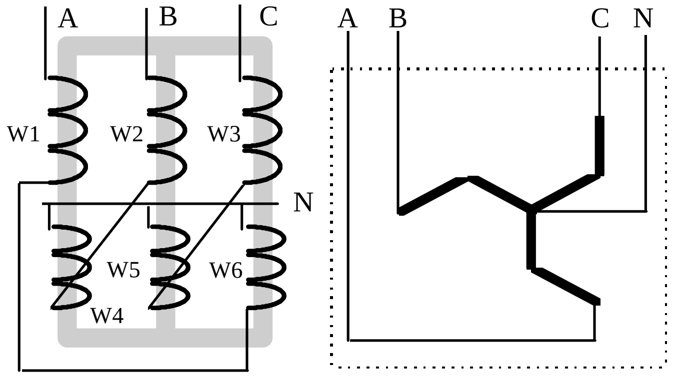

Figure 9.8. A six winding trapper and zigzag configuration

A multiphase harmonic analysis is used for this case. The loads are modeled as constant power loads at the fundamental frequencies and current sources at harmonic frequencies. Phase angles and magnitudes of the current sources are determined using the load flow results and harmonic source spectra. The single-phase loads are assumed to contain two types of harmonic producing loads, switched mode power supply type loads, dominated by PCs, and composite type loads dominated by fluorescent lights. The three-phase loads consist of motors and adjustable speed drives. The supply system is modeled as balanced voltage sources behind a system fault impedance. Models for the harmonic trapper which has a core-type design should be developed with care. One of the main concerns is that the model should be able to correctly simulate the circulation of the zero sequence flux. The core-type design forces a large amount of zero sequence flux to circulate outside the magnetic core. To simulate these effects, a six-phase coupled [Z] matrix is used with each phase representing one winding. Data of the [Z] matrix are calculated from the short and open circuit impedances determined with both positive and zero sequence excitations. The actual trapper configurations are represented using node renaming in the input data.

Figure 9.9 shows the waveforms of the neutral voltage at the receptacle panel. The waveform obtained without harmonic trapper is also displayed in the figure for comparison purposes. It can be seen from the figure that the neutral voltage can be quite high (about 20V RMS) if no mitigation measures are taken. The harmonic trappers can reduce the voltage to as little as 3V RMS. The neutral voltage is dominated by the 3rd harmonic component. The results also shown that Δ-Y and zigzag configurations have almost the same effect in terms of reducing the neutral voltage (the waveforms are indistinguishable in Figure 9.9).

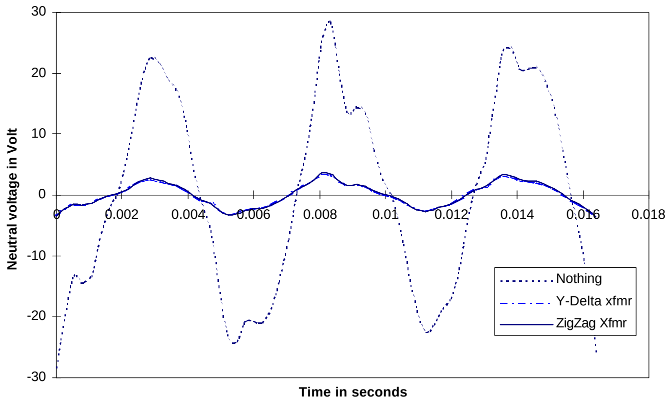

Figure 9.9. Neutral voltage at the receptacle panel

Table 9.2. Harmonic trapper winding currents and conductor neutral currents (A)

		W-1	W-2	W-3	W-4	W-5	W-6
Y-D	I_1	80.5	93.0	75.8	9.8	9.8	9.8
	$I_{h\text{-}rms}$	53.8	53.8	53.6	50.0	50.0	50.0
	I_{rms}	96.9	107.4	92.8	50.9	50.9	50.9
Zigzag	I_1	26.8	37.9	21.6	37.9	21.6	26.7
	$I_{h\text{-}rms}$	53.6	53.6	53.6	53.6	53.6	53.6
	I_{rms}	59.9	65.6	57.8	65.6	57.8	59.9
Neutral current (RMS)		No harmonic source				**38.2**	
		With h-source but no trapper				**187.0**	
		with Y-Δ trapper				**22.8**	
		with Zigzag trapper				**23.5**	

Table 9.2 lists the loading conditions, in the form of winding currents, associated with both configurations. It can be seen from the table that the zigzag configuration results in smaller RMS winding currents. The Y-Δ configuration is therefore less desirable in terms of losses and device overheating. The neutral conductor currents in RMS values were also calculated for various configurations and are shown in the same table. The entry of "No harmonic source" is the current obtained with the assumption that loads do not contain harmonic sources. The results suggest that the increase of neutral current is mainly due to the harmonic currents from the loads. Due to space limitations, other important issues such as transformer de-rating and harmonic injections into the supply system are not discussed. They can be easily investigated using the same system model and analysis tool.

9.7 Case Study III

This hypothetical study illustrates harmonic propagation in a utility distribution system. The system, shown in Figure 9.10, is discussed in detail in the chapter of case studies. Voltage unbalance in this system ranges from 2-4 %. Harmonic sources are single-phase sources typical of residential and small commercial load areas.

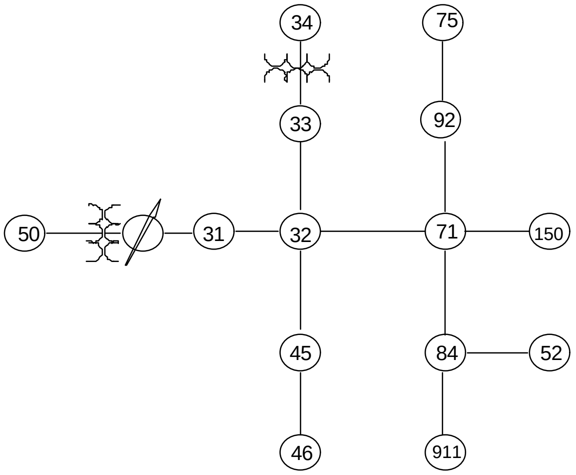

Figure 9.10. A unbalanced utility distribution system

A case of adding a three-phase 110 HP adjustable speed drive is studied. The front end of this drive was modeled in ATP as a Δ-Y transformer feeding a rectifier bridge with a capacitive filter and a resistive load. The ATP time simulation is used to determine steady-state harmonic current injections of the drive. Figure 9.11 shows the spectra of the current drawn by the drive and the spectrum under ideal balanced conditions.

Although the changes in characteristic harmonic magnitudes are small, one can notice that a significant third harmonic appears in the unbalanced case. As discussed in Chapter 1, harmonics are not associated with a specific sequence in unbalanced systems. Thus, for example, third harmonic currents will flow in ungrounded capacitors and filters. Thus detailed multiphase modeling is warranted for utility distribution systems

9.8 Summary

In this paper, important aspects of unbalanced harmonic analysis for multiphase power systems are reviewed. The need for multiphase analysis is mainly due to three considerations: the unbalanced system, the unbalanced sources and the propagation nature of harmonics. Although considerable progress has been made in the area of multiphase harmonic analysis, there are still problems to be solved and improvements to be made. For example, some of the future work in this areas includes:

1) Quantification of the effects of various load models on the propagation of harmonics in a power system with subsequent refinement of multiphase harmonic load models.
2) Development of analysis methods that can assess the collective effects of a large number of randomly operating harmonic sources in a utilization system.

3) Improvement of models and associated solution algorithms for harmonic-producing devices. The models should be practical but provide more accurate results.

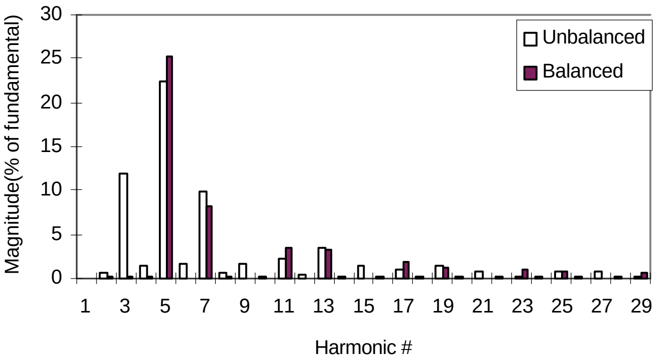

Figure 9.11. ASD current spectra (fundamental omitted)

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