Power Electronics and Power Systems

Elias Kyriakides
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Electric Power Engineering Research and Education

A Festschrift for Gerald T. Heydt

Springer

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Foreword

This Festschrift documents a portion of the contributions of Gerald Thomas Heydt to the electrical engineering profession and, specifically, the field of electric power engineering. These contributions are as unique as the man himself, who is known for professionalism, innovation, responsiveness, and so many more attributes that continue to emerge as time goes on. On this occasion of Jerry's 70th birth year, the authors of this Festschrift have provided clear highlights of his work in harmonics and power quality, advanced control of energy and power systems, new T&D technologies, and most importantly his education of students. His pioneering work on stochastic methods is surfacing now in the context of uncertainty due to renewable resources, hybrid vehicles, and demand participation.

This strong collection of ideas and accomplishments lacks depth in one significant topic—service. Jerry Heydt performs professional service with great vigor and dedication. He knows that paper reviews, proposal reviews, committee participation, letter writing, and leadership are critical to the growth and prosperity of a profession. In addition, he has made it clear to the young people in our profession that service is a key factor in all of the other aspects of our work including education and research. His service to his students, fellow faculty, and our profession is nothing short of spectacular in every dimension.

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Preface

It is a great honor and pleasure to present this Festschrift honoring Regents' Professor Gerald Thomas Heydt on the occasion of his 70th birthday. Jerry Heydt is a colleague, teacher, mentor, and above all a friend. He has made pioneering contributions in the area of electric power systems. His main technical achievements and accolades span three key areas: electric power quality, electric power transmission, and electric distribution networks. Over the last four decades, he has made lasting contributions in power engineering research and education that have profoundly impacted the field.

Gerald Thomas Heydt was born in 1943 in New York City. He graduated from the Bronx High School of Science in 1960. Prof. Heydt obtained his Bachelor of Engineering in Electrical Engineering from the Cooper Union in New York—a highly selective institution of higher education that offered full tuition scholarship to its students—in 1965. He then earned his Master of Science in Electrical Engineering and the Doctor of Philosophy from Purdue University in West Lafayette, Indiana, in 1967 and 1970, respectively. After his Ph.D, he joined the faculty of Purdue University, where he became Professor in 1980. During this period, he also worked briefly for the Commonwealth Edison in Chicago, Illinois. In 1990, he served as the Program Manager of the Power System program at the National Science Foundation in Washington DC. In 1994, he moved to Arizona State University (ASU) in Tempe, Arizona, where he also became the Site Director of the NSF Center for the Power Systems Engineering Research Center (PSERC). In 2002, Prof. Heydt was named Regents' Professor at ASU, the highest professorial rank in the University, recognizing both his technical and educational contributions to the University and the society. In 2009, he also became the Site Director of a National Science Foundation engineering research center called the Future Renewable Electric Energy Distribution and Management Center.

Professor Heydt's pioneering work in the area of power quality revolutionized the thinking of the power industry and led utilities and organizations to focus on the quality of the electric power supplied to the customer and to seek ways to alleviate the numerous problems in this area. His book on power quality was the only resource on this topic for a long time and is now the most cited resource in power quality. Today, power quality is a "hot" topic and a tremendous research effort around the globe is directed in this area. Gerald Heydt is credited with pioneering the initial research efforts in power quality research.

Numerous organizations have recognized Professor Heydt for his academic and research work. In 1997, Heydt was elected to the US National Academy of Engineering (NAE) for "contributions to the technology of electric power quality." Election to NAE is considered the highest distinction conferred to an engineer. In 1991, he was elected a Fellow of the Institute of Electrical and Electronics Engineers (IEEE) "For leadership in electric power engineering education and research on harmonic signals in electric power systems."

Professor Heydt is a passionate educator. He played a key role in resurrecting the activities of the IEEE Power and Energy Society (PES) Power Engineering Education Committee (now renamed the Power and Energy Education Committee). He is also an outstanding mentor and advisor. His teaching philosophy and contributions to power engineering education led the IEEE Power and Energy Society to recognize him with the IEEE PES Outstanding Power Engineering Educator award in 1995. Ethics and honesty in research and in his life are some of his distinguishing characteristics. These values are instilled in his students, colleagues, and collaborators.

This book is the result of a very successful event organized on Sunday, October 13, 2013 at Arizona State University: the Gerald T. Heydt Festschrift Symposium. The symposium included presentations from leading researchers whom Professor Heydt has mentored and collaborated with over the past four decades in power quality and electrical power systems. During this symposium, organized in conjunction with his 70th birthday, Professor Heydt was honored for his four decades of industry-changing innovation, scholarship, mentoring, and teaching in electric power engineering.

The book aims at presenting key advances in the three research areas where Prof. Heydt has had outstanding contributions. Some of the chapters describe work that Prof. Heydt was directly involved with, while other chapters are motivated by his research. Peter W. Sauer, the W. W. Grainger Professor of Electrical Engineering at the University of Illinois at Urbana-Champaign and fellow member of the NAE, introduces the book in the foreword. Prof. Sauer is a longtime collaborator and one of the first Ph.D. graduates of Professor Heydt.

The book comprises nine chapters. Chapters 1 and 2 focus on Power Quality. Chapter 1 introduces power system harmonics and discusses the injection of harmonic currents from nonlinear loads into distribution systems. Methods for harmonic analysis and algorithms for harmonic power flow study are also discussed. Chapter 2 describes a classification tool, based on a meta-heuristic algorithm, that is used for the classification of power quality disturbances.

Chapters 3–6 describe work in Transmission Engineering. Chapter 3 provides the experiences from five different projects that were collaboratively completed by Salt River Project and the team of Prof. Heydt at ASU. The projects investigated the application of synchrophasor technology in several aspects of wide area monitoring of power systems and in the parameter identification of synchronous machines. Chapter 4 introduces the reliability and availability analysis of wind and solar generation. Chapter 5 demonstrates the use of the geographical information system coordinates to aid in the calculation of unscheduled flows in wide-area power grids. The impact of wind variability on unscheduled flows is also investigated. Chapter 6 investigates the transmission expansion planning in modern power systems. The process for this complex decision-making process is outlined and mathematical models are described.

Chapter 7 provides an overview of the progress of automation in distribution systems and discusses several contemporary issues that are relevant for the modern distribution systems. This chapter also presents a detailed discussion of distribution automation functions, together with a cost-to-benefit analysis.

Chapters 8 and 9 focus on research, education, service, and workforce development in power engineering. Chapter 8 gives a personal account of the impact of Prof. Heydt to research, education, and service, as well as of his impact to the lives and careers of his colleagues. Chapter 9 provides the results of a regional labor market and workforce study that concentrated on electric power employers. The study aimed at looking into issues such as the aging utility workforce, retirements, and challenging population trends and made relevant conclusions and recommendations for the labor and skill gaps in the electric power industry.

It was our honor and privilege to organize the Gerald T. Heydt Festschrift Symposium in 2013. We hope the readers of this festschrift will find the chapters useful for their research and education.

Sincerely,
Elias Kyriakides, Siddharth Suryanarayanan, and Vijay Vittal

Memories from the Symposium

Prof. Heydt with attendees of the symposium

The night before the symposium at Frank Kush Field for a Sun Devil's game

Prof. Heydt with some of the symposium attendees

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Chapter 1
Power System Harmonics

Surya Santoso and Anamika Dubey

1.1 Introduction

Electric power quality defines and quantifies the characteristics and quality of electric service. The specific definition of power quality can vary among different utilities and customers, therefore, there is no universal agreement over the definition of power quality and its scope. In general, electric power quality is measured and quantified as a function of deviation in the rated magnitude or electrical frequency of the load voltage or supply current waveforms. Therefore, an electric supply is said to be of poor power quality if the load voltage or supply current deviates from its rated magnitude and waveshape, or if the frequency composition of the sinusoidal voltage or current waveform changes. This broad definition also includes power system outages, which is generally a reliability concern in transmission and distribution operations. However, a momentary outage caused by the operation of overcurrent protection devices in clearing temporary faults is considered as a power quality issue.

Since a major part of power system engineering is concerned with the improvement of the quality of power supply, the term power quality can encompass topics ranging from traditional transmission and distribution engineering (e.g., substation design, grounding, etc.) to power system protection and power system planning. However, generally power quality phenomenon refers to the measurement, analysis, and improvement of voltage and current waveforms, so as to maintain the power supply (voltage and current) as a sinusoidal waveform at rated magnitude and frequency. This definition includes all momentary

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phenomenon leading to problems in regulation and frequency of the power supply. For the scope of this chapter, we will restrict our discussion to the problems primarily relating to bus voltage and current waveshape and frequency characteristics. Several nonlinear loads such as rectifiers, adjustable-speed drives (ASD), and fluorescent lamps inject nonlinear current into the distribution circuit and may distort the sinusoidal load voltage and supply current waveforms. The distortions in the waveshape of the electric supply are measured in terms of harmonics. The harmonic components, which are integral multiples of the fundamental frequency, injected by nonlinear loads, modify the frequency characteristics of the power supply.

The objective of this chapter is to introduce the topic of power system harmonics and to discuss approaches used to analyze the distribution circuit in the presence of nonlinear loads. The chapter begins with an introduction on power system harmonics, harmonic sources, and their effects on the distribution system. Next, power system quantities are defined under non-sinusoidal operating conditions and commonly used power system indices used to measure harmonic distortions are defined. The characteristics of nonlinear loads injecting harmonic currents into the distribution system are discussed next. Because network components are generally modeled at the fundamental power frequency, their operational characteristics and circuit models are developed under non-sinusoidal conditions. Next, methods for harmonic analysis and algorithms for harmonic power flow study are discussed. Finally, harmonic filters used to mitigate harmonic concerns in the distribution grid are discussed. Note that the material for this chapter is primarily taken from the book Electric Power Quality written by Dr. Heydt [1]. He has done seminal work in the area of power quality, particularly in power system harmonics and harmonic power flow study [1–8]. His algorithms for harmonic power flow study were some of the first in this field. This chapter is a humble tribute to his valuable contribution in the area of power quality and power system harmonics.

1.2 Harmonics in Power Systems

This section introduces the problem of harmonics in power systems and their effects on distribution system power quality. Several power system quantities that measure and quantify power system harmonics are also discussed. Power system harmonics are typically introduced into the distribution system in the form of currents whose frequencies are the integral multiples of the fundamental power system frequency. These currents are produced by nonlinear loads, such as arc furnaces, rectifiers, fluorescent lamps, and electronic devices, which may distort the voltage and current waveforms. A high level of power system harmonics may lead to serious power quality problems.

In general, the power quality problems associated with harmonic distortions are caused by current distortions produced by nonlinear loads and thus originate at the customer load locations. The distorted current, which is also referred to as harmonic current, then interacts with the utility supply system impedance causing distortions in the load voltage and current, thus adversely affecting other users connected to the distribution system. Therefore, the nonlinear loads present in the distribution system result in a non-sinusoidal and periodic load current, which on interaction with the system impedance results in a non-sinusoidal periodic load voltage. Both non-sinusoidal voltage and current can be expressed as a weighted sum of sinusoids, whose frequencies are integral multiples of the fundamental frequency. This expression is called Fourier series expansion and the higher order frequency terms in the Fourier series are termed harmonics. Note that these harmonics are integral multiples of the fundamental frequency.

Let, $i(t)$, be the distorted current waveform of time period T. The current waveform is expressed as a Fourier series, given by (1.1).

$$i(t) = a_0 + \sum_{n=1}^{\infty}[a_n \cos(n\omega_1 t) + b_n \sin(n\omega_1 t)], \tag{1.1}$$

where $\omega_1 = \frac{2\pi}{T}$, and n is the harmonic order.

$$\begin{aligned} a_0 &= \frac{1}{T}\int_0^T i(t)dt \\ a_n &= \frac{2}{T}\int_0^T i(t)\cos(n\omega_1 t)dt \\ b_n &= \frac{2}{T}\int_0^T i(t)\sin(n\omega_1 t)dt. \end{aligned} \tag{1.2}$$

In general, even order harmonics do not exist in a three-phase power system. The even order harmonics only originate when a current waveform is asymmetrical along the time axis. Since loads in the power system mostly inject symmetrical current, except for few nonlinear single-phase loads, such as rectifiers and fluorescent lamps, even order harmonic components are significantly smaller than the odd order harmonic components. Therefore, for power system harmonic analysis, the distorted current waveform can be expressed as a weighted sum of only odd order harmonics (1.3).

$$i(t) = I_1 \sin(\omega_1 t) + \sum_{n=3,5,7,\ldots}^{\infty} I_n \sin(n\omega_1 t). \tag{1.3}$$

Next, we will discuss power system quantities used for harmonic analysis. The power system quantities, such as root-mean-square (rms) value, apparent power, and power factor, are originally defined at the fundamental frequency. In the presence of the nonlinear loads, with non-sinusoidal load voltages and currents, the power system quantities need to be redefined. In the following section, important power system quantities are redefined under non-sinusoidal conditions [9].

1.2.1 Root-Mean-Square

For a sinusoidal current waveform, $i(t) = I_1 \sin(\omega_1 t + \theta_1)$, the rms value is given in (1.4), where I_{rms} is the rms value of the current waveform.

$$I_{\text{rms}} = \frac{1}{\sqrt{2}} I_1. \tag{1.4}$$

Under non-sinusoidal conditions, the current waveform can be expressed using the Fourier series expansion, given by (1.5).

$$i(t) = I_1 \sin(\omega_1 t + \theta_1) + \sum_{n=3,5,7,\ldots}^{\infty} I_n \sin(n\omega_1 t + \theta_n). \tag{1.5}$$

The rms value of the current waveform in (1.5) is given by (1.6).

$$\begin{aligned} I_{\text{rms}} &= \sqrt{\frac{1}{2} \sum_{n=1,3,5,\ldots}^{\infty} I_n^2} \\ &= \sqrt{\left[\frac{I_1}{\sqrt{2}}\right]^2 + \left[\frac{I_3}{\sqrt{2}}\right]^2 + \left[\frac{I_5}{\sqrt{2}}\right]^2 + \cdots} \\ &= \sqrt{\frac{I_1^2}{2} + \frac{1}{2} \sum_{n=3,5,7,\ldots}^{\infty} I_n^2} \\ &= \sqrt{I_{\text{rms}_1}^2 + I_{\text{rms}_H}^2}. \end{aligned} \tag{1.6}$$

Similarly, rms voltage under non-sinusoidal conditions is given by (1.7).

$$\begin{aligned} V_{\text{rms}} &= \sqrt{\frac{V_1^2}{2} + \frac{1}{2} \sum_{n=3,5,7,\ldots}^{\infty} V_n^2} \\ &= \sqrt{V_{\text{rms}_1}^2 + V_{\text{rms}_H}^2} \end{aligned} \tag{1.7}$$

1.2.2 Power in Non-sinusoidal Conditions

Next, a brief review of the active and reactive power in the presence of harmonics is presented. Consider a voltage $v(t)$ and current $i(t)$ expressed in terms of their harmonic components:

$$\begin{aligned} v(t) &= V_1 \sin(\omega_1 t + \phi_1) + \sum_{n=3,5,7,\ldots}^{\infty} V_n \sin(n\omega_1 t + \phi_n) \\ i(t) &= I_1 \sin(\omega_1 t + \theta_1) + \sum_{n=3,5,7,\ldots}^{\infty} I_n \sin(n\omega_1 t + \theta_n). \end{aligned} \tag{1.8}$$

Apparent Power (S) is defined as

$$S = V_{\mathrm{rms}} I_{\mathrm{rms}}. \tag{1.9}$$

Using the expression for rms current and voltage as defined in (1.6) and (1.7), S is given by (1.10).

$$\begin{aligned} S^2 &= V_{\mathrm{rms}}^2 I_{\mathrm{rms}}^2 \\ &= \left[V_{\mathrm{rms}_1}^2 + V_{\mathrm{rms}_H}^2\right]\left[I_{\mathrm{rms}_1}^2 + I_{\mathrm{rms}_H}^2\right]. \end{aligned} \tag{1.10}$$

On expanding the expression for the apparent power (1.10), we obtain

$$\begin{aligned} S^2 &= V_{\mathrm{rms}}^2 I_{\mathrm{rms}}^2 \\ &= V_{\mathrm{rms}_1}^2 I_{\mathrm{rms}_1}^2 + V_{\mathrm{rms}_1}^2 I_{\mathrm{rms}_H}^2 + V_{\mathrm{rms}_H}^2 I_{\mathrm{rms}_1}^2 + V_{\mathrm{rms}_H}^2 I_{\mathrm{rms}_H}^2. \end{aligned} \tag{1.11}$$

Next, using the expression derived in (1.11), several power expressions are defined under non-sinusoidal operating condition.

Fundamental Apparent Power (S_1) is defined as

$$S_1 = V_{\mathrm{rms}_1} I_{\mathrm{rms}_1}. \tag{1.12}$$

And fundamental active power (P_1) and reactive power (Q_1) are given by

$$\begin{aligned} P_1 &= S_1 \cos(\phi_1 - \theta_1) \\ Q_1 &= S_1 \sin(\phi_1 - \theta_1). \end{aligned} \tag{1.13}$$

Non-fundamental Apparent Power (S_{N}) is observed in the system due to the interaction of current and voltage distortions. The expression of non-fundamental apparent power (S_{N}) is given as follows

$$\begin{aligned} S_N^2 &= V_{\text{rms}_1}^2 I_{\text{rms}_H}^2 + V_{\text{rms}_H}^2 I_{\text{rms}_1}^2 + V_{\text{rms}_H}^2 I_{\text{rms}_H}^2 \\ &= S_{CDP}^2 + S_{VDP}^2 + S_H^2, \end{aligned} \tag{1.14}$$

where

$$\begin{aligned} S_{CDP} &= \text{Current distortion power} \\ S_{VDP} &= \text{Voltage distortion power} \\ S_H &= \text{Harmonic apparent power.} \end{aligned} \tag{1.15}$$

Current Distortion Power (S_{CDP}) is observed due to the interaction of the harmonic component of current with the fundamental voltage component. As shown in (1.16), S_{CDP} is expressed as the product of rms value of harmonic current and fundamental voltage component.

$$\begin{aligned} S_{CDP} &= V_{\text{rms}_1} I_{\text{rms}_H} \\ &= V_{\text{rms}_1} \times \sqrt{\sum_{n=3,5,7,\ldots}^{\infty} I_{\text{rms}_n}^2}. \end{aligned} \tag{1.16}$$

Similarly, **Voltage Distortion Power** (S_{VDP}) is defined as the product of rms value of harmonic voltage and the rms value of fundamental current (1.17).

$$\begin{aligned} S_{VDP} &= V_{\text{rms}_H} I_{\text{rms}_1} \\ &= \left[\sqrt{\sum_{n=3,5,7,\ldots}^{\infty} V_{\text{rms}_n}^2}\right] \times I_{\text{rms}_1}. \end{aligned} \tag{1.17}$$

Harmonic Apparent Power (S_{H}) is defined as the product of harmonic components of non-sinusoidal voltage and current (1.18).

$$\begin{aligned} S_H &= V_{\text{rms}_H} I_{\text{rms}_H} \\ &= \left[\sqrt{\sum_{n=3,5,7,\ldots}^{\infty} V_{\text{rms}_n}^2}\right] \times \left[\sqrt{\sum_{n=3,5,7,\ldots}^{\infty} I_{\text{rms}_n}^2}\right]. \end{aligned} \tag{1.18}$$

Using the expression for S_{H}, total harmonic active power P_{H} and total harmonic nonactive power N_{H} are defined (1.19).

$$\begin{aligned} P_H &= \sum_{n=3,5,7,\ldots}^{\infty} P_n \\ &= \sum_{n=3,5,7,\ldots}^{\infty} V_{\text{rms}_n} I_{\text{rms}_n} \cos(\phi_n - \theta_n) \\ N_H &= \pm\sqrt{S_H^2 - P_H^2}. \end{aligned} \tag{1.19}$$

1.2.3 Power Factor

For the sinusoidal case, the power factor is given by

$$\mathrm{PF} = \frac{P_1}{S_1}, \tag{1.20}$$

where P_1 and S_1 are fundamental active and apparent power, respectively.

Under non-sinusoidal conditions, the power factor takes both fundamental and harmonic power into account. Therefore, the power factor with current and voltage harmonics in the system is defined as the ratio of the total active power at all power frequencies and the total apparent power (1.21).

$$\mathrm{PF} = \frac{P}{S} = \frac{P_1 + P_H}{S}, \tag{1.21}$$

where P_1 is the fundamental active power, P_H is the total harmonic active power, and S is the total apparent power.

1.2.4 Total Harmonic Distortion

Total harmonic distortion (THD) is one of the classical power quality indices used to measure distortions in current and voltage waveforms. For a periodic waveform of period $T = 2\pi/\omega$, the THD of the waveform is defined as the ratio of rms value of the harmonics components (V_{rms_H}) and the fundamental component (V_{rms_1}). The current and voltage THD are defined in (1.22).

$$\begin{aligned} \mathrm{THD}_V &= \frac{V_{\mathrm{rms}_H}}{V_{\mathrm{rms}_1}} = \frac{\sqrt{\sum_{n=2}^{\infty} V_{\mathrm{rms}_n}^2}}{V_{\mathrm{rms}_1}} \\ \mathrm{THD}_I &= \frac{I_{\mathrm{rms}_H}}{I_{\mathrm{rms}_1}} = \frac{\sqrt{\sum_{n=2}^{\infty} I_{\mathrm{rms}_n}^2}}{I_{\mathrm{rms}_1}} \end{aligned} \tag{1.22}$$

THD is generally expressed as a percentage. The THD of either the voltage or the current waveform can be calculated to analyze the harmonic distortion in the quantity under consideration. The THD can be readily calculated to quantify harmonic distortion, however, the information of the full frequency spectrum is lost.

1.2.5 Total Demand Distortion

The total demand distortion (TDD) index is a measure of current distortion. TDD is defined as the ratio of rms value of harmonic component of the current waveform and the maximum load current (I_L).

$$\mathrm{TDD} = \frac{I_{\mathrm{rms}_H}}{I_L} = \frac{\sqrt{\sum_{n=2}^{\infty} I_{\mathrm{rms}_n}^2}}{I_L}, \tag{1.23}$$

where the maximum load current is defined as

$$I_L = \frac{P_D}{\sqrt{3} \times \mathrm{PF} \times kV_{LL}}. \tag{1.24}$$

Here, P_{D} is the average peak load demand measured over a year, PF is the average billed power factor, and kV_{LL} is line-to-line voltage measured at the load.

1.2.6 Distortion Index

The distortion index (DIN) is a commonly used standard to quantify the voltage and current harmonic distortions, outside North America. It is defined as follows:

$$\mathrm{DIN} = \frac{V_{\mathrm{rms}_H}}{V_{\mathrm{rms}}} = \frac{\sqrt{\sum_{n=2}^{\infty} (V_{\mathrm{rms}_n})^2}}{\sqrt{\sum_{n=1}^{\infty} (V_{\mathrm{rms}_n})^2}}. \tag{1.25}$$

The relationship between DIN and THD is given as in (1.26).

$$\mathrm{DIN} = \frac{\mathrm{THD}_V}{\sqrt{1 + \mathrm{THD}_V^2}}. \tag{1.26}$$

1.3 Sources of Harmonics

The harmonic distortions occur at load buses connected to nonlinear loads. These buses are modeled as sources of harmonic signals, injecting harmonic currents into the distribution circuit. The nature of the harmonic signal depends upon the type of nonlinearity introduced by the load. Thus, a fluorescent lamp would not have the same voltage–current-frequency characteristics as a rectifier. This section presents

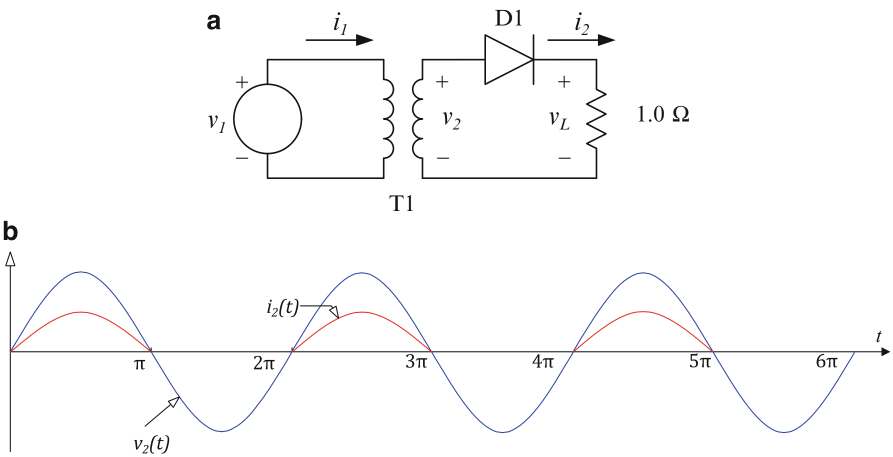

Fig. 1.1 (**a**) Simple ideal single-phase rectifier. (**b**) Corresponding voltage and current waveforms on the DC side

a review on the devices likely to induce harmonic distortions into the power system, and the characteristics of the harmonic currents produced by such devices.

1.3.1 Single- and Three-Phase AC/DC Power Converters

Power converters are devices capable of converting electrical energy from one frequency to another, typically from AC to DC or vice versa. Rectifiers and inverters convert AC to DC and DC to AC, respectively. Figure 1.1a shows a simple single-phase rectifier. Let transformer T1 and diode D1 be ideal elements. Diode D1 will conduct when

$$v_2(t) > 0. \tag{1.27}$$

The current and voltage waveforms $i_2(t)$ and $v_2(t)$ generated by the single-phase rectifier are shown in Fig. 1.1b. The Fourier series for the voltage and current waveforms produced by the single-phase rectifier shown in Fig. 1.1a are given by (1.28) and (1.29).

$$v_2(t) = \sin(t). \tag{1.28}$$

$$i_2(t) = \frac{1}{\pi} + \frac{1}{2}\sin(t) - \frac{2}{\pi}\sum_{n=1}^{\infty}\frac{1}{4n^2 - 1}\cos(2nt). \tag{1.29}$$

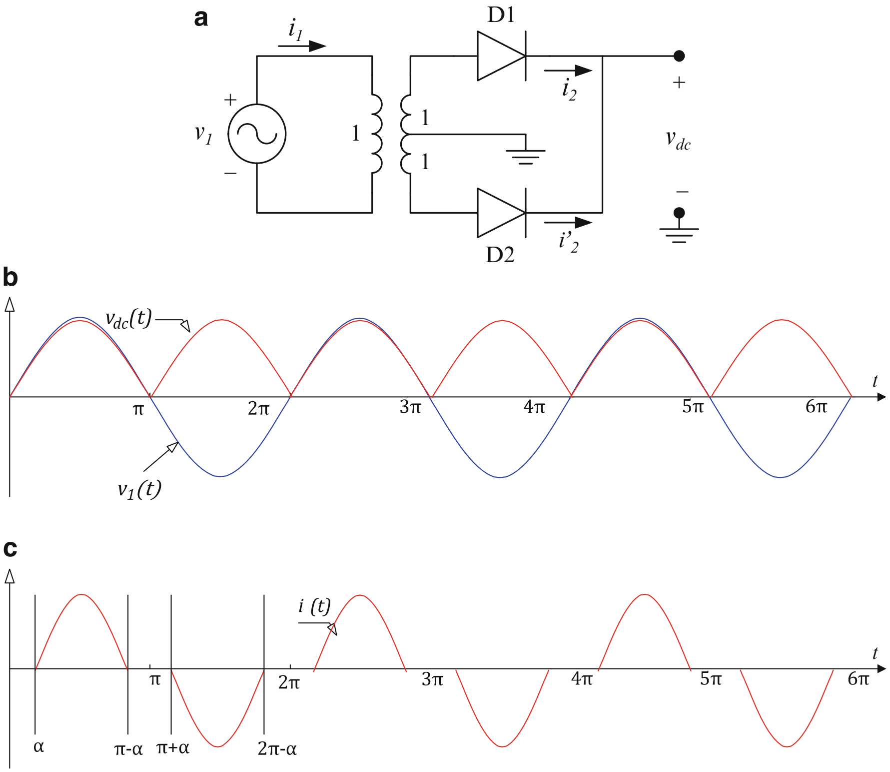

Fig. 1.2 (**a**) Half-wave single-phase rectifier. (**b**) DC circuit voltage for the half-wave single-phase rectifier. (**c**) Primary current for the half-wave rectifier

Next, Fig. 1.2a shows a more complex single-phase rectifier known as a half-wave rectifier. This circuit had been widely used in radio receivers and other communication equipment. This configuration is superior to the rectifier shown in Fig. 1.1a, as it does not produce any DC in the average magnetic flux produced by the secondary winding. Therefore, the transformer does not get biased by the DC value and the core saturation is avoided. Secondly, this configuration results in a smoother DC waveform as shown in Fig. 1.2b, thus facilitating easy filtering.

If the rectifier load is purely resistive, diode D1 will be on for $0 < t < \pi$, and diode D2 will be on for $\pi < t < 2\pi$. If no filtering is used, current i_1 will be sinusoidal. If filtering is used, the resulting current is shown in Fig. 1.2c. The value of α will depend upon the RC time constant of the filter. If C is too large, α will approach 2π; if C is too small, α will be closer to zero. Furthermore, current $i_1(t)$ can be expressed as the Fourier series given in (1.30).

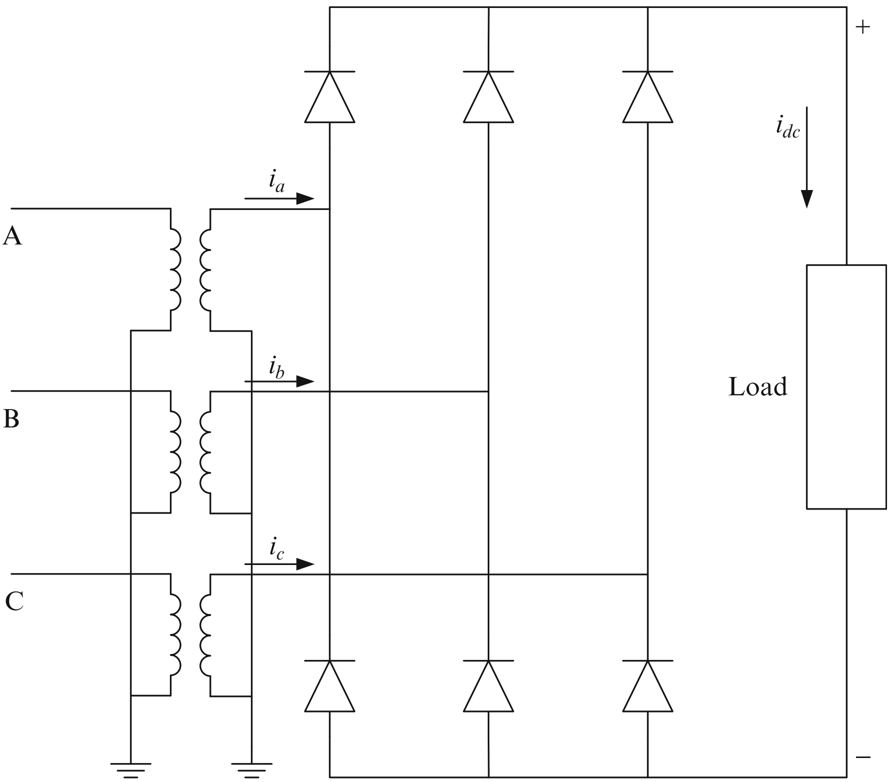

Fig. 1.3 Three-phase six-pulse power converter

$$i_1(t) = \frac{1}{\pi}[\pi - 2\alpha - \sin 2\alpha] \sin t - \frac{1}{6\pi}[2 \sin 2\alpha + \sin 4\alpha] \sin 3t + \cdots . \quad (1.30)$$

Three-phase power converters are superior to their single-phase counterpart, as they do not generate third harmonic currents. However, they still generate harmonic currents at their characteristic frequencies. Here, the characteristic frequencies are the integral multiples of the fundamental frequency, present in the Fourier series expansion of the converter's AC side current.

Figure 1.3 shows a three-phase six-pulse power converter, which is most commonly used in the 2–1,000 kVA range, with voltage rating ranging from 220 V to 13.8 kV. This power converter can be operated as a line-commutated unit or a forced-commutated unit, where diodes can be silicon-controlled rectifiers (SCR) or gate turn-off (GTO) thyristors. In forced-commutated units, control signals are used to turn on the switches (SCR or GTO), while the supply voltage determines the turn-off point. For a line-commutated unit, the phase A current, i_a, follows phase A voltage, v_{an}, when phase A voltage is the smallest of the three-phase voltages. The other phase currents are generated similarly. All three-phase currents and voltages for the three-phase six-pulse converter are shown in Fig. 1.4.

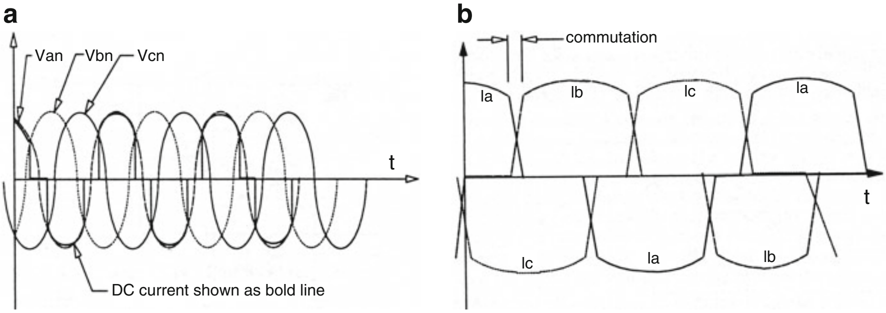

Fig. 1.4 (**a**) Voltages in three-phase six-pulse power converter. (**b**) Corresponding three-phase currents [1]

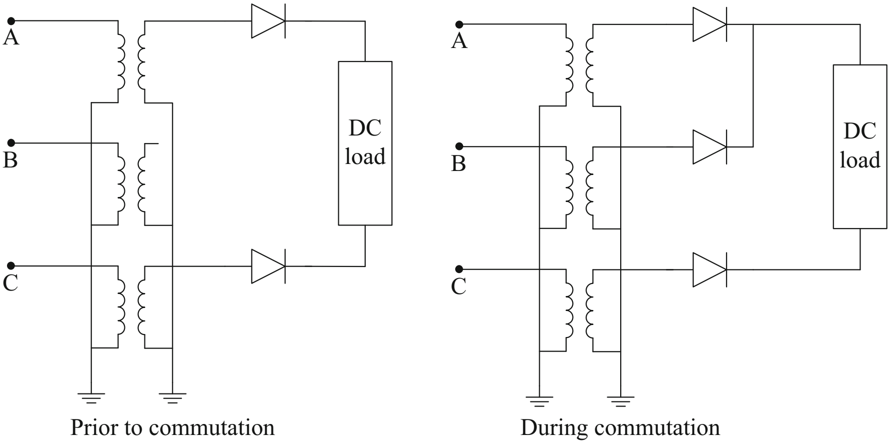

Fig. 1.5 Equivalent circuits of the three-phase six-pulse power converter, before and during commutation [1]

The operating principle for the three-phase six-pulse converter is as follows. For a time period of $0 < \theta < \frac{\pi}{3}$, the current i_a flows in the positive leg of the DC circuit. At $\theta = \frac{\pi}{3}$, the current path changes from phase A to phase B. This is referred to as commutation (see Fig. 1.5). Commutation is generally not instantaneous and is typically in the range of 0.05–1.4 ms. The practical effects of commutation relate to the harmonic impacts of the commutator. The details on commutation effects can be found in [1].

Next, the characteristics of the harmonics produced by the rectifier are discussed. The waveshapes of the phase currents are analyzed and Fourier series expansion is performed. The phase currents $(i_a(t), i_b(t), i_c(t))$, shown in Fig. 1.4, appear on both the primary and secondary sides of the transformers. This is because the DC components of the currents are absent. High inductance of the DC circuit causes I_{dc} to be fixed. The Fourier series of the phase A current is given by

$$i_a(t) = \frac{2\sqrt{3}}{\pi}\cos t + \frac{2\sqrt{3}}{\pi}\sum_{n=1}^{\infty}\left(\frac{(-1)^n}{6n-1}\cos(6n-1)t + \frac{(-1)^n}{6n+1}\cos(6n+1)t\right). \tag{1.31}$$

Clearly, the ideal six-pulse three-phase converter with $L_{dc} = \infty$ will induce harmonic currents on the AC side of the order of only, $6n \pm 1, n = 0, 1, \ldots$, termed characteristic harmonics.

1.3.2 Rotating AC Machines

Generally the pole faces of rotating electric machines are designed such that the low order harmonics in the supply will cancel. Depending upon the machine type, the harmonic cancelation can be done for up to the 11th-order harmonics. Furthermore, due to symmetry, AC machines produce no even order harmonics.

1.3.3 Fluorescent Lightning

Fluorescent lamps are very efficient sources of lighting because unlike incandescent lamps they do not dissipate much energy as heat. Therefore, the electrical energy supplied to the lamp is converted very efficiently to light. The fluorescent lamp works on the principle of gas ionization. Prior to when the gas in the fluorescent tube ionizes, the tube is an open circuit. After the gas ionization, the tube voltage drops dramatically. The exact V–I characteristics of the tube depends upon the length of the tube, the pressure, and type of gas. This is shown in Fig. 1.6. Figure 1.6 also shows that the current waveform $i(t)$ is rich in third-order harmonics.

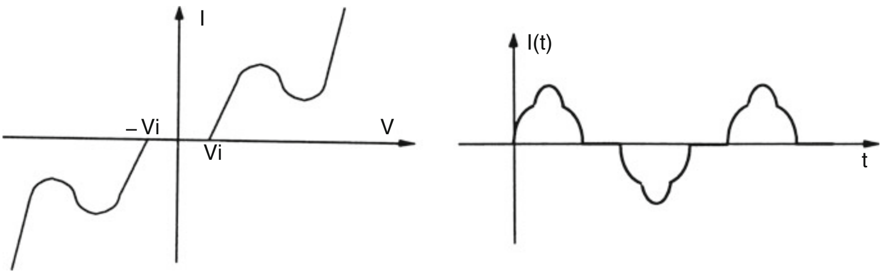

Fig. 1.6 V–I characteristics of a typical fluorescent lamp [1]