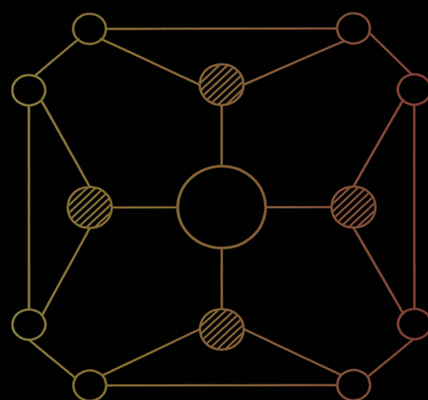
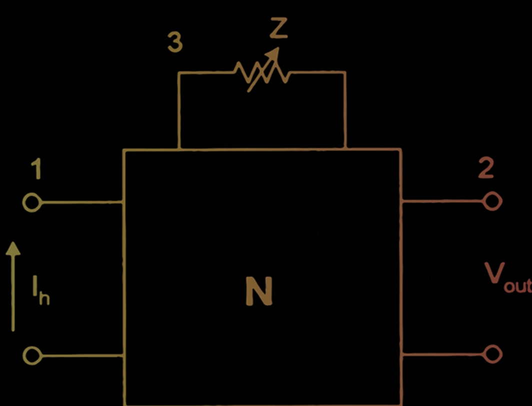
Power Systems Handbook - Volume 3

Harmonic Generation Effects Propagation and Control



J.C. Das



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Power Systems Handbook

Harmonic Generation Effects Propagation and Control

Volume 3

Power Systems Handbook

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Volume 1: Short-Circuits in AC and DC Systems:
ANSI, IEEE, and IEC Standards

Volume 2: Load Flow Optimization and Optimal Power Flow

Volume 3: Harmonic Generation Effects Propagation and Control

Volume 4: Power System Protective Relaying

Harmonic Generation Effects Propagation and Control

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Series Preface

This handbook on power systems consists of four volumes. These are carefully planned and designed to provide state-of-the-art material on the major aspects of electrical power systems, short-circuit currents, load flow, harmonics, and protective relaying.

An effort has been made to provide a comprehensive coverage, with practical applications, case studies, examples, problems, extensive references, and bibliography.

The material is organized with sound theoretical base and its practical applications. The objective of creating this series is to provide the reader with a comprehensive treatise that could serve as a reference and day-to-day application guide for solving the real-world problem. It is written for plasticizing engineers and academia at the level of upper-undergraduate and graduate degrees.

Though there are published texts on similar subjects, this series provides a unique approach to the practical problems that an application engineer or consultant may face in conducting system studies and applying it to varied system problems.

Some parts of the work are fairly advanced on a postgraduate level and get into higher mathematics. Yet the continuity of the thought process and basic conceptual base are maintained. A beginner and advanced reader will equally benefit from the material covered. An underground level of education is assumed, with a fundamental knowledge of electrical circuit theory, rotating machines, and matrices.

Currently, power systems, large or small, are analyzed on digital computers with appropriate software. However, it is necessary to understand the theory and basis of these calculations to debug and decipher the results.

A reader may be interested only in one aspect of power systems and may choose to purchase only one of the volumes. Many aspects of power systems are transparent between different types of studies and analyses—for example, knowledge of short-circuit currents and symmetrical component is required for protective relaying and fundamental frequency load flow is required for harmonic analysis. Though appropriate references are provided, the material is not repeated from one volume to another.

The series is a culmination of the vast experience of the author in solving real-world problems in the industrial and utility power systems for more than 40 years.

Another key point is that the solutions to the problems are provided in Appendix D. Readers should be able to independently solve these problems after perusing the contents of a chapter and then look back to the solutions provided as a secondary help. The problems are organized so these can be solved with manual manipulations, without the help of any digital computer power system software.

It is hoped the series will be a welcome addition to the current technical literature.

The author thanks CRC Press editor Nora Konopka for her help and cooperation throughout the publication effort.

—J.C. Das

Preface to Volume 3: Harmonic Generation Effects Propagation and Control

The power system harmonics is a subject of interest to many power system professionals engaged in harmonic analysis and mitigation. It is one of the major power quality concerns.

Volume 3 provides coverage of generation, effects, and control of harmonics, including interharmonics, measurements, estimation of harmonics, harmonic resonance, and harmonic limitations according to standards. The intention is that the book can serve as a practical guide to practicing engineers on harmonics.

A beginner should be able to form a clear base for understanding the subject of harmonics and an advanced reader's interest should be stimulated to explore further. In writing this book, an undergraduate level of knowledge is assumed. It has the potentiality of serving as advance undergraduate and graduate textbook. Surely, it can serve as continuing education textbook and supplementary reading material.

The effects of harmonics can be experienced at a distance, and the effect on power system components is a dynamic and evolving field. These interactions have been analyzed in terms of current thinking. The concepts of modeling filter designs and harmonic penetrations (propagations) in industrial systems, distribution, and transmission systems are amply covered with the application of SVCs and FACTS controllers. An introduction to the active filters, multilevel inverters, and active current shaping is provided.

A chapter is included on harmonic analysis in wind and solar generating plants. Many case studies and practical examples are included. The problems at the end of a chapter can be solved by hand without resort to any computer software packages. Appendix A contains Fourier analysis, pertinent to harmonic analysis, and Appendix B provides solutions to the problems.

—J.C. Das

Author

J.C. Das is an independent consultant, Power System Studies, Inc. Snellville, Georgia. Earlier, he headed the electrical power systems department at AMEC Foster Wheeler for 30 years. He has varied experience in the utility industry, industrial establishments, hydroelectric generation, and atomic energy. He is responsible for power system studies, including short circuit, load flow, harmonics, stability, arc flash hazard, grounding, switching transients, and protective relaying. He conducts courses for continuing education in power systems and is the author or coauthor of about 70 technical publications nationally and internationally. He is the author of the following books:

- *Arc Flash Hazard Analysis and Mitigation*, IEEE Press, 2012.
- *Power System Harmonics and Passive Filter Designs*, IEEE Press, 2015.
- *Transients in Electrical Systems: Analysis Recognition and Mitigation*, McGraw-Hill, 2010.
- *Power System Analysis: Short-Circuit Load Flow and Harmonics*, Second Edition, CRC Press 2011.
- *Understanding Symmetrical Components for Power System Modeling*, IEEE Press, 2017.

These books provide extensive converge, running into more than 3000 pages, and are well received in the technical circles. His interests include power system transients, EMTP simulations, harmonics, passive filter designs, power quality, protection, and relaying. He has published more than 200 electrical power system study reports for his clients.

He has published more than 200 study reports of power systems analysis addressing one problem or the other.

Das is a Life Fellow of the Institute of Electrical and Electronics Engineers, IEEE, (USA), Member of the IEEE Industry Applications and IEEE Power Engineering societies, a Fellow of the Institution of Engineering Technology (UK), a Life Fellow of the Institution of Engineers (India), a Member of the Federation of European Engineers (France), a Member of CIGRE (France), etc. He is registered Professional Engineer in the states of Georgia and Oklahoma, a Chartered Engineer (CEng) in the UK, and a European Engineer (EurIng) in Europe. He received a meritorious award in engineering, IEEE Pulp and Paper Industry in 2005.

He earned a PhD in electrical engineering at Atlantic International University, Honolulu, an MSEE at Tulsa University, Tulsa, Oklahoma, and a BA in advanced mathematics and a BEE at Panjab University, India.

1

Harmonics Generation

Harmonics in power systems can be studied under distinct sections:

- Generation of characteristic and noncharacteristic harmonics
- Interharmonics and flicker
- Resonance, secondary resonance, and harmonic resonance
- Effects of harmonics
- Limitations of harmonics according to the IEEE and IEC standards
- Measurements of harmonics
- Harmonic propagation, modeling, and analysis
- Mitigation of harmonics, passive and active filters

Harmonics cause distortions of the voltage and current waveforms, which have adverse effects on electrical equipment. Harmonics are one of the major power quality concerns. The estimation of harmonics from nonlinear loads is the first step in a harmonic analysis and this may not be straightforward. There is an interaction between the harmonic producing equipment, which can have varied topologies, and the electrical system. Over the course of recent years, much attention has been focused on the analysis and control of harmonics, and standards have been established for permissible harmonic current and voltage distortions.

In this chapter, we will discuss the nature of harmonics and their generation by electrical equipment. Harmonic emission can have varied amplitudes and frequencies. The most common harmonics in power systems are sinusoidal components of a periodic waveform, which have frequencies that can be resolved into some multiples of the fundamental frequency. Fourier analysis is the mathematical tool employed for such analysis, and Appendix A provides an overview. It is recommended that the reader becomes familiarized with Fourier analysis before proceeding with the subject of harmonics. Power systems also have harmonics that are noninteger multiples of the fundamental frequency and have aperiodic waveforms, see Chapter 2. The generation of harmonics in power system occurs from two distinct types of loads as follows:

1. Linear time-invariant loads are characterized so that an application of a sinusoidal voltage results in a sinusoidal flow of current. These loads display constant steady-state impedance during the applied sinusoidal voltage. If the voltage is increased, the current also increases in direct proportion. Incandescent lighting is an example of such a load. Transformers and rotating machines, under normal loading conditions, approximately meet this definition, though the flux wave in the air gap of a rotating machine is not sinusoidal. Tooth ripples and slotting may produce forward and reverse rotating harmonics. Magnetic circuits

can saturate and generate harmonics. As an example, saturation in a transformer on abnormally high voltage produces harmonics, as the relationship between magnetic flux density B and the magnetic field intensity H in the transformer core is not linear. The inrush current of a transformer contains odd and even harmonics, including a dc component. Yet, under normal operating conditions, these effects are small. Synchronous generators in power systems produce sinusoidal voltages and the loads draw nearly sinusoidal currents. For the sinusoidal input voltages, the harmonic pollution produced due to these load types of loads is small.

2. The second category of loads is described as nonlinear. In a nonlinear device, the application of a sinusoidal voltage does not result in a sinusoidal flow of current. These loads do not exhibit constant impedance during the entire cycle of applied sinusoidal voltage. *Nonlinearity is not the same as the frequency dependence of impedance*, i.e., the impedance of a reactor changes in proportion to the applied frequency, but it is linear at each applied frequency. On the other hand, nonlinear loads draw a current that may even be discontinuous, or flow in pulses for a part of the sinusoidal voltage cycle. Some examples of nonlinear loads are as follows:
   - Adjustable drive systems
   - Cycloconverters
   - Arc furnaces and rolling mills
   - Switching mode power supplies (SMPSs)
   - Computers, copy machines, and television sets
   - Static var compensators (SVCs)
   - HVDC transmission
   - Electric traction
   - Switching mode power supplies
   - Wind and solar power generation
   - Pulse burst modulation (PBM)
   - Battery charging and fuel cells
   - Slip recovery schemes of induction motors
   - Fluorescent lighting and electronic ballasts
   - Silicon-controlled rectifier (SCR) heating, induction heating, and arc welding

The distortion produced by nonlinear loads can be resolved into a number of categories:

- A distorted waveform having a Fourier series with fundamental frequency equal to power system frequency, and a periodic steady state exists. This is the most common case in harmonic studies.
- A distorted waveform having a submultiple of power system frequency, and a periodic steady state exists. Certain types of pulsed loads and integral cycle controllers produce these types of waveforms.
- The waveform is aperiodic, but perhaps almost periodic. A trigonometric series expansion may still exist. Examples are arcing devices, e.g., arc furnaces,

fluorescent, mercury, and sodium vapor lighting. The process is not periodic in nature, and a periodic waveform is obtained if the conditions of operation are kept constant for a length of time.

The components in a Fourier series that are not an integral multiple of the power frequency are called noninteger harmonics, see Chapter 2.

The arc furnace loads are highly polluting; cause phase unbalance, flicker, impact loading, harmonics, and resonance; and may give rise to torsional vibrations in rotating equipment.

1.1 Sequence Components of Harmonics

In a three-phase balanced system under nonsinusoidal conditions, the *h*th-order harmonic voltage (or current) can be expressed as follows:

$$V_{ah} = V_h \sin(h\omega_0 t + \theta_h) \tag{1.1}$$

$$V_{bh} = V_h \sin\left(h\omega_0 t - \frac{2h\pi}{3} + \theta_h\right) \tag{1.2}$$

$$V_{ch} = V_h \sin\left(h\omega_0 t + \frac{2h\pi}{3} + \theta_h\right) \tag{1.3}$$

Based on Equations 1.1 through 1.3 and counterclockwise rotation of the fundamental phasors, we can write

$$\begin{aligned}
V_a &= V_1 \sin\omega t + V_2 \sin 2\omega t + V_3 \sin 3\omega t + V_4 \sin 4\omega t + V_5 \sin 5\omega t + \cdots \\
V_b &= V_1 \sin(\omega t - 120°) + V_2 \sin(2\omega t - 240°) + V_3 \sin(3\omega t - 360°) + V_4 \sin(4\omega t - 480°) \\
&\quad + V_5 \sin(5\omega t - 600°) + \cdots \\
&= V_1 \sin(\omega t - 120°) + V_2 \sin(2\omega t + 120°) + V_3 \sin 3\omega t + V_4 \sin(4\omega t - 120°) \\
&\quad + V_5 \sin(5\omega t + 120°) + \cdots \\
V_c &= V_1 \sin(\omega t + 120°) + V_2 \sin(2\omega t + 240°) + V_3 \sin(3\omega t + 360°) + V_4 \sin(4\omega t + 480°) \\
&\quad + V_5 \sin(5\omega t + 600°) + \cdots \\
&= V_1 \sin(\omega t + 120°) + V_2 \sin(2\omega t - 120°) + V_3 \sin 3\omega t + V_4 \sin(4\omega t + 120°) \\
&\quad + V_5 \sin(5\omega t - 120°) + \cdots
\end{aligned} \tag{1.4}$$

Under balanced conditions, the *h*th harmonic (frequency of harmonic = h times the fundamental frequency) of phase b lags h times 120° behind that of the same harmonic in phase a. The *h*th harmonic of phase c lags h times 240° behind that of the same harmonic in phase a. In the case of triplen harmonics, shifting the phase angles by three times 120° or

TABLE 1.1

Sequence of Harmonics

Harmonic Order	Sequence of the Harmonic
1	
2	–
3	0
4	+
5	–
6	0
7	+
8	–
9	0
10, 11, 12	+, –0

three times 240° results in cophasial vectors. Table 1.1 shows the sequence of harmonics, and the pattern is clearly positive–negative–zero. We can write

$$\text{Harmonics of the order } 3h+1 \text{ have positive sequence} \tag{1.5}$$

$$\text{Harmonics of the order } 3h+2 \text{ have negative sequence} \tag{1.6}$$

and

$$\text{Harmonics of the order } 3h \text{ are of zero sequence} \tag{1.7}$$

All triplen harmonics generated by nonlinear loads are zero sequence phasors. These add up in the neutral. In a three-phase four-wire system, with perfectly balanced single-phase loads between the phase and the neutral, all positive and negative sequence harmonics will cancel out, leaving only the zero sequence harmonics. In an unbalanced single-phase load, the neutral carries zero sequence and the residual unbalance of positive and negative sequence currents. Even harmonics are absent in the line because of phase symmetry (Appendix A) and unsymmetrical waveforms will add even harmonics to the phase conductors.

1.2 Increases in Nonlinear Loads

Nonlinear loads are continually on the increase. It is estimated that, during the next 10 years, 60% of the loads on utility systems will be nonlinear. Concerns for harmonics originate from meeting a certain power quality, which leads to the related issues of (1) effects on the operation of electrical equipment, (2) harmonic analysis, and (3) harmonic control. A growing number of consumer loads are sensitive to poor power quality and it is estimated that power-quality problems cost US industry tens of billions of dollars per year. While the expanded use of consumer automation equipment and power electronic controls is leading to higher productivity, these very loads are a source of electrical noise, and harmonics are less tolerant to poor power quality. For example, adjustable speed drives (ASDs) are less tolerant to voltage sags and swells, and a voltage dip of 10% of certain duration may precipitate a shutdown.

1.3 Harmonic Factor

An index of merit has been defined as a harmonic distortion factor [1] (harmonic factor). It is the ratio of the root mean square (RMS) of the harmonic content to the RMS value of the fundamental quantity, expressed as a percentage of the fundamental:

$$\mathrm{DF} = \sqrt{\frac{\sum \text{of squares of amplitudes of all harmonics}}{\text{square of the amplitude of the fundamental}}} \times 100\% \tag{1.8}$$

Voltage and current harmonic distortion indices, defined in Chapter 5, are the most commonly used indices. Total harmonic distortion (THD) in common use is the same as DF.

1.3.1 Equations for Common Harmonic Indices

We can write the following equations.

RMS voltage in the presence of harmonics can be written as follows:

$$V_{\mathrm{rms}} = \sqrt{\sum_{h=1}^{h=\infty} V_{h,\mathrm{rms}}^2} \tag{1.9}$$

And similarly the expression for the current is

$$I_{\mathrm{rms}} = \sqrt{\sum_{h=1}^{h=\infty} I_{h,\mathrm{rms}}^2} \tag{1.10}$$

The total distortion factor for the voltage is

$$\mathrm{THD}_V = \frac{\sqrt{\sum_{h=2}^{h=\infty} V_{h,\mathrm{rms}}^2}}{V_{\mathrm{f,rms}}} \tag{1.11}$$

where $V_{\mathrm{f,rms}}$ is the fundamental frequency voltage. This can be written as follows:

$$\mathrm{THD}_V = \sqrt{\left(\frac{V_{\mathrm{rms}}}{V_{\mathrm{f,rms}}}\right)^2 - 1} \tag{1.12}$$

or

$$V_{\mathrm{rms}} = V_{\mathrm{f,rms}}\sqrt{1 + \mathrm{THD}_V^2} \tag{1.13}$$

Similarly

$$\mathrm{THD}_I = \frac{\sqrt{\sum_{h=2}^{h=\infty} I_{h,\mathrm{rms}}^2}}{I_{\mathrm{f,rms}}} = \sqrt{\left(\frac{I_{\mathrm{rms}}}{I_{\mathrm{f,rms}}}\right)^2 - 1} \tag{1.14}$$

$$I_{\mathrm{rms}} = I_{\mathrm{f,rms}} \sqrt{1 + \mathrm{THD}_I^2} \tag{1.15}$$

where $I_{\mathrm{f,rms}}$ is the fundamental frequency current.

The total demand distortion (TDD) is defined as follows:

$$\mathrm{TDD} = \frac{\sqrt{\sum_{h=2}^{h=\infty} I_h^2}}{I_{\mathrm{L}}} \tag{1.16}$$

where I_{L} is the load demand current.

The partial weighted harmonic distortion (PWHD) of current is defined as follows:

$$\mathrm{PWHD}_I = \frac{\sqrt{\sum_{h=14}^{h=40} h I_h^2}}{I_{\mathrm{f,rms}}} \tag{1.17}$$

Similar expression is applicable for the voltage. The PWHD evaluates influence of current or voltage harmonics of higher order. The sum parameters are calculated with single harmonic current components I_h.

1.4 Three-Phase Windings in Electrical Machines

The armature windings of a machine consist of phase coils that span approximately a pole pitch. A phase winding consists of a number of coils connected in series, and the EMF generated in these coils is time displaced in phase by a certain angle. The air gap is bounded on either side by iron surfaces and provided with slots and duct openings and is skewed. Simple methods of estimating the reluctance of the gap to carry a certain flux across the gap are not applicable and the flux density in the air gap is not sinusoidal. Figure 1.1 shows that armature reaction varies between a pointed and flat-topped trapezium for a phase spread of π/3. Fourier analysis of the pointed waveform in Figure 1.1 gives

$$F = \frac{4}{\pi} F_m \cos \omega t \left[\sum_{h=1}^{h=\infty} \frac{1}{h} k_{mn} \sin hx \right] \tag{1.18}$$

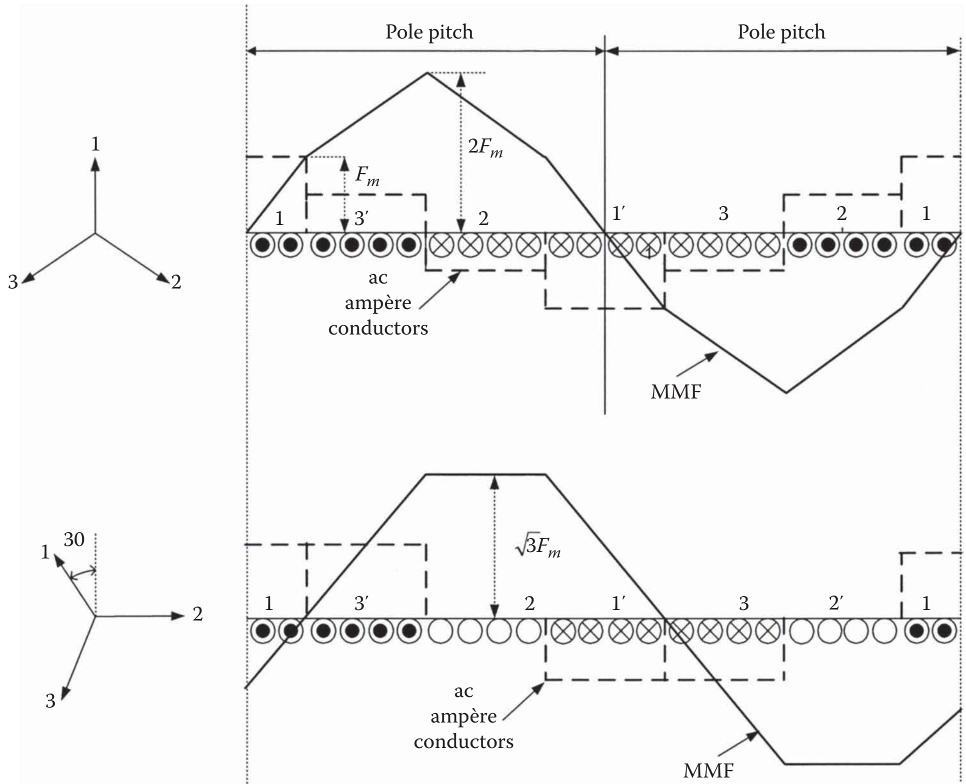

FIGURE 1.1
Armature reaction of a three-phase winding spanning a pole pitch.

where k_{mn} is a winding distribution factor for the *h*th harmonic:

$$k_{mn} = \frac{\sin(1/2)h\sigma}{g' \sin(1/2)\ (h\sigma/g')} \tag{1.19}$$

in which g' is the number of slots per pole per phase and σ is the phase spread, *h* is order of harmonic.

The MMFs of three phases will be given by considering the time displacement of currents and space displacement of axes as follows:

$$\begin{aligned} F_t &= \frac{4}{\pi} F_m \cos\omega t \left[\sum_{h=1}^{h=\infty} \frac{1}{n} k_{mn} \sin hx \right] + \frac{4}{\pi} F_m \cos\left(\omega t - \frac{2}{3}\pi\right) \\ &\times \left[\sum_{h=1}^{h=\infty} \frac{1}{h} k_{mn} \sin h\left(x - \frac{2}{3}\pi\right) \right] \\ &+ \frac{4}{\pi} F_m \cos\left(\omega t - \frac{4}{3}\pi\right) \left[\sum_{h=1}^{h=\infty} \frac{1}{h} k_{mn} \sin h\left(x - \frac{4}{3}\pi\right) \right] \end{aligned} \tag{1.20}$$

This gives

$$F_t = \frac{6}{\pi} F_m \left[F_{mi} \sin(x - \omega t) + \frac{1}{5} k_{m5} \sin(5x - \omega t) - \frac{1}{7} k_{m7} \sin(7x - \omega t) + \cdots \right] \tag{1.21}$$

where k_{m5} and k_{m7} are harmonic winding factors.

The MMF has a constant fundamental, and harmonics are of the order of 5, 7, 11, 13, …, or $6m \pm 1$, where m is any positive integer. The third harmonic and its multiples (triplen harmonics) are absent, though in practice, some triplen harmonics are produced. The harmonic flux components are affected by phase spread, fractional slotting, and coil span. The pointed curve is obtained when $\sigma = 60°$ and $\omega t = 0$. The flat topped curve is obtained when $\omega t = \pi/6$.

1.4.1 Cogging and Crawling of Induction Motors

Parasitic magnetic fields are produced in an induction motor due to harmonics in the MMF originating from

- Windings
- Certain combination of rotor and stator slotting
- Saturation
- Air gap irregularity
- Unbalance and harmonics in the supply system voltage

The harmonics move with a speed reciprocal to their order, either with or against the fundamental. Harmonics of the order of $6m+1$ move in the same direction as the fundamental magnetic field while those of $6m-1$ move in the opposite direction.

1.4.2 Harmonic Induction Torques

The harmonics can be considered to produce, by an additional set of rotating poles, rotor EMF's, currents, and harmonic torques akin to the fundamental frequency at synchronous speeds depending upon the order of the harmonics. Then, the resultant speed–torque curve will be a combination of the fundamental and harmonic torques. This produces a saddle in the torque speed characteristics and the motor can crawl at the lower speed of 1/7th of the fundamental, see Figure 1.2a. This torque speed curve is called the *harmonic induction torque curve*.

This harmonic torque can be augmented by stator and rotor slotting. In n-phase winding, with g' slots per pole per phase, EMF distribution factors of the harmonics are

$$h = 6Ag' \pm 1 \tag{1.22}$$

where A is any integer, 0, 1, 2, 3, ….

The harmonics of the order $6Ag'+1$ rotate in the same direction as the fundamental, while those of order $6Ag'-1$ rotate in the opposite direction.

A four-pole motor with 36 slots, $g' = 3$ slots per pole per phase, will give rise to 17th and 19th harmonic torque saddles, observable at +1/19 and –1/17 speed, similar to the saddles shown in Figure 1.2a.

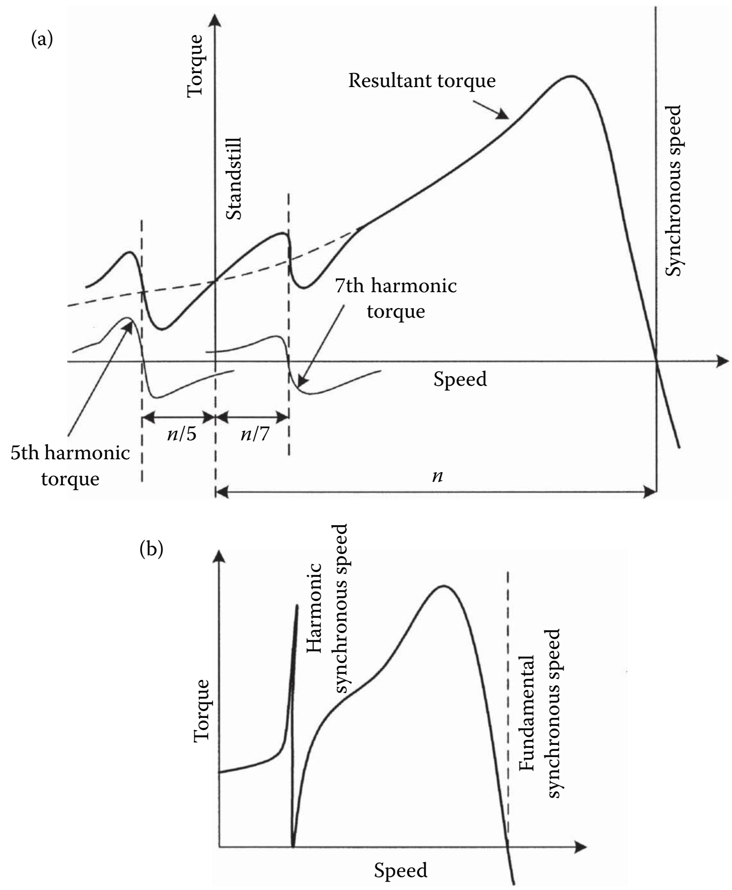

FIGURE 1.2
(a) Harmonic induction torques and (b) synchronous torques in an induction motor.

Consider 24 slots in the stator of a four-pole machine. Then $g' = 2$ and 11th and 13th harmonics will be produced strongly. The harmonic induction torque thus produced can be augmented by the rotor slotting. For a rotor with 44 slots, 11th harmonic has 44 half waves each corresponding to a rotor bar in a squirrel cage induction motor. This will accentuate 11th harmonic torque and produce strong vibrations.

If the numbers of stator slots are equal to the number of rotor slots, the motor may not start at all, a phenomenon called *cogging.*

The phenomena will be more pronounced in squirrel cage induction motors as compared to wound rotor motors, as the effect of harmonics can be reduced by coil pitch, see Section 3.4. In the cage induction motor design, S_2 (number of slots in the rotor) should not exceed S_1 (number of slots in the stator) by more than 50%–60%; otherwise, there will be some tendency toward saddle harmonic torques.

1.4.3 Harmonic Synchronous Torques

Consider that the fifth and seventh harmonics are present in the gap of a three-phase induction motor. With this harmonic content and with certain combination of the stator and rotor slots, it is possible to get a stator and rotor harmonic torque producing a *harmonic synchronizing* torque, as in a synchronous motor. There will be a tendency to develop sharp synchronizing torque at some lower speed, see Figure 1.2b. The motor may crawl at a lower speed.

The rotor slotting will produce harmonics of the order of

$$h = \frac{S_2}{p} \pm 1 \tag{1.23}$$

where S_2 is the number of rotor slots. Here, the plus sign means rotation with the machine. Consider a four-pole (p = number of pair of poles = 2) motor with $S_1 = 24$ and with $S_2 = 28$. The stator produces reversed 11th harmonic (reverse going) and 13th harmonic (forward going). The rotor develops a reversed 13th and forward 15th harmonic. The 13th harmonic is produced both by stator and rotor but of opposite rotation. The synchronous speed of the 13th harmonic is 1/13 of the fundamental synchronous speed. Relative to rotor, it becomes

$$-\frac{(n_s - n_r)}{13} \tag{1.24}$$

where n_s is the synchronous speed and n_r is the rotor speed. The rotor, therefore, rotates its own 13th harmonic at a speed of

$$-\frac{(n_s - n_r)}{13} + n_r \tag{1.25}$$

relative to the stator. The stator and rotor 13th harmonic fall into step when

$$+\frac{n_s}{13} = -\frac{(n_s - n_r)}{13} + n_r \tag{1.26}$$

This gives $n_r = n_s/7$, i.e., torque discontinuity is produced not by 7th harmonic but by 13th harmonic in the stator and rotor rotating in opposite directions. The torque–speed curve is shown in Figure 1.3.

- The synchronous torque at 1800/7 = 257 rpm
- Induction torque due 13th stator harmonic = 138 rpm
- Induction torque due to reversed 11th harmonic = 164 rpm

Typical synchronous torques in four-pole cage induction motors are listed in Table 1.2. If $S_1 = S_2$, the same order harmonics will be strongly produced, and each pair of harmonics will produce a synchronizing torque, and the rotor may remain at standstill (cogging), unless the fundamental frequency torque is large enough to start the motor.

The harmonic torques are avoided in the design of induction machines by proper selection of the rotor and stator slotting and winding designs.

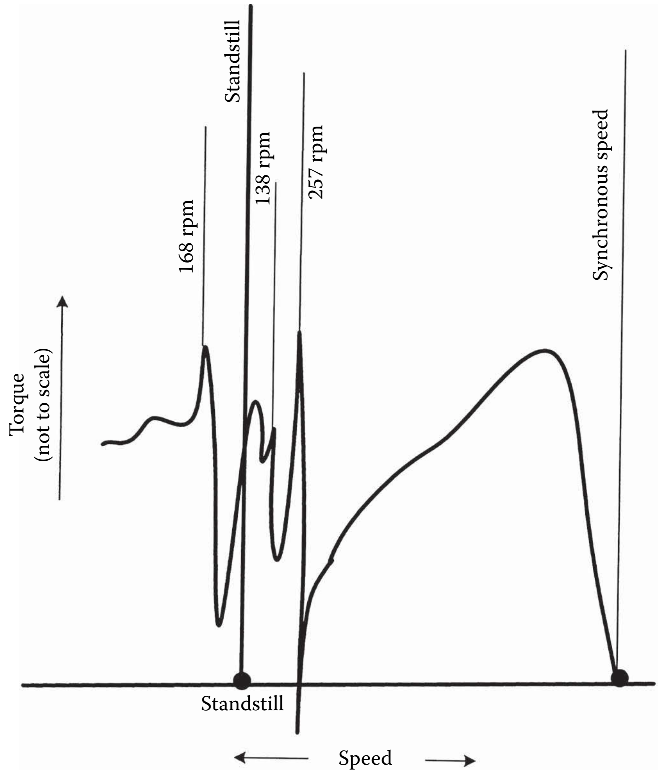

FIGURE 1.3
Torque speed curve of a four-pole, 60 Hz motor, considering harmonic synchronous torques.

TABLE 1.2
Typical Synchronous Torques Four-Pole Cage Induction Motors

Stator Slots	Rotor Slots	Stator Harmonics		Rotor Harmonics	
S_1	S_2	Negative	Positive	Negative	Positive
24	20	–11	+13	–9	+11
24	28	–11	+13	–13	+15
36	32	–17	+19	–15	+17
36	40	–17	+19	–19	+21
48	44	–23	+25	–21	+23

1.5 Tooth Ripples in Electrical Machines

Tooth ripples in electrical machinery are produced by slotting as these affect air-gap permeance. Figure 1.4 shows ripples in the air-gap flux distribution (exaggerated) because of variation in gap permeance. The frequency of flux pulsations corresponds to the rate at which slots cross the pole face, i.e., it is given by $2gf$, where g is the number of slots per pole and f is the system frequency. This stationary pulsation may be regarded as two waves

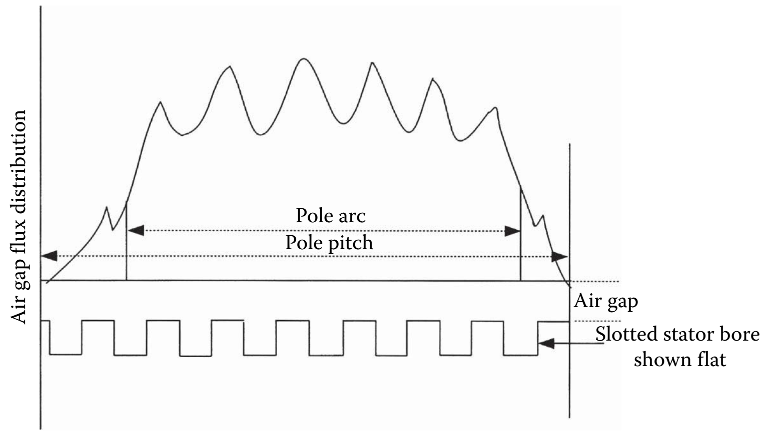

FIGURE 1.4
Gap flux distribution due to tooth ripples.

of fundamental space distribution rotating at angular velocity $2g\omega$ in forward and backward directions. The component fields will have velocities of $(2g \pm 1)\omega$ relative to the armature winding and will generate harmonic EMFs of frequencies $(2g \pm 1)f$ cycles per second. However, this is not the main source of tooth ripples. Since the ripples are due to slotting, these do not move with respect to conductors. Therefore, these cannot generate an EMF of pulsation. With respect to the rotor, the flux waves have a relative velocity of $2g\omega$ and generate EMFs of $2gf$ frequency. Such currents superimpose an MMF variation of $2gf$ on the resultant pole MMF. These can be again resolved into forward and backward moving components with respect to the *rotor*, and $(2g \pm 1)\omega$ with respect to the *stator*. Thus, stator EMFs at frequencies $(2g \pm 1)f$ are generated, which are the principle tooth ripples.

1.6 Synchronous Generators Waveforms

The terminal voltage wave of synchronous generators must meet the requirements of NEMA, which states that the deviation factor of the open line-to-line terminal voltage of the generator shall not exceed 0.1.

Figure 1.5 shows a plot of a hypothetical generated wave, superimposed on a sinusoid, and the deviation factor is defined as follows:

$$F_{\mathrm{DEV}} = \frac{\Delta E}{E_{\mathrm{OM}}} \tag{1.27}$$

where E_{OM} is calculated from a number of samples of instantaneous values:

$$E_{\mathrm{OM}} = \sqrt{\frac{2}{J}\sum_{j=1}^{J} E_j^2} \tag{1.28}$$

The deviation from a sinusoid is very small.

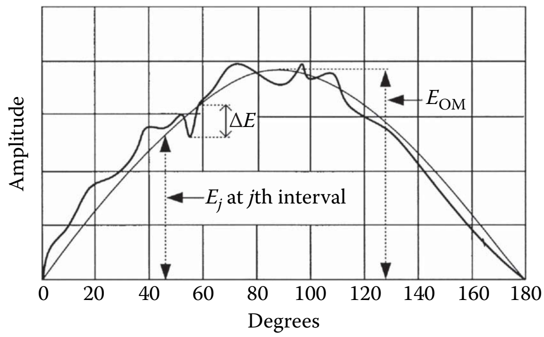

FIGURE 1.5
Measurements of deviation factor of a generator voltage.

Generator neutrals have predominant third harmonic voltages. In a wye-connected generator, with the neutral grounded through high impedance, the third harmonic voltage for a ground fault increases toward the neutral, while the fundamental frequency voltage decreases. The third harmonic voltages at line and neutral can vary considerably with load.

1.7 Transformers: Harmonics

Harmonics in transformers originate as a result of saturation, switching, high-flux densities, and winding connections. The following summarizes the main factors with respect to harmonic generation:

1. For economy in design and manufacture, transformers are operated close to the knee point of saturation characteristics of magnetic materials. Figure 1.6 shows a *B–H* curve and the magnetizing current waveform. A sinusoidal flux wave, required by sinusoidal applied voltage, demands a magnetizing current with a harmonic content. Conversely, with a sinusoidal magnetizing current, the induced EMF is peaky and the flux is flat topped.

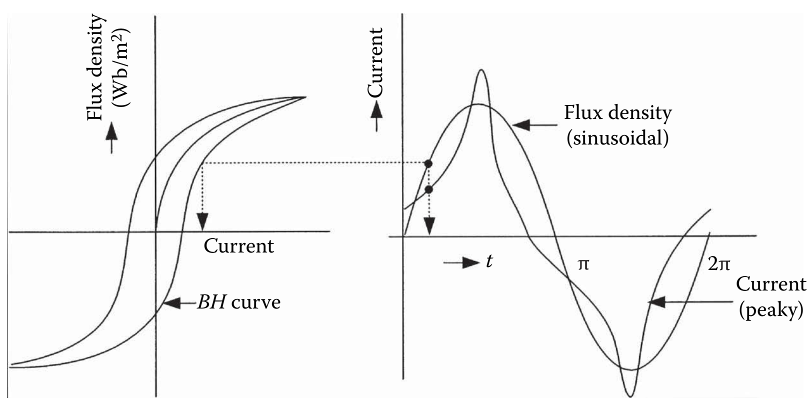

FIGURE 1.6
B–H curve of magnetic material and peaky transformer magnetizing current.

2. An explanation of the generation of the peaky magnetizing current considering the third harmonic is provided in Figure 1.7. A sinusoidal EMF, E_a, generates a sinusoidal current flow, I_a, in lagging phase quadrature with E_a. These set up a flat-topped flux wave, ϕ_1, which can be resolved into two components: $\phi\alpha$ the fundamental flux wave and ϕ_3 the third harmonic flux wave (higher harmonics are neglected). The third harmonic flux can be supposed to produce a third harmonic EMF E_3 and a corresponding third harmonic current I_3, which when summed with I_a makes the total current peaky.
3. In a system of three-phase balanced voltages, the 5th, 7th, 11th, and so on produce voltages displaced by 120° mutually, while the triplen harmonic voltages are cophasial. If the impedance to the third harmonic is negligible, only a very small third harmonic EMF is required to circulate a magnetizing current additive to the fundamental frequency, so as to maintain a sinusoidal flux. This is true if the transformer windings are delta connected. In wye–wye connected transformers with isolated neutrals, as all the triplen harmonics are either directed inward or outward, these cancel between the lines, no third harmonic currents flow, and the flux wave in the transformer is flat topped. The effect on a wye-connected point is to make it oscillate at three times the fundamental frequency, giving rise to distortion of the phase voltages (Figure 1.8). Tertiary delta-connected windings are included in wye–wye connected transformers for neutral stabilization.
4. Three-phase core-type transformers have magnetically interlinked phases, and the return paths of triplen harmonic fluxes lie outside the core, through the tank and transformer fluid, which have high reluctance. In five-limb transformers, the end limbs provide return paths for triplen harmonics.

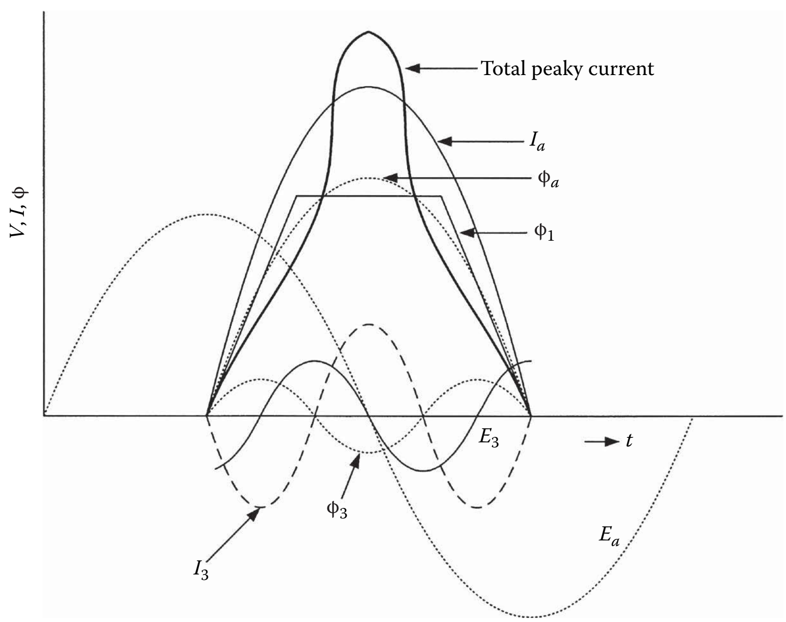

FIGURE 1.7
Origin of flat-topped flux wave in a transformer, third-harmonic current, and overall peaky magnetizing current.

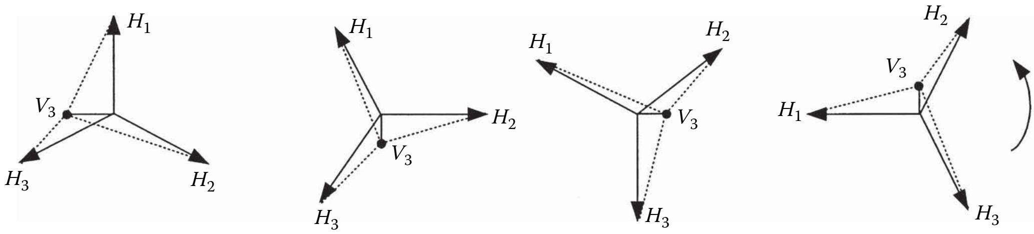

FIGURE 1.8
Phenomena of neutral oscillation in a wye–wye connected transformer, due to third-harmonic voltages.

5. It can be said that power transformers generate very low levels of harmonic currents in steady-state operation, and the harmonics are controlled by design and transformer winding connections. The higher order harmonics, i.e., the fifth and seventh, may be <0.1% of the transformer full-load current.
6. Energizing a power transformer does generate a high order of harmonics, including a dc component. Figure 1.9 shows three conditions of energizing of a power transformer: (1) the switch closed at the peak value of the voltage, (2) the switch closed at the zero value of the voltage, and (3) energizing with some residual trapped flux in the magnetic core due to retentivity of the magnetic materials. Figure 1.9d shows the spectrum of magnetizing inrush current, which resembles a rectified current and its peak value may reach 8–15 times the transformer full-load current, mainly depending on the transformer size. The asymmetrical loss due to conductor and core heating rapidly reduces the flux wave to symmetry about the time axis and typically the inrush currents last for a short duration (0.1 s).

   Typical harmonics generated by the transformer inrush current are shown in Figure 1.10. Overexcitation of transformers in steady-state operation can produce harmonics. The generated fundamental frequency EMF is given by

$$V = 4.44 f T_{\text{ph}} B_m A_c \tag{1.29}$$

   where T_{ph} is the number of turns in a phase, B_m is the flux density (consisting of fundamental and higher order harmonics), and A_c is the area of core. Thus, the factor V/f is a measure of the overexcitation, though these currents do not normally cause a wave distortion of any significance. Exciting currents increase rapidly with voltage, and transformer standards specify application of 110% voltage without overheating the transformer. Under certain system upset conditions, the transformers may be subjected to even higher voltages and overexcitation. ANSI protective device number 24, volts per hertz relay is used for overexcitation protection.

1.8 Harmonics due to Saturation of Current Transformers

Saturation of current transformers under fault conditions produces harmonics in the secondary circuits. Accuracy classification of current transformers is designated by one letter, C or T, depending on current transformer construction [2]. Classification C covers bushing-type transformers with uniformly distributed windings, and the leakage

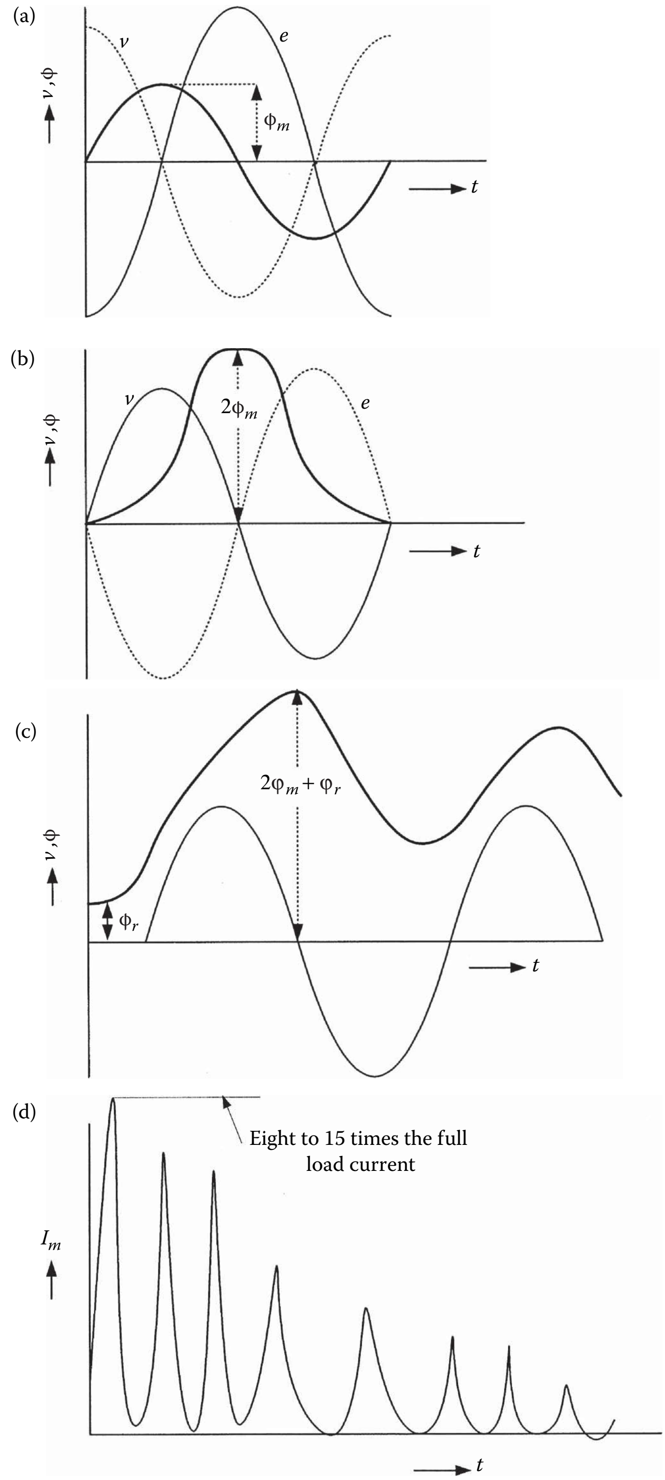

FIGURE 1.9
(a through d) Switching inrush current transients in a transformer (see the text).

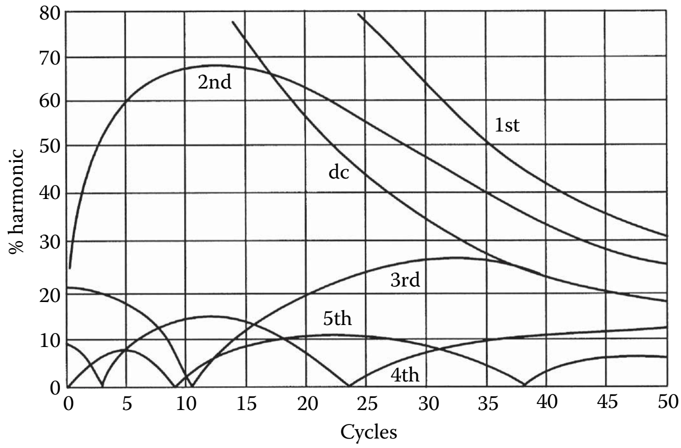

FIGURE 1.10
Harmonic components of the inrush current of a transformer.

flux has a negligible effect on the ratio within the defined limits. A transformer with relaying accuracy class C200 means that the percentage ratio correction will not exceed 10% at any current from 1 to 20 times the rated secondary current at a standard burden of 2.0 Ω, which will generate 200 V. The secondary voltage as given by maximum fault current reflected on the secondary side multiplied by connected burden ($R + jX$) should not exceed the assigned C accuracy class. When current transformers are improperly applied, saturation can occur, as shown in Figure 1.11 [3]. A completely saturated CT

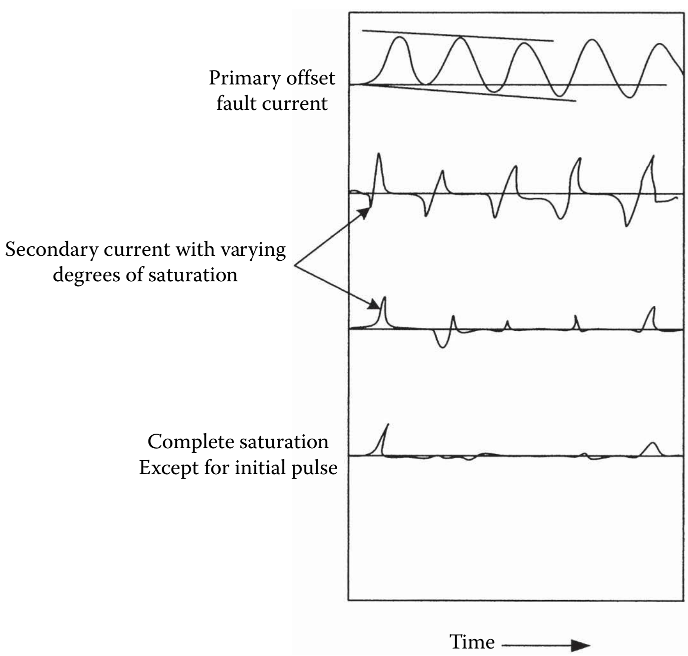

FIGURE 1.11
Saturation of a current transformer on asymmetrical fault current and origin of harmonics.

does not produce a current output, except during the first pulse, as there is a finite time to saturate and desaturate. The *transient* performance should consider the dc component of the fault current, as it has far more effect in producing severe saturation of the current transformer than the ac component.

As the CT saturation increases, so does the secondary harmonics, before the CT goes into a completely saturated mode. Harmonics of the order of 50% third, 30% fifth, 18% seventh, and 15% ninth and higher order may be produced. These can cause improper operation of the protective devices. This situation can be avoided by proper selection and application of current transformers, see Volume 4.

1.9 Switching of Shunt Capacitor Banks

High frequencies of inrush currents on switching of shunt capacitors occur, which are discussed in Volume 1. The frequency of the system transient is typically <1 kHz for an isolated capacitor bank and <5 kHz for back-to-back switching. Series filter reactors and switching inrush current limiting reactors reduce these frequencies. The fast front of the switching surge voltage can cause a part-winding resonance and harmonic generation in a transformer, if the frequency coincides with the transformer's natural frequency which is of the order of 10–100 kHz, the first resonance occurring in the range 7–15 kHz. The likelihood of exciting a part-winding resonance on switching is remote, but switching overvoltages are of major concern, see Volume 1.

The power capacitors do not generate harmonics by themselves, but are the main cause of amplification of the harmonics due to resonance and increased harmonic distortion. These can also reduce harmonic distortion, when applied as filters. This important aspect of power capacitor is discussed in the chapters to follow.

1.10 Subharmonic Frequencies

Volume 2 shows that series compensation of transmission lines with capacitors can generate subharmonic frequencies and how these can be damped with some FACTS devices. Switching of long lines close to a generator can cause oscillations. Power oscillations can be described as follows:

- *Interarea mode oscillations*: These oscillations occur when one set of machines swings against another set of machines in a different area of the transmission system. The oscillations are typically in the range 0.2–0.5 Hz.
- *Local mode oscillations*: These oscillations occur between one or more machines in a plant swinging against a large power source or network. The oscillations are typically in the range 0.7–2.0 Hz.
- *Interunit mode oscillations*: These oscillations occur when one machine swings against another machine in the same area in the same power plant. The oscillations are typically in the range 1.5–3.0 Hz.

Power system stabilizers in the excitation systems of the machines are used to stabilize the oscillations.

It can, generally, be said that the harmonics in the power systems from sources other than nonlinear loads are comparatively small, though these cannot always be ignored. Major sources of harmonies are nonlinear loads [4].

1.11 Static Power Converters

The primary sources of harmonics in the power system are power converters, rectifiers, inverters, and ASDs. The *characteristic* harmonics are those produced by the power electronic converters during normal operation and these harmonics are integer multiples of the fundamental frequency of the power system. N*oncharacteristic* harmonics are usually produced by sources other than power electronic equipment and may be at frequencies other than the integer multiple of the fundamental power frequency. The converters do produce some noncharacteristic harmonics, as ideal conditions of commutation and control are not achieved in practice. The ignition delay angles may not be uniform, and there may be an unbalance in the supply voltages and the bridge circuits.

1.11.1 Single-Phase Bridge Circuit

The single-phase rectifier full-bridge circuit of Figure 1.12 is first considered. It is assumed that there is no voltage drop or leakage current, the switching is instantaneous, the voltage source is sinusoidal, and the load is resistive. For full-wave conduction, the waveforms of input and output currents are then as shown in Figure 1.12b and c. The *average* dc current is

$$I_{\mathrm{dc}} = \frac{1}{2\pi}\int_0^{2\pi}\frac{E_m}{R}\sin\omega t\,\mathrm{d}\omega t = \frac{2E_m}{\pi R} \tag{1.30}$$

and the rms value or the effective value of the output current, including all harmonics, is

$$I_{\mathrm{rms}} = \sqrt{\frac{1}{2\pi}\int_0^{\pi}\left(\frac{E_m}{R}\right)^2\sin^2\omega t\,\mathrm{d}\omega t} = \frac{E_m}{\sqrt{2}R} \tag{1.31}$$

The *input current has no harmonics*. The average dc voltage is given by

$$E_{\mathrm{dc}} = \frac{2E_m}{\pi} \tag{1.32}$$

The output ac power is defined as follows:

$$P_{\mathrm{ac}} = E_{\mathrm{rms}}I_{\mathrm{rms}} = \frac{(0.707E_{\mathrm{rms}})^2}{R} \tag{1.33}$$

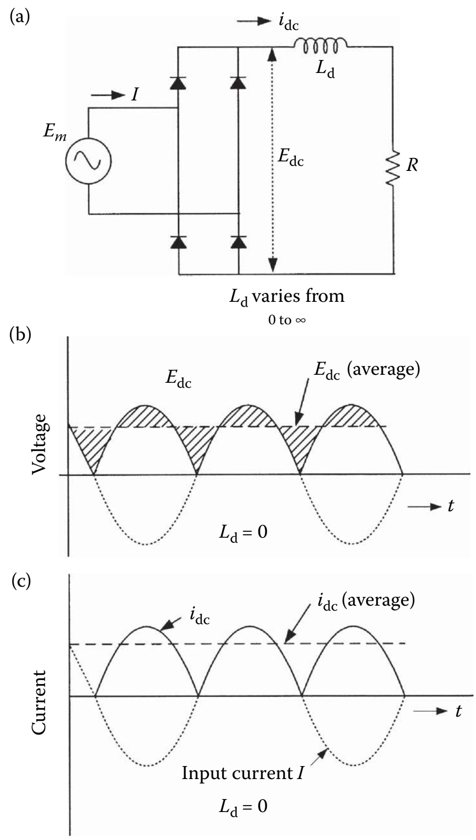

FIGURE 1.12
(a) A single-phase full rectifier bridge circuit, with resistive load; and (b and c) waveforms with zero dc reactor.

where E_{rms} considers the effect of harmonics on the output. The dc output power is

$$P_{dc} = E_{dc}I_{dc} = \left(\frac{2E_m}{\pi}\right)\left(\frac{2E_m}{\pi R}\right) = \frac{0.405E_m^2}{R} \tag{1.34}$$

The efficiency of rectification is given by P_{dc}/P_{ac} (81%). The *form factor* is a measure of the shape of the output voltage or current and it is defined as follows:

$$\text{FF} = \frac{I_{rms}}{I_{dc}} = 1.11 \tag{1.35}$$

The *ripple factor*, which is a measure of the ripple content of the output current or voltage, is defined as the rms value of output voltage or current, including all harmonics, divided by the average value:

$$\text{RF} = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} = \sqrt{\text{FF}^2 - 1} \tag{1.36}$$

For the single-phase bridge circuit with resistive load, the ripple factor is

$$\mathrm{RF} = \sqrt{\left(\frac{I_{\mathrm{rms}}}{I_{\mathrm{dc}}}\right)^2 - 1} = 0.48 \tag{1.37}$$

This shows that the ripple content of the dc output voltage is high, see Figure 1.12b. This is not acceptable even for the simplest of applications. Let a series reactor be added in the dc circuit. The load current is no longer a sine wave, but the average current is still equal to $2E_m/\pi R$. The ac line current is no longer sinusoidal, but approximates a poorly defined square wave with superimposed ripples, see Figure 1.13a and b. The inductance has reduced the harmonic content of the load current by increasing the harmonic content of the ac line current. When the inductance is large, the ripple across the load is insignificant and can be assumed constant, and the ac current wave is now a square wave, see Figure 1.13c and d.

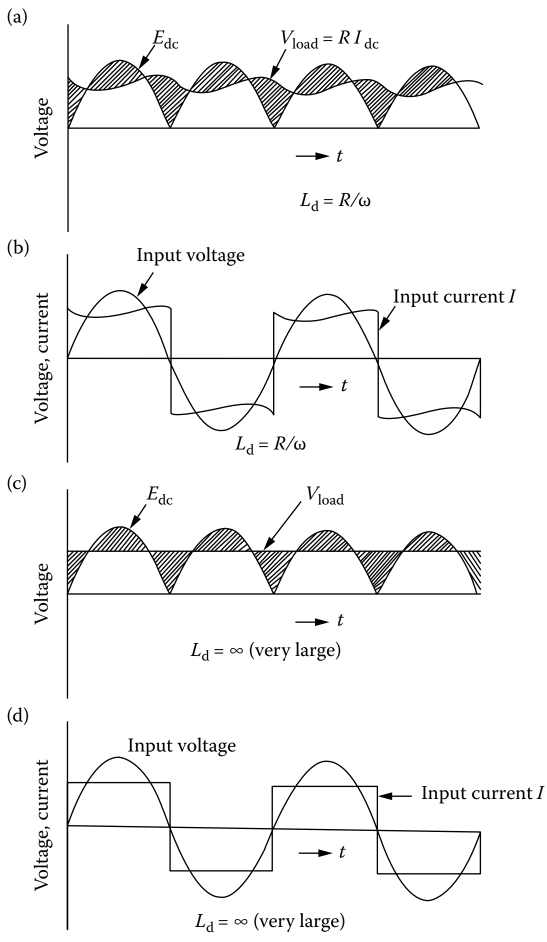

FIGURE 1.13
(a) Waveforms of a single-phase full rectifier bridge with small dc output reactor and (b) with large dc output reactor.

1.11.1.1 Phase Control

An SCR can be turned on by applying a short pulse to its gate and turned off due to natural or line commutation. The term thyristor pertains to the family of semiconducting devices for power control. The angle by which the conduction is delayed after the input voltage starts to go positive until the thyristor is fired is called the delay angle. Figure 1.14b shows waveforms with a large dc reactor, and Figure 1.14c shows waveform with no dc reactor but identical firing angle. Thyristors 1–4 are fired in pairs as shown in Figure 1.14b. Even when the polarity of the voltage is reversed, the current keeps flowing in thyristors 1 and 2 until thyristors 3 and 4 are fired, see Figure 1.14a. Firing of thyristors 3 and 4 reverse biases thyristors 1 and 2 and turns them off. (This is referred to as class F-type forced commutation or line commutation.) The average dc voltage is

$$E_{\mathrm{dc}} = \frac{2}{2\pi}\int_{\alpha}^{\pi+\alpha} E_m \sin \omega t \, \mathrm{d}\omega(\omega t) = \frac{2E_m}{\pi}\cos\alpha \tag{1.38}$$

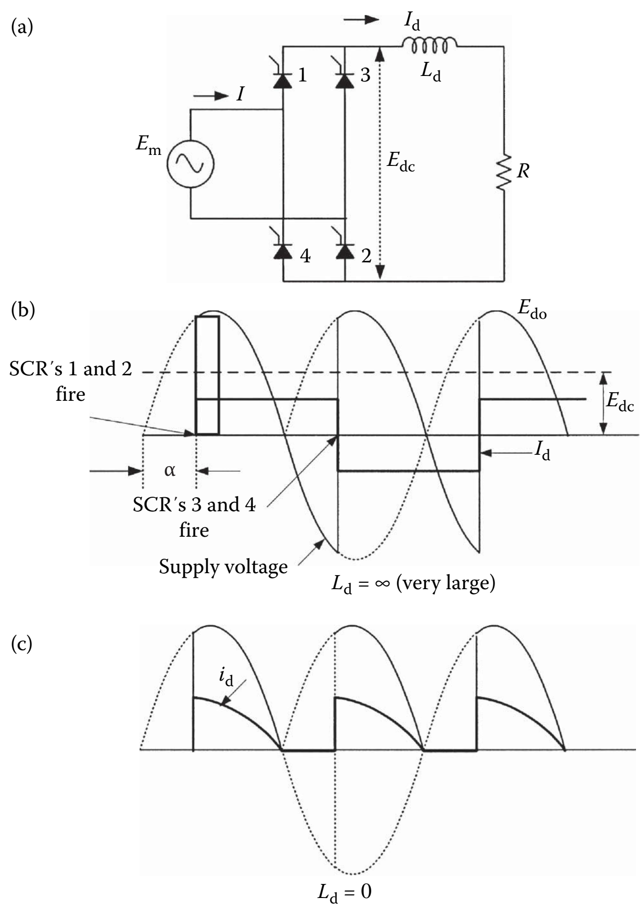

FIGURE 1.14
(a) Circuit of a single-phase fully controlled bridge; and (b and c) waveforms with large dc reactor and with zero dc reactor.

and the Fourier analysis of the rectangular current wave in Figure 1.14b gives

$$a_h = -\frac{4I_a}{h\pi}\sin\ h\alpha, \quad h = 1,3,5,\ldots$$
$$= 0 \qquad h = 2,4,6,\ldots \tag{1.39}$$

$$b_h = \frac{4I_a}{h\pi}\cos\ h\alpha \quad h = 1,3,5,\ldots$$
$$= 0 \qquad h = 2,4,6,\ldots \tag{1.40}$$

Since

$$I = \sum_{h=1,2,\ldots}^{\infty} \left[a_h \cos(h\omega t) + b_h \sin(h\omega t)\right] \tag{1.41}$$

The rms input current is given by

$$I = \frac{4}{\pi} I_{\mathrm{d}} \left[\sin(\omega t - \alpha) + \frac{1}{3}\sin 3(\omega t - \alpha) + \frac{1}{5}\sin 5(\omega t - \alpha) + \cdots\right] \tag{1.42}$$

Triplen harmonics are present. Figure 1.15 shows harmonics as a function of the delay angle for a resistive load. The overlap angle (defined further) decreases the magnitude of the harmonics. When the output reactor is small, the current goes to zero, the input current wave is no longer rectangular, and the line harmonics increase.

1.11.1.2 Power Factor, Distortion Factor, and Total Power Factor

For sinusoidal voltages and currents, the power factor is defined as kW/kVA and the power factor angle ϕ is

$$\phi = \cos^{-1}\frac{\mathrm{kW}}{\mathrm{kVA}} = \tan^{-1}\frac{\mathrm{kvar}}{\mathrm{kW}} \tag{1.43}$$

The power factor of a converter is made up of two components: displacement and distortion. The effect of the two is combined in total power factor. The displacement component is the ratio of active power of the fundamental wave in watts to apparent power of fundamental wave in voltampères. This is the power factor as seen by the watt-hour and var-hour meters. The distortion component is that part associated with harmonic voltages and currents.

$$\mathrm{PF_t} = \mathrm{PF_f} \times \mathrm{PF_{distortion}} \tag{1.44}$$

At fundamental frequency, the displacement power factor will be equal to the total power factor, as the displacement power factor does not include kVA due to harmonics, while the total power factor does include it. For harmonic generating loads, the total power factor will always be less than the displacement power factor. The discussion is continued in Chapter 7.