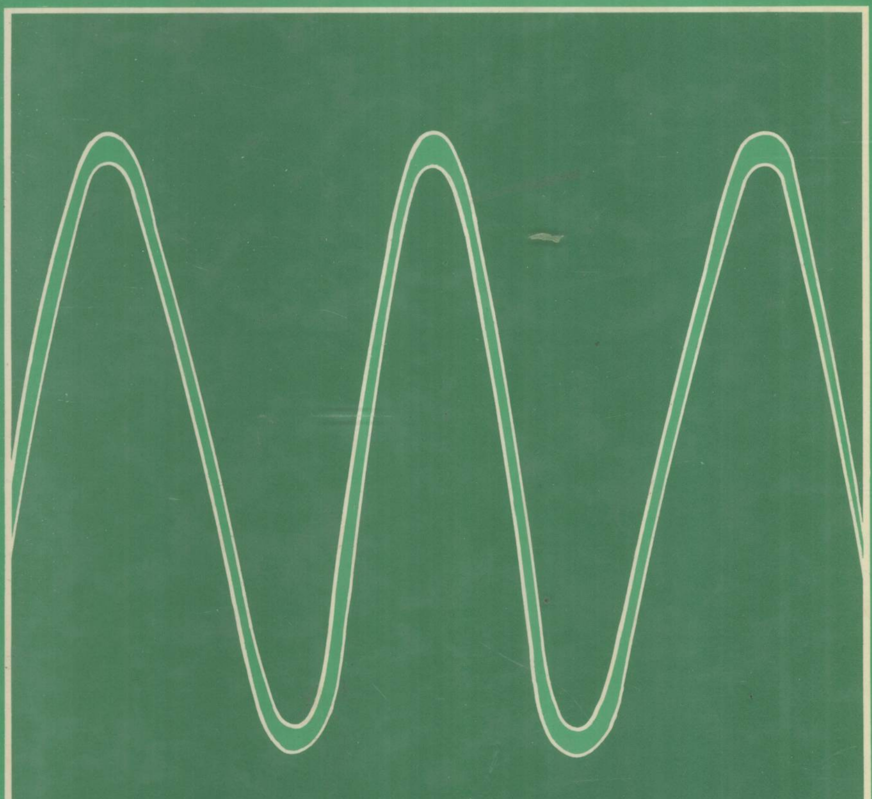
POWER SYSTEM HARMONICS



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Preface

While the behaviour of a power system at the main generated frequency is reasonably well understood, the presence of harmonic frequencies means different things to different people and very often doesn't mean anything at all!

Is it then necessary and possible to derive enough information of sufficient general interest and practical application at this stage?

Judging by the present activity of international committees and by the growing number of conferences and technical papers in the field of power system harmonics, a book on this subject is relevant and timely.

The selection of the main underlying concepts and generally accepted techniques would have been a subjective and difficult task for a single author. However, after many individual proposals by the three authors involved, a reasonably unified pattern has eventually emerged which will, we hope, satisfy the present needs of the professional engineers involved in power system planning and operation. The book should also stimulate teachers, researchers and students in the power system and power electronics disciplines.

As well as describing the main harmonic causes and effects, the book covers four areas dealing with analysis, instrumentation, penetration and elimination. The present philosophies used for the setting of harmonic standards and limitations are also discussed.

The vast amount of information used in the preparation of the manuscript makes it impossible to acknowledge them here individually; instead they will be referred to at the end of the chapters. However, we must single out the support and encouragement received from Professor J. K. Bargh, Head of the Department of Electrical and Electronic Engineering (University of Canterbury) and from New Zealand Electricity, especially from K. D. McCool (General Manager), P. S. Barnett, M. C. Underhill, P. J. Morfee, L. A. Wilson, P. R. Hyland and R. J. Simpson.

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1

Introduction

1.1 BACKGROUND

In an ideal electrical power system, energy is supplied at a single and constant frequency, and at specified voltage levels of constant magnitudes. However, none of these conditions are fulfilled in practice. The problem of voltage and frequency deviations, and the means of keeping them under control, are the subject matter of conventional power system analysis. The problem of waveform distortion, so far neglected in power system treatises, constitutes the basis of this book.

Power system distortion is not a new phenomenon, and containing it to acceptable proportions has been a concern of power engineers from the early days of alternating current. The recent growing concern for this problem results from the increasing numbers and power ratings of the highly non-linear power electronic devices used in the control of power apparatus and systems.

The deviation from perfect sinusoids is generally expressed in terms of harmonic components. In this introductory chapter we are setting the scene by briefly defining the nature of harmonics and their importance. Subsequent chapters will deal in detail with the harmonic causes, effects, monitoring and penetration. Some consideration will also be given to the setting of limits.

To put the subject in historical perspective, it is necessary to go back to the 18th and 19th centuries when various mathematicians, and in particular J. B. J. Fourier (1768–1830), set up the basis for harmonic calculations.

With reference to power system harmonics, it was largely in Germany in the 1920s and 1930s when the subject of waveform distortion caused by static convertors was developed. The most influential source of convertor theory published during that period in the English language is the book by Rissik.(1) A classical paper on harmonic generation by static convertors was written in 1945 by J. C. Read(2) and is still widely used by designers today.

During the 1950s and 1960s the study of convertor harmonics was advanced in the field of high voltage direct current transmission. During this period a large number of papers were published. These are summarized in a book by Kimbark(3) which contains over 60 references in the field of power system harmonics. In the past few years the subject has been regularly discussed at international meetings and extensive bibliographies are produced from time to time. The latest example is the IEEE Power System Harmonics Working Group Report.[4]

1.2 NATURE OF HARMONICS

The term 'harmonic' originates from acoustics, where it signifies the vibration of a string or column of air at a frequency which is a multiple of the basic repetition (or fundamental) frequency. Similarly with electrical signals, a harmonic is defined as the content of the signal whose frequency is an integer multiple of the actual system frequency, i.e. the main frequency produced by the generators.

When a complex signal is viewed in an oscilloscope its shape is observed in the time domain; that is, for any given instant in time, the amplitude of the waveform is displayed. If the same signal is applied to a hi-fi amplifier, then the ear hears the resultant sound as a mixture of frequencies; that is, it sounds like a full musical chord. The waveform may therefore be described by its time domain or its frequency domain data. The transfer between these two domains forms the basis of Chapter 2.

It must be made clear from the outset that such a transfer is only perfectly applicable when the distorted waveform is maintained for an infinite number of cycles. This is not the case in practice, where variations in loading conditions will alter the system harmonic content. However, this problem presents no difficulty provided that the condition to be analysed persists for a reasonable time. It is thus necessary to distinguish between a harmonic, where the waveshape remains unaltered, and a transient where there is significant cycle to cycle variation in the waveshape.

Finally the phase relationship of the harmonic to the fundamental frequency is significant in determining the waveshape. In acoustics it is generally accepted that the audible effect is not affected by such a phase relationship. This is not the case with electrical signals, where the position of the harmonic and the relative phase of the same harmonic from different sources may alter the overall effect considerably.

1.3 IMPORTANCE OF THE SUBJECT

As with many other forms of pollution the generation of harmonics affects the whole (electrical) environment and probably at much larger distances from its points of origin.

Perhaps the most obvious consequence of power system harmonics is the degradation of telephone communications caused by induced harmonic noise. However, there are other less audible, though often more disastrous, effects such as the maloperation of important control and protection equipment and the overloading of power apparatus and systems. Very often the existence of waveform pollution is only detected following expensive casualties (like the destruction of power factor correction capacitors). Moreover, in the absence of an electrical welfare state, the casualties have to be repaired or replaced, and the equipment protected by filters, at the customers' expense, even though such preventive measures provide a general environmental improvement.

In recent years there have been considerable developments in industrial processes that rely on controlled rectification for their operation, and therefore generate current harmonics. However, the design of such equipment generally assumes the existence of a voltage source free of harmonic distortion, a situation which only occurs if the power system supplying the equipment has a very low harmonic impedance. Consequently the smaller industrial users of electricity are being subjected to increasing difficulties caused by the interaction of their own control equipment with the power supply.

Electricity supply authorities normally abrogate responsibility on harmonic matters by introducing standards or recommendations for the limitation of voltage harmonic levels at the points of common coupling between consumers.

However, determining limits on harmonic levels is not a straightforward exercise. Current knowledge is not sufficiently advanced to ascertain the extent to which any given power system can sustain a level of harmonics and remain viable in terms of the functions that the system is required to perform. As most current knowledge of harmonics has stemmed from a background of events, the standards and limitations so far produced have reflected the results of past practical experience with the aim of preventing similar problems in the future. This subject is discussed in Chapter 8.

Until a reasonable understanding of the power system harmonic phenomena is reached, the electric supply industry will remain in a position of higher than acceptable risk of having to respond to problems after they have occurred.

Two major impediments to such understanding are the ability to make accurate measurements (discussed in Chapters 6 and 7) and the state of power supply models capable of in-depth analysis to the degree of complexity required (discussed in Chapter 9).

Concern for waveform distortion should be shared by all electrical engineers in order to establish the right balance between exercising control by distortion and keeping distortion under control. There is a need for early co-ordination of decisions between the interested parties, in order to achieve acceptable economical solutions. The basis for such acceptability must be discussed at the earliest possible stage between manufacturers, power supply and communications authorities.

In order to educate the profession in this respect the electrical engineering curricula should convey the necessary interdisciplinary message. In particular power systems educators should try to broaden their frequency spectrum and lose respect for the frequency domain. They should also clarify the fact that zero sequence and third harmonic are not necessarily the same thing, and that the power factor is not exclusively concerned with the main power frequency. Fourier analysis, and in particular the fast Fourier transform, should be discussed with relevance to power as well as communication waveforms. Finally the teaching of power electronics should give sufficient coverage to its negative contribution, i.e. the problem of waveform distortion.

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2

Harmonic analysis

2.1 INTRODUCTION

In 1822 the French mathematician Jean Babtiste Joseph Fourier (1768–1830) in his work *Theorie analytique de la chaleur*[1] postulated that any continuous function repetitive in an interval T can be represented by the summation of a fundamental sinusoidal component, with a series of higher order harmonic components at frequencies which are integer multiples of the fundamental frequency.

Harmonic analysis is the process of calculating the magnitudes and phases of the fundamental and higher order harmonics of the periodic waveform. The resulting series is known as the Fourier series and establishes a relationship between a time domain function and that function in the frequency domain.

The Fourier series of a general periodic waveform is derived in the first part of this chapter and its characteristics discussed with reference to simple waveforms.

More generally, the Fourier transform and its inverse are used to map any function in the interval from $-\infty$ to ∞, in either the time or frequency domain, into a continuous function in the inverse domain. The Fourier series therefore represents the special case of the Fourier transform applied to a periodic signal.

In practice, data is often available in the form of a sampled time function, represented by a time series of amplitudes, separated by fixed time intervals of limited duration. When dealing with such data a modification of the Fourier transform, the discrete Fourier transform, is used. The implementation of the discrete Fourier transform by means of the fast Fourier transform algorithms forms the basis of most modern spectral and harmonic analysis systems. The development of the Fourier and discrete Fourier transforms is also examined in this chapter along with the implementation of the fast Fourier transform.

2.2 BASIC CONCEPTS

Periodic functions[2]

A function $x(t)$ is said to be periodic if it is defined for all real t and if there is some positive number T such that

$$x(t+T) = x(t) \quad \text{for} \quad \text{all } t. \tag{2.2.1}$$

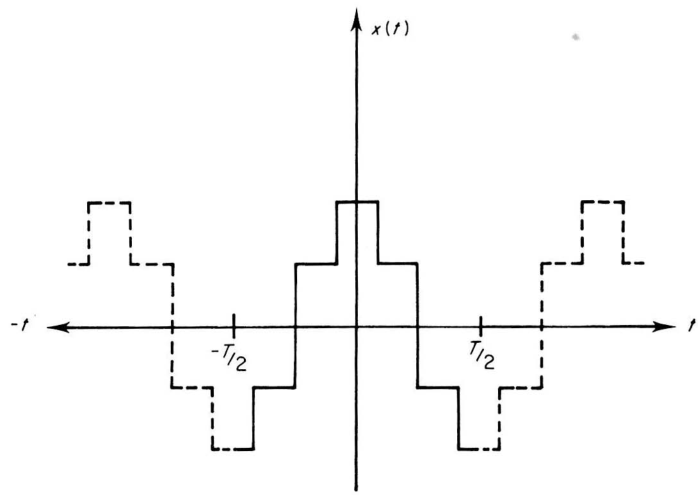

Figure 2.1. Periodic function

T is called the period of the function. Such a function can be represented by the periodic repetition of the waveform at intervals of T, as depicted in Figure 2.1.

If k is any integer then it follows that

$$x(t + kT) = x(t) \quad \text{for} \quad \text{all t.} \tag{2.2.2}$$

If two functions $x_1(t)$ and $x_2(t)$ have the same period T, then the function

$$x_3(t) = ax_1(t) + bx_2(t), \tag{2.2.3}$$

where a and b are constants, also has the period T.

It should be noted that the function

$$x(t) = \text{constant} \tag{2.2.4}$$

is also a periodic function in the sense of the definition, because it satisfies equation (2.2.2) for any positive period T.

Orthogonal functions[(2)]

Two non-zero functions $x_1(t)$ and $x_2(t)$ are considered orthogonal over an interval $T_1 \rightarrow T_2$ if

$$\int_{T_1}^{T_2} x_1(t)x_2(t)\mathrm{d}t = 0. \tag{2.2.5}$$

Furthermore, a set of r functions

$$\{x_1(t), x_2(t), \ldots, x_r(t)\}$$

form an orthogonal set over the interval $T_1 \to T_2$ if

$$\int_{T_1}^{T_2} x_i(t)x_j(t)\,dt = 0 \quad \text{for} \quad i = 1 \text{ to } r, j = 1 \text{ to } r, i \neq j. \tag{2.2.6}$$

2.3 FOURIER ANALYSIS

Fourier series and coefficients[2,3]

The Fourier series of a periodic function $x(t)$ has the expression

$$x(t) = a_0 + \sum_{n=1}^{\infty}\left(a_n \cos\left(\frac{2\pi nt}{T}\right) + b_n \sin\left(\frac{2\pi nt}{T}\right)\right). \tag{2.3.1}$$

This constitutes a frequency domain representation of the periodic function.

In this expression a_0 is the average value of the function $x(t)$, whilst a_n and b_n, the coefficients of the series, are the rectangular components of the nth harmonic. The corresponding nth harmonic vector is

$$A_n\underline{/\phi_n} = a_n + jb_n \tag{2.3.2}$$

with a magnitude

$$A_n = \sqrt{(a_n^2 + b_n^2)}$$

and a phase angle

$$\phi_n = \tan^{-1}\left(\frac{b_n}{a_n}\right).$$

For a given function $x(t)$, the constant coefficient, a_0, can be derived by integrating both sides of equation (2.3.1) from $-T/2$ to $T/2$ (over a period T), i.e.

$$\int_{-T/2}^{T/2} x(t)dt = \int_{-T/2}^{T/2}\left[a_0 + \sum_{n=1}^{\infty}\left[a_n\cos\left(\frac{2\pi nt}{T}\right) + b_n \sin\left(\frac{2\pi nt}{T}\right)\right]\right]dt. \tag{2.3.3}$$

The Fourier series of the right hand side can be integrated term by term, giving

$$\int_{-T/2}^{T/2} x(t)\,dt =$$

$$a_0\int_{-T2}^{T/2} dt + \sum_{n=1}^{\infty}\left[a_n\int_{-T/2}^{T/2}\cos\left(\frac{2\pi nt}{T}\right)dt + b_n\int_{-T/2}^{T/2}\sin\left(\frac{2\pi nt}{T}\right)dt\right]. \tag{2.3.4}$$

The first term on the right hand side equals Ta_0, while the other integrals are zero. Hence the constant coefficient of the Fourier series is given by

$$a_0 = \frac{1}{T}\int_{-T/2}^{T/2} x(t)dt, \tag{2.3.5}$$

which is the area under the curve of $x(t)$ from $-T/2$ to $T/2$, divided by the period of the waveform, T.