5

Harmonic Monitoring

5.1 Introduction

Harmonic monitoring involves the capturing and processing of voltage and current signals at various points of the power system. The signals to be captured are normally of high voltage and current levels, and thus require large transformation ratios before they can be processed by the instruments.

As an introduction to the subject, a summary of the harmonic measurement requirements specified by the IEC are considered first. This is followed by an assessment of the characteristics of conventional and special types of current and voltage transformers for use in harmonic measurements.

The transducers are normally placed in outdoor switchyards and the transformed low-level signals have to travel through a hostile electromagnetic environment before they reach the control rooms; thus the transmission of data in that environment also needs to be considered.

Once the captured signals reach the control room, the whole science of signal processing becomes available for the derivation of the harmonic spectrum. Chapter 2 has already described the main waveform processing techniques available with reference to the power system signals. The implementation of these techniques in modern digital instrumentation is also described in this chapter.

5.2 Measurement Requirements

5.2.1 The IEC 61000 4-7 Document [1]

Standard IEC 61000 4-7 describes the techniques for measuring harmonic distortion in the power system. For the purpose of formulating the requirements for measurement instruments the standard divides the harmonics broadly into three categories:

(1) quasi-stationary (slowly varying);
(2) fluctuating;
(3) rapidly changing (very short bursts of harmonics).

Power System Harmonics, Second Edition J. Arrillaga, N.R. Watson
© 2003 John Wiley & Sons, Ltd ISBN: 0-470-85129-5

The differing characteristics of the three categories of harmonics place different requirements on the design of the measuring instrument. For measuring quasi-stationary harmonics, there can be gaps between the rectangular observation window of 0.1–0.5 s wide. On the other hand, to access fluctuating harmonics, the rectangular window width has to be decreased to 0.32 s or a Hanning's window of 0.4–0.5 s width has to be used. Moreover, there should not be any gap between successive rectangular windows and there should be a half-by-half overlapping of the successive Hanning's window (described in Section 2.11.3). Lastly, rapidly changing harmonics have to be measured with a 0.08–0.16 s wide rectangular window without any gap between successive windows.

Instruments designed for measuring quasi-stationary harmonics are only appropriate to survey the long-term (such as thermal) effects of harmonics, or for the measurement of constant harmonic currents, such as those produced by television receivers. The measurement of fluctuating harmonic currents, such as those produced by motor reversal or speed change in household appliances with phase control and regulation, has to be made continuously without any gaps between successive observation intervals. Continuous real-time measurement capability is absolutely necessary for assessing the instantaneous effects of the rapidly changing harmonics, or short bursts of harmonics, on sensitive equipment such as electronic controls or ripple control receivers.

Measurements of up to the 50th harmonic order are commonly recommended but there are discussions on increasing it up to the 100th in certain cases. With such large amounts of data to be recorded, statistical evaluation over different observation intervals can be used to compress the data. Five time intervals are recommended in this standard:

(1) Very short interval (T_{vs}): 3 s

(2) Short interval (T_{sh}): 10 min

(3) Long interval (T_{L}): 1 h

(4) One-day interval (T_{D}): 24 h

(5) One-week interval (T_{W}): 7 d

If instantaneous effects are considered important, the maximum value of each harmonic should be recorded and the cumulative probability (at least 95% and 99%) of these maxima should be calculated. On the other hand, if long-term thermal effects are considered, the maximum of the r.m.s. value at each harmonic and its cumulative probabilities (at 1%, 10%, 50%, 90%, 95% and 99%) are to be calculated and recorded, i.e.

$$C_{n,rms} = \sqrt{\frac{\left(\sum_{k=1}^{M} C_{n,k}^2\right)}{M}} \tag{5.1}$$

where all the M single calculated values C_n shall be determined over the time interval T_{vs} for selectable individual harmonics (preferably up to $n = 50$).

5.2.2 Inter-Harmonics

IEC 61000 4-7 also contains a small subsection on inter-harmonics as a broad extension of harmonic phenomena. However, it leaves several important issues unresolved, and recommends that issues such as the range of frequencies to be considered and the centre frequency should be selected in accordance with the studied phenomenon, e.g. their influence on ripple control receivers or on flicker.

A study report prepared by a joint IEEE/CIGRE/CIRED working group on inter-harmonics [2] identifies the main problem associated with measurement of inter-harmonics as being that a waveform consisting of two or more non-harmonically related frequencies may not be periodic. Hence, most power system monitoring equipment, which is based on the FFT, will encounter errors due to the end-effect. This effect can be minimised by the signal processing techniques commonly used in the communication and broadcast industries, whereby the sampling of the signal need not be synchronised to the power frequency. The use of proper windowing functions and application of zero padding before performing the FFT can improve the frequency resolution of the measured inter-harmonic magnitudes significantly. For instance, the Hanning window with four-fold of zero padding technique [2] should also be suitable for measuring inter-harmonics in power systems.

The type of inter-harmonic measurement to be used also depends on the purpose of the assessment. Purposes include the diagnosis of a specific problem, general survey of an electromagnetic environment, compatibility testing and compliance monitoring. The IEC proposes to fix the sampling interval of the waveform to 10 and 12 cycles for 50 Hz and 60 Hz systems, resulting in a fixed set of spectra with 5 Hz resolution, for harmonic and inter-harmonic evaluation. The sampling will be phase-locked to the mains frequency, thereby minimising the contamination of the harmonic components by the inter-harmonic components. However, recent indications are that the IEC will opt to simplify the assessment process by summing the components between harmonics into one single inter-harmonic group, and reserving the original method of showing all inter-harmonic components at 5 Hz steps for specific cases. The frequency bins directly adjacent to the harmonic bins are omitted.

$$X_{IH}^2 = \sum_{i=2}^{8} X_{10n+i}^2 \quad \text{(50 Hz system)} \tag{5.2}$$

$$X_{IH}^2 = \sum_{i=2}^{10} X_{12n+i}^2 \quad \text{(60 Hz system)} \tag{5.3}$$

where n is the inter-harmonic group of interest and i is the inter-harmonic bin being summed.

Similarly, distortion indices equivalent to those for harmonics can be defined for inter-harmonics. The corresponding total inter-harmonic distortion (TIHD) factor is

$$\text{TIHD} = \frac{\sqrt{\sum_{i=1}^{n} V_i^2}}{V_1} \tag{5.4}$$

where i is the total number of inter-harmonics considered and n is the total number of frequency bins present including subharmonics (i.e. inter-harmonic frequencies that are less than the fundamental frequency). If the subharmonics are important, they can be analysed separately as another index called appropriately the total subharmonic distortion (TSHD).

$$\mathrm{TSHD} = \frac{\sqrt{\sum_{s=1}^{S} V_s^2}}{V_1} \tag{5.5}$$

where S is the total number of frequency bins present below the fundamental frequency. Other distortion factors and statistical evaluation of harmonics can also be applied for the assessment of inter-harmonics in power systems.

5.2.3 Harmonic Phase-Angle Displacement

The measurement of phase angles between harmonic voltages and currents, together with their amplitudes, is required for the following purposes:

(1) to evaluate harmonic flows throughout the system;
(2) to identify harmonic sources and harmonic sinks;
(3) to assess summation factors of harmonic currents from different disturbing loads if they are connected to the same node;
(4) to establish system-equivalent circuits for calculating the impact of new disturbing loads, or the effectiveness of the countermeasures such as filters.

The direction of the active power flow at the harmonic order of interest can help to identify the source of the disturbance. To find the direction of the active power flow, the phase angle between the harmonic voltage at the point of common coupling and the plant feeder current has to be measured. If the active power flows into the public system, the plant is a harmonic source; otherwise it is a sink of harmonic currents from the system. The phase-lag of harmonic voltage and current in relation to the fundamental (absolute phase angle) need not be known in this case. Such absolute phase angle is only needed for evaluating the coupling between frequencies of nonlinear loads. However, the measurement of absolute phase angles provides the following additional advantages:

(1) Measurements at different nodes of similar or different systems can be compared.
(2) It becomes possible to deduce whether the connection or rearrangement of different systems, or locally spread disturbing loads, will increase or decrease the harmonic level in the system. Harmonic distortions with similar phase angles will superimpose, raising the harmonic level, while those with opposite phase angles will compensate each other, thereby lowering the harmonic level.
(3) Phase angles of disturbing loads, especially from rectifier circuits without firing control, can be detected in order to evaluate their overall disturbing effect or to find countermeasures.

Extra care is needed in operating the measuring instrument and in interpreting the results, when precise synchronisation across multiple channels is required to measure absolute phase angles.

5.2.4 Harmonic Symmetrical Components

If the loads and transmission and distribution systems are balanced, the three voltages and currents have identical wave shape and are separated by exactly $\pm\frac{1}{3}$ of the fundamental period. In such case, only characteristic harmonics exist: these are of zero sequence for orders $n = 3m(m = 1, 2, 3\ldots)$, of positive sequence for the $n = 3m - 2$ orders, and of negative sequence for the $n = 3m - 1$ orders. However, asymmetries always exists, causing non-characteristic harmonics in the system. These asymmetries can be evaluated by monitoring the symmetrical components of the harmonics.

Positive-sequence (or negative-sequence) impedances differ from zero-sequence impedances for nearly all loads and network equipment including transmission lines, cables and transformers. Therefore, a separate treatment of the system is necessary for assessing the harmonic voltages caused by the injected currents. Secondly, the effect of each sequence component differs for most loads and network equipment. Zero-sequence voltages do not affect delta-connected loads such as motors and capacitor banks. Only the non-characteristic components (positive sequence or negative sequence) of the third harmonic voltages cause additional losses in delta-connected motors. Moreover, commonly used transformers with delta–star or star–zigzag winding connections do not transfer zero-sequence currents and voltages.

5.3 Transducers

The function of a current or voltage transformer is to provide a replica of the power system current or voltage, at a level compatible with the operation of the instrumentation, in circumstances where direct connection is not possible.

While the behaviour of the conventional current and voltage transformers at fundamental frequency is well understood and defined, the behaviour at higher frequencies has not been as fully examined. With the need to measure power system harmonic content, their performance in transforming current and voltage signals containing harmonic components is essential to the measurement process.

Although the frequency response of a transducer may be poor, it can still be used for harmonic measurements if such a response is known and compensated for at the front end of the measuring instrument.

In line with the accuracy requirements suggested for instrumentation, the IEC 61000-4-7 standard indicates that the errors of voltage and current transformers shall not exceed 5% (related to the measured value) in magnitude and 5° in phase angle.

5.3.1 Current Transformers

The most common type of current transformer is the toroidally-wound transformer with a ferromagnetic core. This has, by virtue of its construction, low values of primary and secondary leakage inductance and primary winding resistance. Under normal operating conditions, the transformer primary current will be substantially less than that required for saturation of the core, and operation will be on the nominally linear portion of the magnetisation characteristic.

The frequency response of current transformers is effectively determined by the capacitance present in the transformer and its relationship with the transformer inductance. This capacitance may be present as inter-turn, inter-winding or stray capacitance. Test have shown that while this capacitance can have a significant effect on the high-frequency response, the effect on frequencies to the 50th harmonic is negligible [3,4].

In addition to harmonic frequencies, it is also possible that the primary current will contain a d.c. component. If present, this d.c. component will not be transformed but will cause the core flux of the transformer to become offset. A similar condition could arise from remnant flux present in the transformer core as a result of switching.

For this reason, where the presence of a d.c. component is suspected, or remanence a possibility, a current transformer with an air gap in the core can be used. This air gap reduces the effect of the d.c. component by increasing core reluctance and enables linearity to be maintained. Because the current transformer burden tends to increase with frequency, the associated power factor reduces with increasing frequency and the transformer will produce a higher harmonic output voltage than it would for a purely resistive load. The resulting increased magnetising current will cause further error.

For measurements of harmonic currents in the frequency range up to 10 kHz, the normal current transformers that are used for switchgear metering and relaying have accuracies of better than 3%. If the current transformer burden is inductive, there will be a small phase shift in the current. Clamp-on current transformers are also available to give an output signal that can be fed directly into an instrument.

The following practical recommendations are worth observing whenever possible:

(1) If the current transformer is a multi-secondary type, the highest ratio should be used. Higher ratios require lower magnetising current and tend to be more accurate.
(2) The current transformer burden should be of very low impedance, to reduce the required current transformer voltage and, consequently, the magnetising current.
(3) The burden power factor should be maximised to prevent its impedance from rising with frequency and causing increased magnetising current errors.
(4) Whenever possible, it is suggested that the secondary of the measuring current transformer is short-circuited and the secondary current monitored with a precision clamp-on current transformer.

Unconventional Types of Current Transformer [5] Various alternatives to the conventional current transformer have been investigated, some of which are already finding a place in power system monitoring. Among them are:

- *Search coils.* The magnetic field in the proximity of a conductor or coil carries information on the components of the current which generates the field. The amplitude of the induced harmonic voltage in a search coil is proportional to the effective coil area, number of turns, the amplitude of the harmonic magnetic field perpendicular to the coil surface and the frequency of the harmonics.

In such measurements, the measured magnetic field can arise from the contributions of more than one source. The magnetic field is inversely proportional to the distance from the source. Where it is possible to place the search coil at a small distance d from the conductor, while other conductors are located at distances larger than $20d$, the measurements of values in the chosen conductor are not substantially changed by fields of the other conductors.

- *Rogowski coils.* These devices are coils wound on flexible plastic mandrels, and they can be used as clamp-on devices. They have no metallic core, so problems of core saturation are avoided in the presence of very large currents, such as the 60–100 kA in the feed to an arc furnace or in the presence of direct current.
- *Passive systems.* In a passive system, a transmitted signal is modulated by a transducer mounted at the conductor. No power source is required at the conductor. Optical systems use the Faraday magneto-optic effect, by which the plane of polarisation of a beam of linear polarised light is rotated by a magnetic field along its axis.

  Designs for Faraday effect current transformers use either the open-path or the closed-path optical system [6].

  Microwave systems make use of gyromagnetic materials to modulate a microwave carrier by a magnetic field. The form of modulation is controlled by the arrangement of the gyromagnetic material and the form of polarisation of the microwave signal.
- *Active systems.* An active system uses a conductor-mounted transducer to provide a modulating signal for a carrier generated at the conductor. Transmission of the carrier to the receiving station is then achieved via a radio or fibre-optic link. The power for the transmitter is usually line derived using a magnetic current transformer together with some battery back-up.
- *Hall effect transducers.* The Hall effect is used in a variety of probes and transducers covering a range of current levels. For current transformer applications, a major problem is that of maintaining calibration over long periods.

5.3.2 Voltage Transformers

Only on low-voltage systems can the analyser be connected directly to the terminals where the voltage components must be determined. On medium- and high-voltage systems, means of voltage transformation are required.

Magnetic voltage transformers, of extensive use for medium voltage levels, are designed to operate at fundamental frequency. Harmonic frequency resonance between winding inductances and capacitances can cause large ratio and phase errors. For voltages to about 11 kV, and harmonics of frequencies under 5 kHz, the accuracy of most potential transformers is within 3%, which is satisfactory, the response being dependent upon the burden used with the transformer [7].

At higher voltage levels, the transformer tends to exhibit resonances at lower frequencies, as the internal capacitance and inductance values vary with insulation requirements

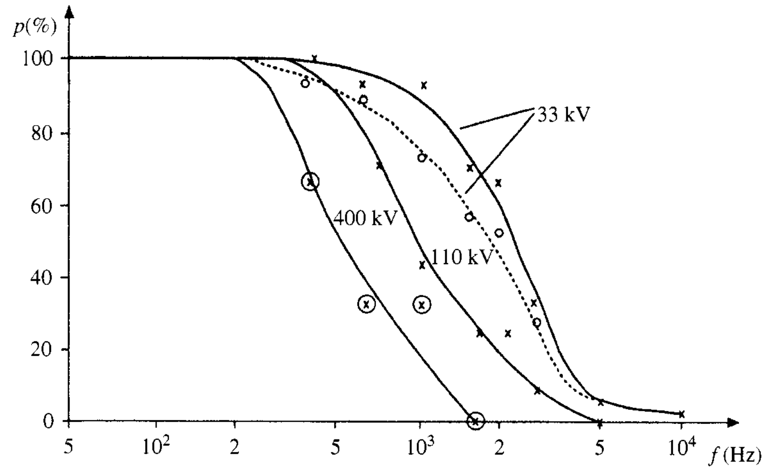

Figure 5.1 Percentage of voltage transformers, the transfer ratio of which has a maximum deviation (from the nominal value) of less than 5% or 5° up to the frequency f. (———) minimum error (5%); (- - - -) maximum error (5%)

and construction. The precise response for a particular unit will be a function of its construction [8].

Figure 5.1 contains test results carried out in over 40 voltage transformers at levels between 6 kV and 400 kV. The figure indicates the percentage of transformers that maintained the required precision (i.e. 5% and 5°) throughout the frequency range. The main conclusions are:

- At medium voltage, all the transformers perform adequately up to 1 kHz, while only 60% of them manage to cover the whole harmonic spectrum. The figures reduce further, to 700 Hz and 50% respectively, when the phase precision level requirement is included.
- At high voltage, the transformers' response deteriorates quickly for frequencies above 500 Hz unless special designs are introduced.
- The conventional voltage transformers of magnetic type do not provide accurate information for harmonic orders above the 5th.

Capacitive Voltage Transformer The capacitive voltage transformer (CVT) combines a capacitive potential divider with a magnetic voltage transformer, as shown in Figure 5.2. This combination enables the insulation requirements of the magnetic unit to be reduced, with an associated saving in cost.

The additional capacitance provided by the capacitive divider will influence the frequency response of the CVT, producing resonant frequencies as low as 200 Hz, which makes them unsuitable for harmonic measurements.

The form of frequency response obtained is also dependent upon the magnitude of the fundamental component and its relationship to any transition point in the magnetisation characteristic of the transformer steel.

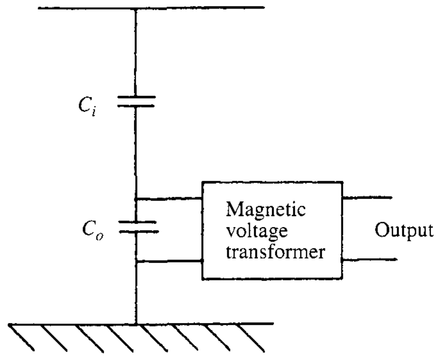

Figure 5.2 Capacitive voltage transformer (CVT)

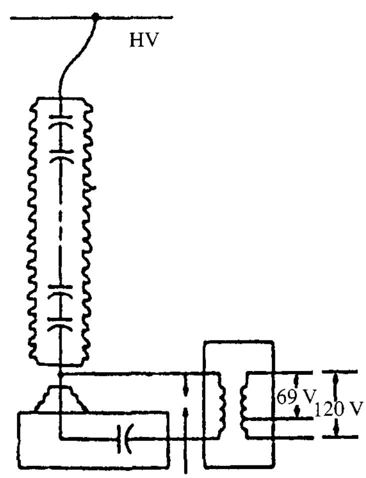

Figure 5.3 Capacitive voltage divider using a bushing tap

Capacitive Dividers For harmonics measurements, either a purpose-built divider could be assembled or, alternatively, use could be made of the divider unit of a capacitive voltage transformer, with the magnetic unit disconnected, or the loss tangent tap on an insulating bushing (Figure 5.3).

When subject to an impulse, such as might arise from local switching, the capacitive divider is subject to *ringing* due to the interaction between the divider capacitors and their internal inductances. This can lead to high common mode voltages, particularly in areas of high earth impedances. To minimise ringing, the capacitors forming the divider circuit should have a low inductance and the low-voltage capacitor should be screened.

In recent years, a number of amplifier-based capacitive divider systems have been developed [9,10]. Although intended primarily for use with high-speed protection schemes, they also have obvious application in harmonic measurements.

The basic arrangement for a single-phase unit is shown in Figure 5.4. High-input impedance instrumentation amplifiers must be included in such measurements. For best

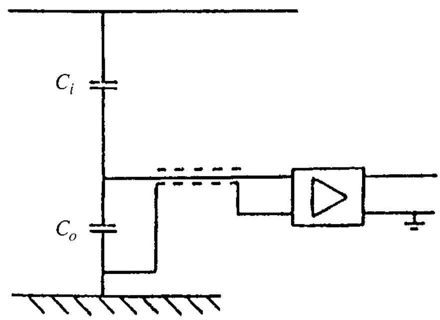

Figure 5.4 Capacitive voltage divider incorporating an amplifying circuit

results, the input amplifier should either be battery operated or use a suitably shielded and isolated supply. The leads from the low-voltage capacitors to the input amplifier should be as short as possible. In general, short leads from the amplifier to the analyser will greatly reduce the angle error when measuring phase angles. These devices have a limit on the burden that they can supply without saturation, hence the requirement for a high-impedance amplifier.

Unconventional Voltage Transformers [5] Electro-optical and electrogyration effects can be used to measure voltage in a manner akin to the Faraday effect used for current measurement.

The electro-optical effect causes linearly polarised light passing through the material to become elliptically polarised. As the two mutually perpendicular components propagate in the crystal at different velocities, they have a difference in phase as they emerge from the material. This phase difference will be proportional to the path length in the material and to either the field (the Pockels effect) or the square of the field (the Kerr effect). By measuring this phase difference, the electric field strength, and hence the voltage, can be obtained.

If a linearly polarised beam is propagated through an electrogyrational material in an electric field, the effect is to rotate the plane of polarisation in a manner analogous to that occurring in magneto-optic materials. The electrogyration effect can, therefore, be used to measure voltage in a manner similar to the Faraday effect current transformers.

5.4 Harmonic Instrumentation

The derivation of voltage and current harmonics is carried out in instrumentation systems that receive the line signals in the time domain and convert them into the frequency domain. The main purposes of a harmonic monitoring system are:

- capturing existing levels of harmonic distortion to check them against recommended or admissible limits;
- testing equipment that generates or causes harmonics in order to ensure its compliance to certain standards or guidelines;

- diagnosing or troubleshooting a situation in which some equipment performance is unacceptable to the utility or to the user;
- observing existing background levels and tracking the trends with time for any hourly, daily, weekly, monthly or seasonal patterns;
- verifying simulation studies or techniques and fine-tuning the modelling of the devices and the system under analysis;
- determining the driving point impedance at a given location. This impedance is useful for gauging the system capability to withstand power quality disturbances.

Monitoring background levels will require the system to be operated continuously over a long period of time and the measured data will have to be stored. The stored data may comprise the average, maximum and minimum values over predetermined intervals so as to provide an overall picture of the phenomenon. On the other hand, the testing of equipment simply requires the use of snapshots under certain operating modes. The captured data most likely will consist of several cycles of the time-domain waveforms, which can be further processed to extract the necessary information.

Some commercial instruments have been specifically designed for power systems use (e.g. harmonic analysers) while others are of more general use (signal analysers). The main difference between these two categories is the need to follow the variations in fundamental frequency in the case of harmonic analysis.

Portable instruments are of small size and lightweight, easy to set up and use in the field. The transducers (clip-on type) and interconnecting cable normally are part of the unit. They normally use microprocessor based circuitry to calculate the individual harmonics up to the 50th, as well as their r.m.s., THD and TIF indices. Some of these devices can also calculate harmonic powers and can upload stored waveforms and calculated data to a PC. Generally, the logging feature allows periodic downloading of the instrument readings to a PC through an RS323 interface.

To reduce cost, portable instruments are normally restricted to one or two channels. Battery operating is essential for usage flexibility without dependence on external wires and power supplies, particularly as the instrument has to be close to the measurement point due to the length of the clip-on cable. Generally, these instruments are not automated and therefore they need a person controlling their operation, although some now have a logging feature. The operator must control the transducer locations, what quantity is displayed, and the storing of data to memory or downloading to PC. The capabilities of these instruments are restricted to the features originally designed into the unit and cannot be changed. Therefore, upgrades are achieved by buying a newer model.

For permanent or semi-permanent monitoring, the instruments require many channels as they are intended to operate without human intervention and, generally, the channels are not designed to be moved from one location to another. Transducers do not come as part of these instruments, as it is assumed that the CTs or VTs already existing in the system will be used. Due to the high cost of such hardware, the functionality is designed into the software to permit upgrades. As some of the measuring points are likely to be in outdoor switchyards, the cables and transducers must be designed to withstand all weather conditions and operate satisfactorily in a hostile electromagnetic environment.

These instruments operate unattended over long periods and software is thus required to automate the data collection, processing and storage. Such instrumentation is normally required at a multitude of sites, therefore synchronisation and the ability to control them all from a central location are important features.

The processing of the waveforms can be carried out in analogue or digital form, although the latter has practically displaced the analogue-type analysers. Analogue instrumentation is based on the use of an adjustable filter which can be tuned to specific frequencies (heterodyne system) or a bank of filters, each of which detects a particular harmonic. The characteristics and implementation of the digital instrumentation are discussed in the following section.

5.4.1 Digital Instrumentation

As shown in Figure 5.5, A/D converters change the analogue signals into digital form as required by digital instruments; these signals are then processed by digital filters or the FFT.

Some digital analysers still use the digital filtering, method, which, in principle, is similar to analogue filtering. Before starting a series of measurements, the range of frequencies to be observed must be defined and this information selects the required digital filters. At the same time, the bandwidth is varied to optimise the capture of all the selected harmonics in the presence of a large fundamental frequency signal. All the recent instruments, however, use the FFT (described in Chapter 2), a very fast method of analysis that permits capturing several signals simultaneously via multi-channel instruments.

Generally, digital instruments use microprocessors for the processing of the signals and co-ordination of their functions. Some instruments include a PC with a data acquisition card that collects the voltage and current signals from the transducers; the PC contains a microprocessor that calculates the harmonic levels, a hard disk for data storage and a screen for the visual display of the results.

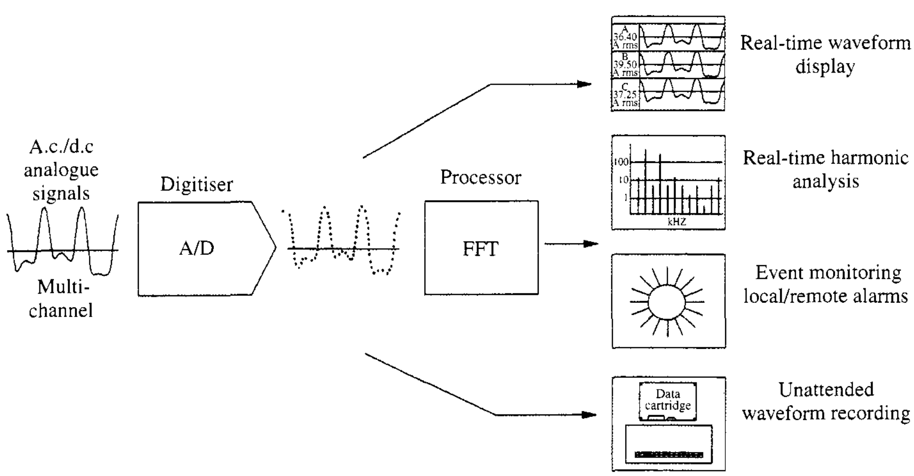

Figure 5.5 Components of a multiwave monitoring system (from Electric Research and Management Inc.)

The main components of an FFT-based instrument are illustrated in Figure 5.6. First, the signal is subjected to low-pass filtering to eliminate all the frequencies above the spectrum of interest; this is normally limited to orders below the 50th. Once filtered, the analogue signal is sampled, converted to digital and stored. The FFT is then applied to the 2^i samples included in a period T_w multiple of the fundamental wave period, i.e. $T_w = NT_1$, the sampling frequency being $f_s = 2^i/(NT_1)$.

To reduce spectral leakage, the samples contained in T_w are sometimes multiplied by a window function as described in Chapter 2.

The FFT process derives the Fourier coefficients a_k and b_k of frequencies $f_x = k(1/T_w)$ for $k = 0, 1, 2, \ldots 2^{i-1}$ and with adequate synchronisation the nth harmonic of the fundamental frequency is given by $n = k/N$.

Finally, an arithmetic processor calculates the harmonic amplitudes

$$C_n = \sqrt{a_n^2 + b_n^2} \tag{5.6}$$

and phases

$$\varphi_n = \arctan\left(\frac{b_n}{a_n}\right) \tag{5.7}$$

An FFT computation can be undertaken for each fundamental cycle, producing a set of harmonics every cycle, or several cycles of samples can be joined together before using a longer FFT to achieve better frequency resolution.

The frequency resolution of the FFT is given by the reciprocal of the record length

$$\Delta f = \frac{1}{T_0}$$

Hence to resolve harmonic values, separated by 50 Hz or 60 Hz, the record length must be one period of the fundamental frequency (20 ms or 16.7 ms). An FFT output bin is not, however, an impulse function centred on a particular harmonic. Instead, it has a non-zero response to frequencies between harmonics. This means that signals

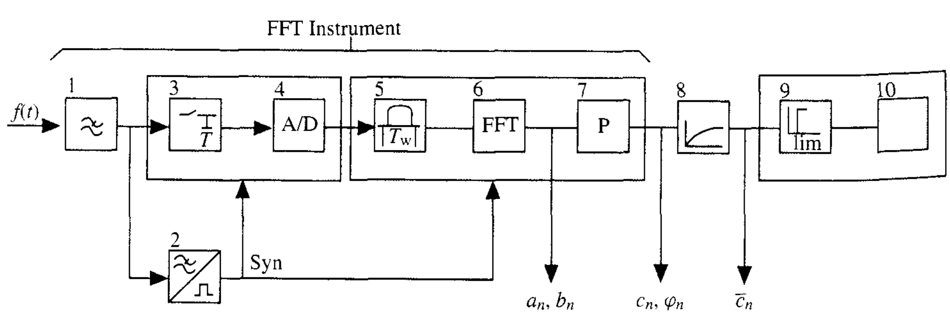

Figure 5.6 An FFT-based instrument 1, anti-aliasing low pass filter; 2, synchronisation; 3, sample and hold; 4, analogue/digital converter; 5, shape of window unit; 6, FFT processor; 7, arithmetic processor; 8, unit for evaluation of transitory harmonics; 9, programmable classifier; 10, counter and storage unit

present in the signal to be transformed, which are not harmonics, will contribute to particular harmonic outputs from the FFT, making them erroneous. The severity of this problem can be reduced by taking the FFT over longer time spans, thereby resolving inter-harmonic frequencies which would otherwise contribute to harmonic outputs. This does, however, require more data processing. In harmonic analysis this is seen as a disadvantage because only harmonics are required—as opposed to a spectrum analyser, which is required to have a very good resolution.

It is possible to achieve the same effect of taking the FFT over several periods by averaging several periods to one and computing the FFT of that, provided that sampling is synchronous with the fundamental. This preserves the bandwidth of the FFT with only a small processing overhead. It must be noted that if subharmonics are required, averaging is not suitable. Instead, the FFT must be taken over multiple cycles to produce the sub-multiples of the 50 Hz or 60 Hz fundamentals.

A modern monitoring system is divided into the three subsystems shown in Figure 5.7.

(1) *Input signal conditioning and acquisition subsystem.* The function of this unit is the conversion of analogue signals into digital formats. This digitisation simplifies the design of analogue circuitry and provides greater flexibility for altering the algorithms to be used for processing the data samples. The main factors to be considered in the design of this unit are:
   — the sampling rates, which for harmonic analysis are in the kHz range;
   — an anti-aliasing filtering, to be determined by the bandwidth of the signal to be measured;
   — provision of immunity to EMI susceptibility to the extremely noisy power system electromagnetic environment;
   — synchronisation and timing (when multiple channels are used);
   — automatic ranging, as the current can vary significantly between light and heavy loading conditions (this ensures that the full dynamic range is used).

(2) *Digital processing and storage subsystem.* Digital samples are transferred to this subsystem for processing and recording. This subsystem can simply be a data logger or a powerful parallel processing computer system. Generally, it is the design of this subsystem that determines if continuous real-time data acquisition is possible or only snapshots can be captured and stored for offline processing. The special requirements to achieve continuous real-time data acquisition are discussed in Section 5.4.2.

(3) *User interface subsystem.* The purpose of this unit is to provide users with access to the measured data, either through on-screen displays or in hard-copy forms. It also provides the users with the ability to control and configure the monitoring system. The basic requirement on this subsystem is to hide the complicated

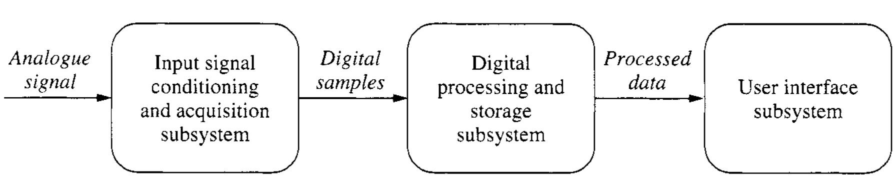

Figure 5.7 Major subsystems making up a monitoring system

details of the monitoring system from the users. A graphical user interface forms the essential 'face', representing the monitoring system, to the user.

5.4.2 Structure of a Modern Monitoring System

Ideally, the harmonic assessment should be carried out continuously over a wide bandwidth and with good resolution, usually at multiple nodes of the power network. Furthermore, in order to capture the very low magnitude higher-order harmonics in the presence of the large fundamental component, an adequate analogue to digital conversion resolution is required.

Most existing instruments are not equipped with the capability of synchronising the acquisition of data samples across multiple channels and between multiple instruments and/or nodes on a power network. Consequently, the steady-state assumption is again taken as implicit when snapshots, gathered at different parts of a power system network, are used alongside each other in order to make simultaneous power quality assessment of the system.

The need to know the precise state of the system at all times is particularly important when endeavouring to locate the distorting sources. This requires good magnitude and phase measurements, often at more than one location on the network and preferably synchronised.

Most existing data acquisition systems use the centralised processing architecture shown in Figure 5.8, which places a constraint on the data processing capability of the system. From the harmonic monitoring perspective, this limited real-time processing capacity results in offline post-processing of the acquired data to derive the necessary information. The lack of online analysis processing capability results in large volumes of raw data having to be acquired and stored. Consequently, the limited system throughput, bandwidth and storage volumes only allow the system to record snapshots.

The centralised configuration relies on the outputs of the CTs and VTs being directly routed to the metering room. Although this configuration is normally sufficient for relay operation or metering purposes, the limited bandwidth and EMI susceptibility of the long analogue communication links create serious concerns over the integrity of the measurements.

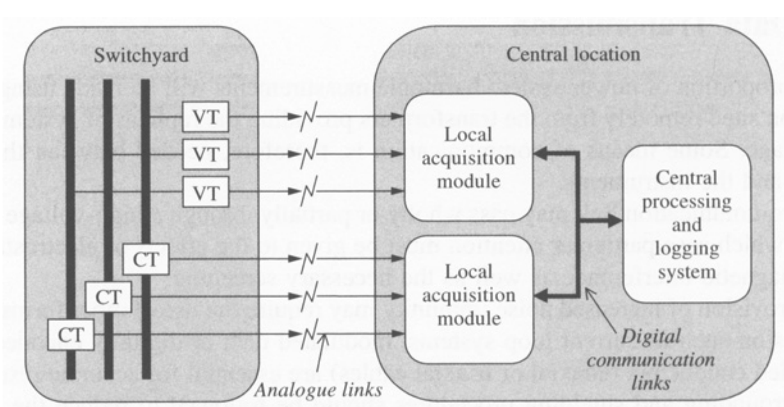

Figure 5.8 Conventional centralised processing architecture

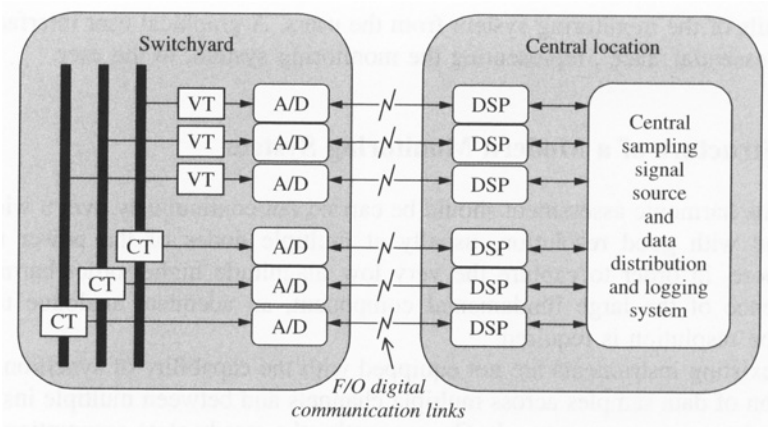

Figure 5.9 A possible distributed processing architecture

Therefore, some form of distributed processing architecture is preferred, such as shown in Figure 5.9. In this configuration the A/D conversion is shifted from the central location to the switchyard close to the transducers. This enables the use of digital communication links between the switchyard and the central system, thus improving the bandwidth, dynamic range and noise immunity of the acquired signals. The use of a fibre optic link reduces the system's susceptibility to electromagnetic noise, which can be significant in a switchyard environment. The second key element is the provision of a digital signal processor (DSP) to undertake the data processing for each individual channel. By dedicating a single DSP (or CPU) to every data channel, computationally intensive manipulations can be implemented online [11].

A centralised source of sampling signals provides the opportunity to synchronise the sampling across all data channels. The DSP usually communicates with the central data collection system through multi-processing bus architectures. This enables the DSP modules to be designed as plug-in cards, facilitating flexible expansion.

Sampling synchronisation between units at different sites can be achieved using GPS-generated timing signals.

5.5 Data Transmission

A high proportion of power system harmonic measurements will be made using instrumentation sited remotely from the transformers providing the replicas of system current and voltage. Some means of communication is, therefore, needed between the transformers and the instruments.

This communication link may pass wholly or partially through a high-voltage switchyard, in which case particular attention must be given to the effects of electrostatic and electromagnetic interference as well as the necessary screening.

The provision of increased noise immunity may require the use of other forms of data transmission such as current loop systems, modulated data or digitally encoded data.

Shielded conductors (coaxial or triaxial cables) are essential for accurate results, but proper grounding and shielding procedures should be followed to reduce the pick-up of parasitic voltages. Moreover, coaxial cable is only suitable for relatively short leads.

Where high common-mode voltages can occur, the communications link may be required to provide insulation up to several kilovolts to protect both users and equipment. This may require the use of isolation amplifiers or, where higher levels of isolation are required, fibre-optic links.

Information may be transmitted either as an analogue signal for direct connection of the instrument, or in a modulated or encoded form using both analogue and digital data systems. If direct analogue transmission is used, then a system of sufficiently high signal to noise ratio is obviously required. For certain harmonic measurements, a dynamic range of the order of 70 dB may well be needed and, hence, the achievable signal to noise ratio must be in excess of this figure.

5.6 Presentation of Harmonic Information

Figure 5.10 illustrates the capturing and transmission of information from the high-voltage network and its presentation in visual form by means of oscilloscopes and harmonic analysers. The former permit observing the time variation of the voltage and current waveforms, while the latter show their respective spectra.

The analogue-type analysers require minutes of processing time to gather the harmonic information and produce either graphs (as shown in Figure 5.11) or tables (e.g. the information corresponding to the graph of Figure 5.11 is shown in Table 5.1). The discrete measurement at widely separate times can lead to substantial interpretation errors. For instance, with reference to Figure 5.12, where the harmonic level varies with time, if the harmonic measurement is registered every 12 minutes as shown, the results will be very misleading.

When using digital systems the problem changes from one of insufficient data to one of extracting relevant information from the vast amount of recorder data. The captured information is often recorded for later offline processing.

As well as time-varying information (shown in Figure 5.12), it is possible to derive cumulative probability graphs (Figure 5.13) or histograms (Figure 5.14).

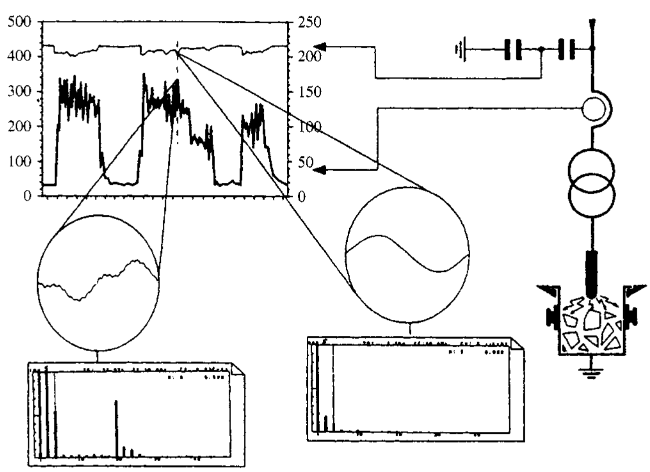

Figure 5.10 Captured and transmitted information from the grid

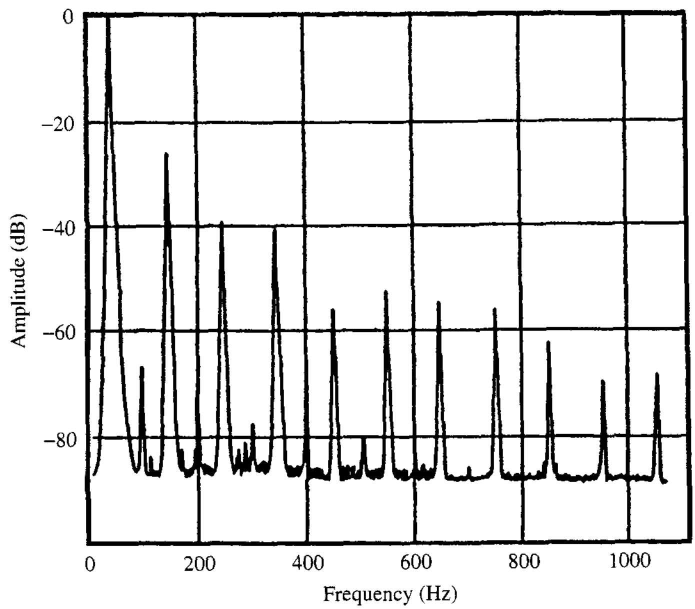

Figure 5.11 Typical harmonic plot from an analogue analyser

Table 5.1 Tabulated information corresponding to the plot in Figure 5.11

Frequency (Hz)	Amplitude (V)
50	240
100	0.1
150	12
200	0.1
250	2.7
300	0.0
350	2.1
400	0.0
450	0.3
500	0.0
550	0.6
600	0.0
650	0.4
700	0.0
750	0.3
800	0.0
850	0.2
900	0.0
950	0.1
1000	0.0

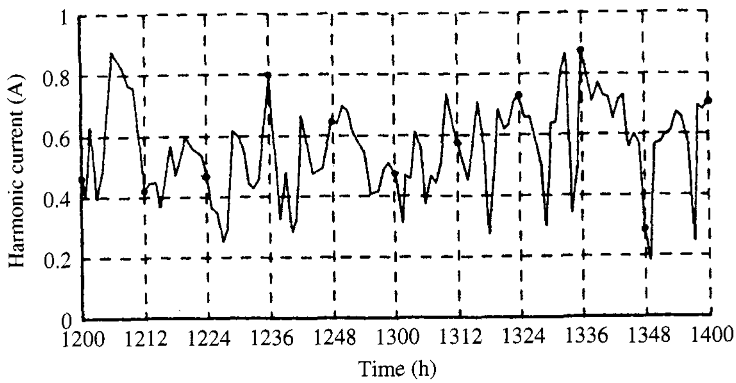

Figure 5.12 Recording of a current harmonic sampled at 12-minute intervals

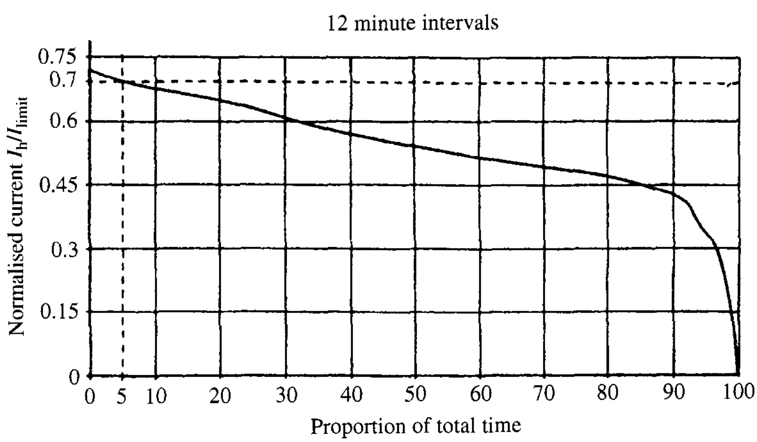

Figure 5.13 Cumulative probability graph

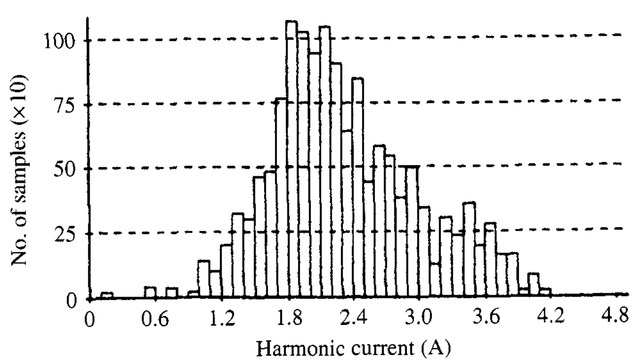

Figure 5.14 Histogram of harmonic amplitudes

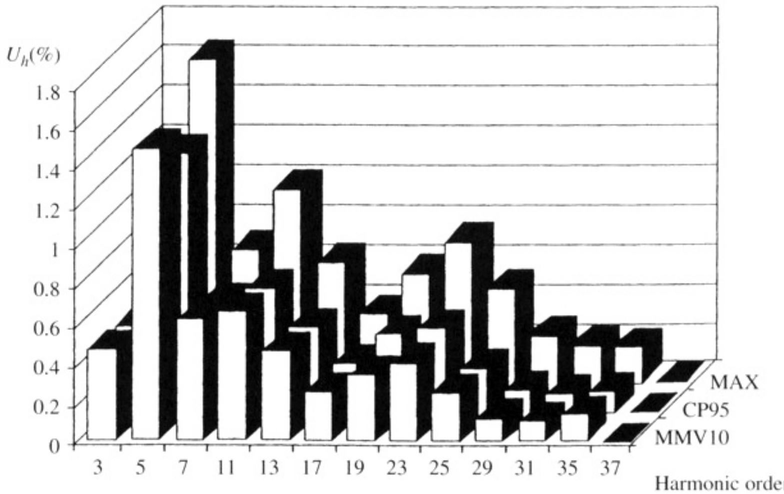

Figure 5.15 Levels of harmonic distortion not exceeded by 80% of the observation points

Another example of data presentation, shown in Figure 5.15, relates to the recommendation from a joint CIGRE/CIRED based on the IEC directives [1]. In this case the measurement at each observation point extends to several days (including the weekend), and for each harmonic and day the maximum value (MAX) the value not to be exceeded with a 95% probability (CP95) and the mean maximum value at 10-minute intervals (MMV10) are retained.

5.7 Examples of Application

This section reports on field measurements carried out in the New Zealand power system to illustrate the use and capability of modern digital instrumentation. The instrument used was CHART (Continuous Harmonic Analysis in Real Time) [11].

5.7.1 Synchronised Tests

Figure 5.16 shows the 220 kV network of New Zealand's South Island system. Between the Islington and North Makawera substations, there are a number of hydro stations and a HVd.c. scheme. The distribution network at Islington had reported a substantial amount of 5th harmonic distortion caused by the presence of a large number of industrial sites connected to this bus. The 5th harmonic current is largely absorbed by the compensation capacitors at the Islington substation. However, the capacitors are usually removed from service during light load conditions, causing the 5th harmonic current to flow into the 220 kV transmission system. On the other hand, at North Makawera, the opposite effect had been observed, with the 5th harmonic current flowing from the 220 kV transmission network into the distribution system. The main consumer of electrical power fed by the North Makawera substation is an aluminium smelter at the Tiwai bus. A recently installed 5th harmonic filter at Tiwai was

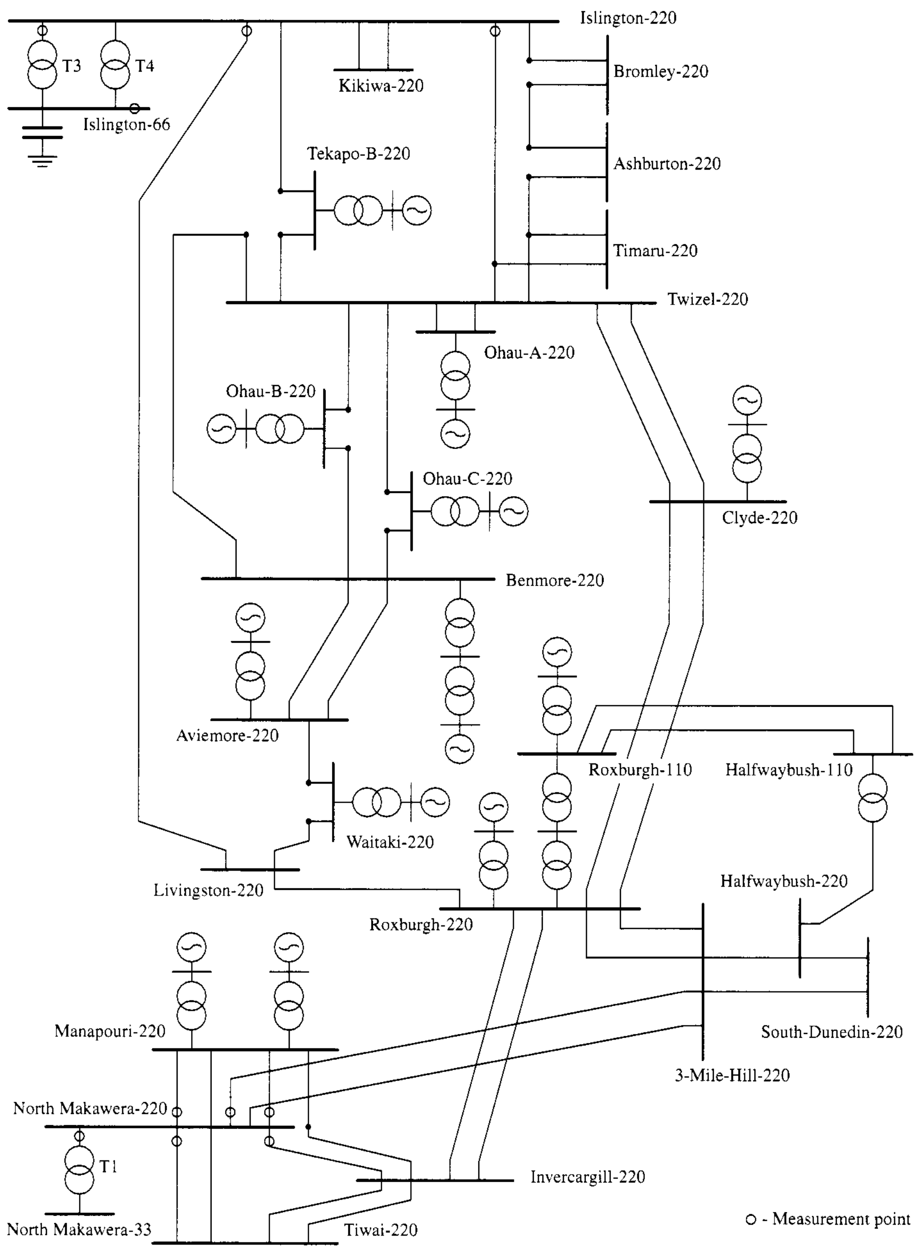

Figure 5.16 CHART measurement points in the synchronised test

frequently overloaded and the source of the 5th harmonic current distortion was traced to the 220 kV transmission system.

The first objective of the test was to decide whether there was any connection between the 5th harmonic problems at the Islington and North Makawera substations. If the two problems were related, the response of the 5th harmonic distortion at North

Makawera to the switching of capacitors at Islington was to be identified. This required that the measurements undertaken at both sites should be synchronised as accurately as possible. The 5th harmonic problems at both substations were known to vary with the daily operation of the South Island system. Therefore, the monitoring systems had to gather harmonic information over a fairly long period, covering a variety of operating conditions. CHART units were installed at the North Makawera and Islington substations (shown in Figure 5.17), to monitor the currents flowing between the 220 kV transmission system and the substations.

At Islington, the two transmission lines considered to have the lowest impedance between the substation and the generating stations around Benmore were the Islington–Livingston and Islington–Timaru–Twizel lines. The three phases on these two

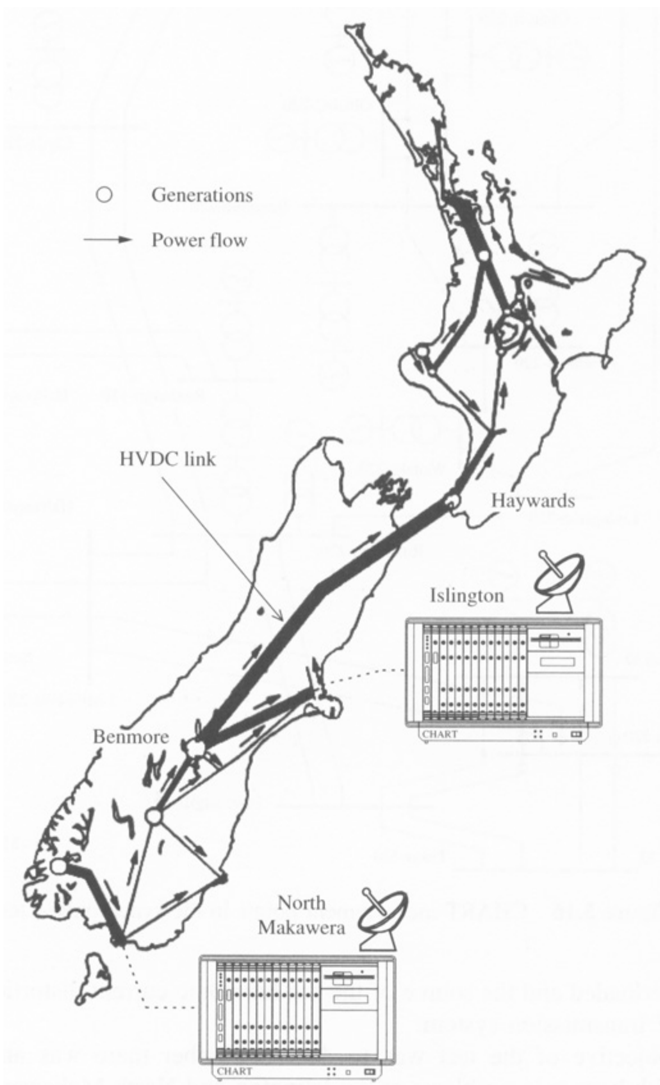

Figure 5.17 Location of CHART units in the synchronised test

circuits were therefore measured. Besides measurements on the 220 kV system, the voltage distortion on the 66 kV bus was also monitored. The CHART unit was also set up to record the current of one of the transformers (T3) interconnecting the 66 kV distribution network and the 220 kV transmission network.

At North Makawera, the main flow of power is between the generation at Manapouri and an aluminium smelter at Tiwai. The CHART unit was set up to monitor the current between these two places and the North Makawera substation. The connections from North Makawera to the rest of the 220 kV network were also monitored by measuring the current between North Makawera and 3-Mile Hill, and between North Makawera and Invercargill. Moreover, the current of transformer T1 feeding the 33 kV distribution network at North Makawera was monitored to determine if there is any 5th harmonic source within the local load. The voltage distortion on the 33 kV distribution busbar was also recorded. However, due to the limited number of channels available on this particular CHART unit (12 channels), it was necessary to forgo some of the phases at several measurement points.

The main requirement of this test was to record the harmonic distortion at both substation simultaneously. The data samples were time-stamped to enable them to be matched in time. It was decided to average the harmonics over one second and to compute the mean, maximum and minimum harmonics over a minute throughout the entire measurement.

The measured fundamental frequencies at Islington and North Makawera are shown in Figure 5.18. The fundamental frequencies are identical at both sites with similar deviations throughout the measurements. This ensured that the sampling processes were synchronised between the two CHART units.

A selection of acquired data is shown in Figure 5.19. A number of steps are observed on the 66 kV bus voltage which may be caused by the switching of the compensation capacitors. However, only three of these show concurrent changes in the 5th harmonic current flowing out of the Islington substation. The three cases are highlighted in the figure together with the possible capacitor switching instants. The currents in the

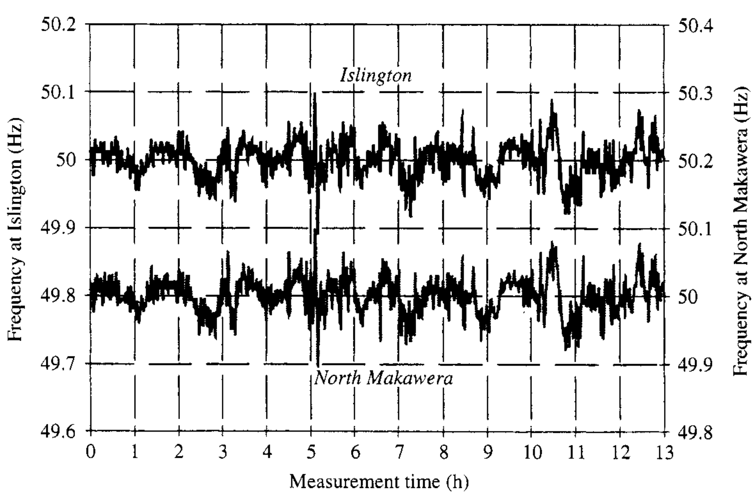

Figure 5.18 Fundamental frequency measured at Islington and North Makawera

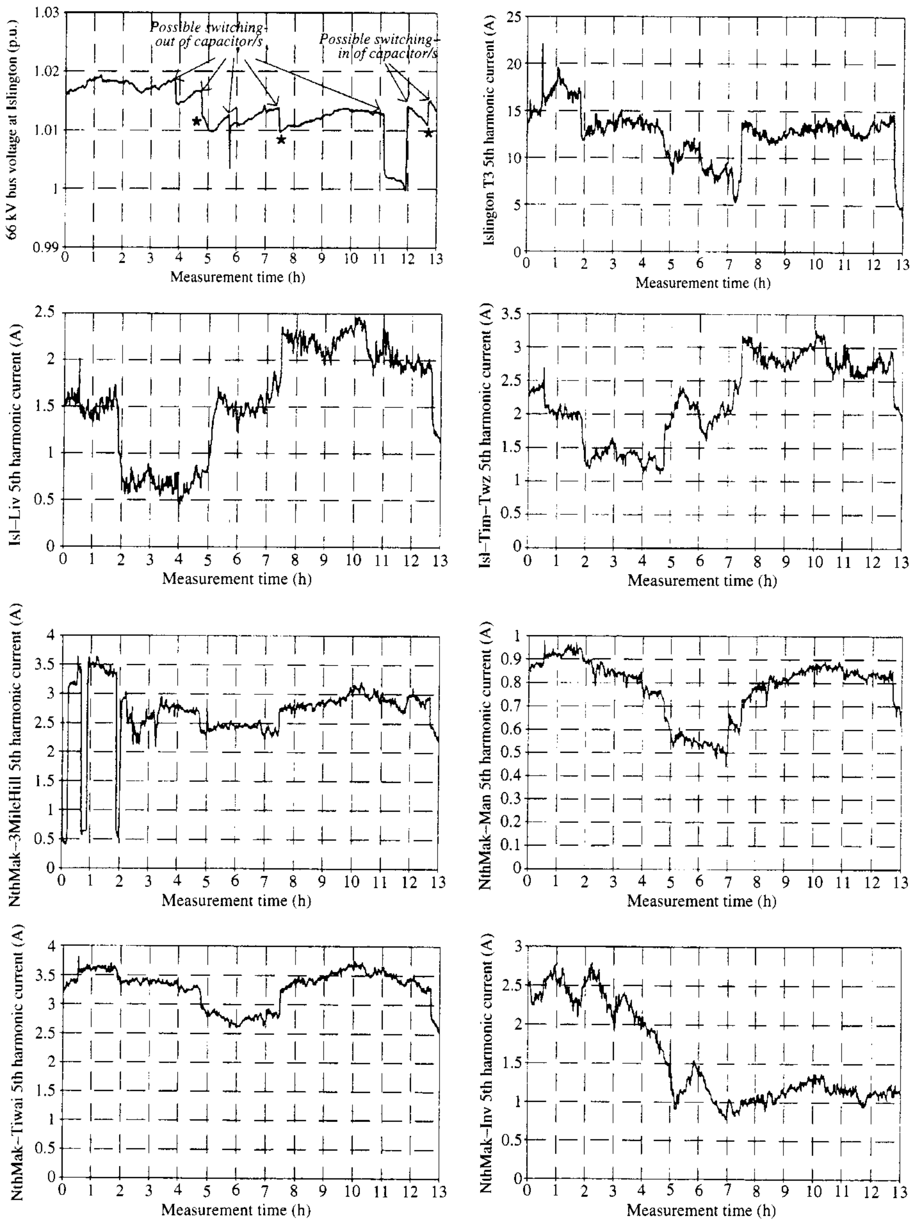

Figure 5.19 Selection of data acquired in the South Island synchronised test

two transmission lines, Islington–Livingston and Islington–Timaru–Twizel, show an increase in the 5th harmonic current when the capacitors are switched out. A decrease in the 5th harmonic current is also observed when the capacitor is switched back into service towards the end of the test.

The variations in the 5th harmonic current at North Makawera do not always correspond with the changes at Islington. Among the three aforementioned instants when there are changes to the 5th harmonic current flowing out of Islington, only the last two show corresponding changes in the distortion at North Makawera. At the second highlighted switching just after the 7th hour, when one of the capacitors is removed from service, the sudden increase in the 5th harmonic currents in the two outgoing lines from Islington coincides with similar increases in the lines between 3-Mile Hill, North Makawera and Tiwai. Similar coincidence is observed when one of the capacitors is put back into service near the end of the test. The decrease in the 5th harmonic current flowing out from the Islington 220 kV system coincides with the decreases in the 5th harmonic distortion around North Makawera.

These observations indicate that under certain operating conditions, the switching of capacitors at Islington substation can affect the 5th harmonic distortions at North Makawera. However, more detailed analyses of the system, in particular during the period when the measurement was carried out, will be required to finalise the above findings.

5.7.2 Group-Connected HVD.C. Converter Test

During a maintenance period at the Benmore HVd.c. converter station, the opportunity arose to test the possibility of operating the converter plant in the group-connection mode, i.e. islanded from the South Island a.c. network; as the filters are connected on the a.c. side of the converter transformers, the generators were subjected to greater harmonic distortion than under the normal configuration. Moreover, the fundamental frequency of the islanded network could deviate from the nominal 50 Hz depending on the d.c. load and the amount of generation.

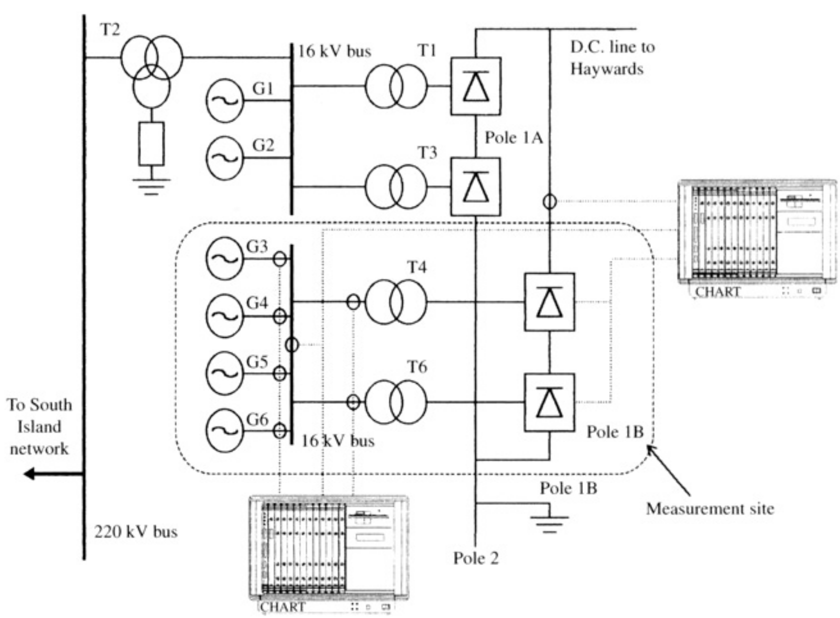

Figure 5.20 CHART measurement points in the Benmore test

Besides capturing the waveforms needed for validation of computer models, this test provided the opportunity to illustrate some of the capabilities of the digital instrumentation. These include the ability to perform alternative data processing tasks, the transparent handling of the different data formats of results from the tests, the ability to track the varying fundamental frequency in the islanded a.c. system and its use to ensure coherent sampling.

Figure 5.20 shows the islanded system at the Benmore converter station. Two CHART units were used to provide a total of 24 data channels. The measurements include the voltage at the 16 kV bus, generator currents, converter transformer currents, Pole 1B

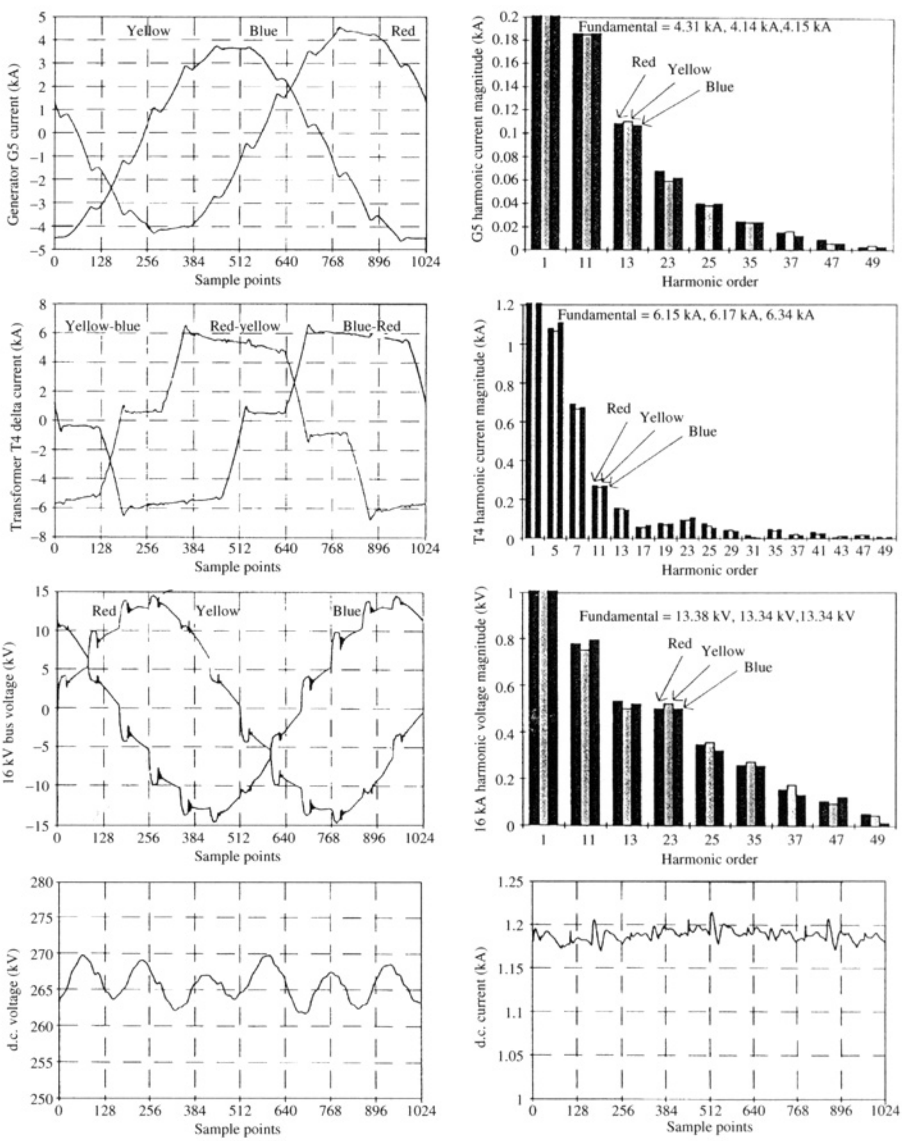

Figure 5.21 Selection of data acquired in the Benmore islanded converter test

d.c. line voltage and current, and the firing angle of the Pole 1B converter. The main task of the test system was to capture the time domain waveforms under different d.c. current and a.c. generation configurations. It was decided to capture two different forms of time-domain data, a small number of samples per fundamental cycle over a longer period for steady-state analysis and a handful of cycles of data with a higher sampling rate. A selection of data acquired during the islanded converter test at Benmore is shown in Figure 5.21.

5.8 Discussion

The main components of power system waveform monitoring, i.e. transducers and instrumentation, have been critically reviewed for their ability to transfer harmonic information. Adequate technology is now available for the transfer of voltage and current information and for their processing. The main limitation for reliable monitoring is its dependence on expensive high-voltage transducers; these are relatively few in number and primarily designed to obtain fundamental frequency related information. The inadequacy relates particularly to the use of capacitor voltage transformers.

A number of alternatives to improve the transducers' response at harmonic frequencies have been described in the literature and some of them are now produced by the industry. However, despite their limitations for harmonic monitoring, conventional CTs and CVTs are still the preferred options for general power system use. A possible solution is the re-calibration of the transducers' performance at the specified harmonic frequencies.

As the most popular technique, the chapter has discussed the FFT implementation of digital processing. Hardware and software system requirements have been described, both for single point and system-wide assessment, the latter requiring perfect sampling synchronisation at geographically separated buses. Examples of local and system-wide field test monitoring, using advanced digital instrumentation, have been included to illustrate their capability in the real environment.

5.9 References

1. IEC 61000-4-7 (1991), Electromagnetic Compatibility (EMC), Part 4: Limits, Section 7: General guide on harmonics and inter-harmonics measurements and instrumentation, for power supply systems and equipment connected thereto.
2. IEEE Inter-harmonic Task Force, CIGRE 36.05/CIRED 2 CC02 Voltage Quality Working Group, Inter-harmonics in Power Systems, January 1997.
3. Douglass, D.A. (1981) Current transformer accuracy with asymmetric and high frequency fault currents, *IEEE Trans.*, **PAS-100**, 1006–12.
4. Malewski, R. and Douville, J. (1976) Measuring properties of voltage and current transformers for the higher harmonics frequencies, Paper presented at the Canadian Communication and Power Conference, Montreal.
5. Mouton, L., Stalewski, A. and Bullo, P. (1978) Non-conventional current and voltage transformers, *Electra*, **59**, 91–122.
6. Rogers, A.J. (1979) Optical measurement of current and voltage on power system, *IEE Conf. Publ.* **174**, 22–6.

7. Douglass, D.A. (1981) Potential transformer accuracy at 60 Hz voltages above and below rating and at frequencies about 60 Hz, *IEEE Trans.*, **PAS-100**, 1370–75.
8. CIGRE Working Group 36-05 (Disturbing loads) (1981) Harmonics characteristics parameters, methods of study, estimating of existing values in the network, *Electra*, **77**, 35–54.
9. Lisser, J. (1976) High accuracy with amplifier type voltage transformer, *Electrical Review*, **198**(21), 31–33.
10. Gray, F.M., Hughes, M.A. and Stalewski, A. (1975) Monitoring of transmission line voltage for protective relaying purposes using capacitive dividers, *IEE Conf. Publ.*, **125**, 214–21.
11. Miller, A.J.V., Lake, C.B. and Dewe, M.B. (1990) Multichannel real-time harmonic analysis using the Intel Multibus II bus architecture, *Proc of the 7th International Intel Real-Time Users Group Conference*, St Louis, Missouri, October, pp. 11–24.