Applications of signal processing tools in a power systems course

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Abstract The scope of a modern electrical engineering curriculum presents a challenging problem. It is quite difficult to design a well rounded and all-encompassing curriculum in a rapidly evolving field such as electrical engineering. In this paper, signal processing tools are presented that allow the student to see immediately the advantages and limitations of these techniques for electric power 'quality'. Three signal processing techniques are considered: discrete Fourier transforms, wavelet filters, and discrete short-time Fourier transforms. The paper explains how the course material and teaching style respond to various requirements for an integrated design experience.

Keywords harmonics; power engineering education; power quality

The electric power industry is undergoing a major change, both technically and politically. To prepare future engineers for the challenges they will face, educators must upgrade the power engineering curriculum to reflect changing trends in the industry. One way to respond to the needs of industry is to introduce engineering students to technologically current approaches while students are still in the classroom setting. This may be accomplished by combining traditional and new material.

Electric power quality can be loosely defined as a measure of how well electric power service can be utilized by customers.[1–6] When wave shapes are irregular, voltage is poorly regulated, harmonics and flicker are present, or there are momentary events that distort the usually sinusoidal wave, and power utilization is degraded. One refers to these conditions as degradation of power quality.

The subject of power quality engineering truly encompasses most areas of electric power engineering, from generation to utilization, and power quality engineering has been a topic of interest from the inception of the power engineering field. Some contemporary factors have made it the subject of more focused interest, however. The advent and widespread use of high-power semiconductor switches at utilization, distribution, and transmission levels has made non-sinusoidal load currents more common. Deregulation of the power industry has made power quality a distinguishing feature of distribution service. Losses in transmission and distribution systems have come under greater scrutiny in recent years, and certain types of power quality degradation result in losses. For all these reasons, electric power quality has become an important topic in power engineering.

At the graduate level, research needs, more advanced application areas, and university hiring have added impact the doctoral programme. At master level, there is a special need in the electric power quality area: this is a subject that relates to maintaining sinusoidal voltage wave shape at all load buses. Increasing reliability and selling power quality related services, such as unbundled services, are specialized niche needs in industry. Equipment manufacturers have also entered the commercial sector in the marketing of new power system components for power quality enhancement. Power quality has special importance in an educational programme because it teaches modelling and interactions of large-scale systems. Measurement and instrumentation also come into play. Power quality issues are relatively new in power education programmes because of commercial interest in these areas and because the advent of high power electronic switched loads has resulted in power quality degradation in some cases.

The role of modeling in power quality assessment and analysis is crucial. For this reason, modelling is one focus of graduate level power quality courses. Overall, the power quality course brings together several areas and disciplines in a way that is informative and motivational to students.

A key element of modemization is the use of computer programs, similar to those used by industry. Available programs include: PSCAD, MATLAB, Electromagnetic Transients Program (EMTP), and TOP. They are user friendly and need only a PC. The TOP program is freeware (http://www.pqsoft.com/top/) allowing students to study and to experiment outside the university teaching laboratories.

Signal processing tools

In signal processing, the time-frequency domain has often been exploited to analyse signals with fast-changing spectral contents. Wavelet analysis[7–9] can be used for similar purposes, and has been exploited recently for several types of voltage and current disturbances[10–15] and for power system protection.[16] Several possible power system applications for wavelet analysis have been proposed: automated disturbance classification;[13] recognition using a wavelet-based neural classifier;[10] propagation of power system transients;[13] detection of faults;[16,17] and visualization of time-varying harmonics.[18] The stated advantage of using wavelets compared to Fourier transforms[19–21] is the tradeoff between frequency and time resolution at different frequencies.

The wavelet transform has received a lot of attention in the literature, at the expense of the short-time Fourier transform (STFT). The advantage of the latter is its ease of interpretation. Power engineers are used to thinking in terms of sinusoidal signals and the STFT fits closest to this. Most of the results obtained using wavelets can equally well be obtained using STFT.

When using wavelet transforms it is often difficult to extract the fundamental or any other single harmonic component of the signal. For an analysis tool to become widely accepted in power system engineering, it is important that it enables analysis in terms of harmonic signals. This paper shows how the spectral contents as a function of time can be obtained by using the STFT.[22,23] Although the STFT has a fixed frequency resolution for all frequencies once the size of the window is chosen, it enables easier interpretation in terms of harmonics.

Studies of power quality phenomena have emerged as an important subject in recent years due to renewed interest in improving the quality of the electricity supply. As sensitive electronic equipment continues to proliferate, power quality will be further emphasized. The identifying features are derived from well-documented theories,[2,21,24–26] power engineers' heuristics gained through long years of experience, and power quality data collected in recent years.

Power quality disturbances

Modem adjustable speed drives (ASD) employ power electronic devices to generate the variable frequency power supply for AC motor speed control, and harmonics are produced in the process.[27] It has commonly been assumed that an ASD can be modelled as harmonic current sources.

An ASD consists of a rectifier, a direct current link, and an inverter.[28] There are two mechanisms through which an ASD generates harmonic currents. The first mechanism is the rectifier operation, which injects harmonic currents into the supply system by an electronic switching process. The second mechanism is the inverter operation. The inverter can introduce additional ripple into the DC link current. This ripple in tum can penetrate to the supply system side. The extent and frequency of inverter-caused ripple are largely a function of inverter design and motor parameters. An ASD can therefore be represented by a generic three-phase bridge converter circuit. A feature of this circuit is that the inverter and motor are collectively modelled as a current source. The magnitudes and phase angles should be determined from the inverter design and motor operating conditions.

Capacitor energising transient events are one of the most common transient events present in power systems. These transient events occur when a capacitor is switched on. At the switching instant, a fast change in the bus voltage occurs because the voltage in the capacitor cannot change instantaneously. The transient frequency is determined by the combination of the capacitance of the capacitor bank and the system inductance. The oscillation in the voltage waveform lasts for less than half a cycle of the power frequency.

There are several kinds of capacitor energising event: normal energising, back-to-back energising, and restrike on capacitor opening events.

We shall present normal energising. Energisation of utility capacitors is a daily operation in the utility system. They are switched into the system in anticipation of load increase at a customer site, to correct power factor, to support voltage on the system, and so on. This energisation of utility capacitors is considered normal energising. The following are the identifying features of normal capacitor switching.

Overvoltage: At the switching instant, the voltage in the capacitor cannot change instantaneously. The bus voltage is pulled down, and then rises as the capacitor begins to charge. During the process, the capacitor voltage may overshoot and ring at the natural frequency. The overvoltage in normal energising is usually between 1.1 and 1.4 p.u.

Polarity and magnitude of step voltage: One of the most common identifying features of normal energising of utility capacitors is the 'polarity' of the step voltage. If the power quality monitor is located at or near capacitors that have no series reactor, a fast initial voltage step will be observed. The voltage step at the instant of closing cannot go beyond zero if the capacitor has no initial net charge at the closing instant or if the capacitor is grounded. If the power quality monitor is located farther away from the capacitor, the voltage step change may not be observed, or at least it is not as prominent. In any event, sudden changes of voltage never cross the zero line, i.e. they do not change polarity. This behaviour is exhibited in nearly all normal energising of utility capacitors.

Oscillation frequency of the phase voltage during the energising event: The oscillation frequency of the phase voltage during any kind of capacitor energising is generally between 300 and 1000 Hz. Thus, the frequency of oscillation is helpful in identifying capacitor energising in general, but it cannot be used to discriminate normal energising from other types of capacitor energising. Extracting the oscillation frequency from the capacitor energising transients is difficult.

Manified transient voltages: Energising a shunt capacitor from a predominantly inductive source creates an oscillatory transient voltage that can approach twice the normal peak voltage. This energising transient is important because it can excite an *LC* circuit, resulting in magnified transient voltages at remote locations. When customers apply low voltage capacitors for power factor correction, significantly higher transient voltage magnitudes can occur at the low voltage bus. ASDs that have large capacitors in the DC link to supply voltage source inverters are particularly sensitive to these capacitor switching transients. There are two reasons for this sensitivity:

1. The DC capacitors form part of an *LC* circuit (with the inductance between the drive and the switched capacitor) that can be excited by the capacitor switching transient. The result is a significant current surge into the DC capacitor, increasing the voltage on the DC link.
2. The drive controls are very sensitive to overvoltages on the DC link. In order to protect the DC capacitor and inverter components, controls are usually set to trip whenever the DC link voltage exceeds approximately 1.2 times the normal DC voltage.

The result is that small ASDs often trip when utilities switch capacitors on the primary distribution system.

Case studies

Two case studies are presented. For the purpose of harmonics education, an ASD with a six-pulse converter is designed and implemented to simulate a nonlinear load. In EMTP this can be done using MODELS. The simulation examples presented are based on the EMTP.

Case 1

This case is tested on a system consists of 13 buses and is representative of a medium-sized industrial plant.[29] The system is shown in Fig. 1, and shows normal energising of the utility capacitor, with the switching instant at 133 ms.

The limitations of the DFT for non-periodic signals can be illustrated using a signal containing a transient impulse; such a signal is typical of a capacitor

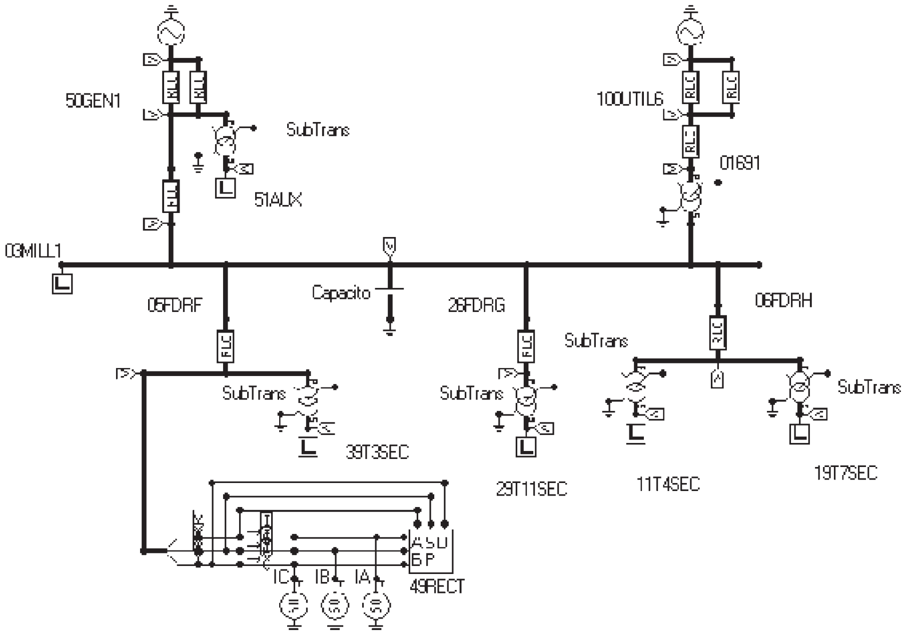

Fig. 1 *Medium-sized industrial plant.*

switching transient. The waveforms are shown in Figs 2 and 3 and the resulting DFT outputs are depicted in Figs 4 and 5. These figures were obtained using TOP.[30]

Figures 6 and 7 show two examples in which discrete STFT is used to obtain pseudo-harmonic signals. Figures 6 and 7 are associated with a high-frequency-resolution and a high-time-resolution case, respectively. Since the product of time and frequency resolution remains a constant according to the Heisenberg-Gabor uncertainty principle,[8]

$$\Delta f \cdot \Delta t \geq 1/4\pi \tag{1}$$

High frequency resolution implies a low time resolution, and vice versa.

Figure 6 shows the output from STFT, with the size of the Hamming window $L = 256$ corresponding to a higher resolution in the frequency domain. The window size of one cycle restricts time resolution to within one cycle. This value was chosen experimentally because it presents good frequency resolution. The sampling frequency was set at 4 kHz, which satisfies the Nyquist limit. High frequency resolution harmonic signals may provide useful information for analysing power system harmonics. A larger harmonic component is represented by a brighter area.

In Figure 7 the Hamming window size is $L = 16$, containing only a quartercycle of the signal, resulting in a higher time resolution. The sampling frequency was set at 13.5 kHz. Each filter output contains a large number of harmonic frequencies, which is not very useful for harmonic-related analysis. However, this output is useful to detect transient changes in a signal.

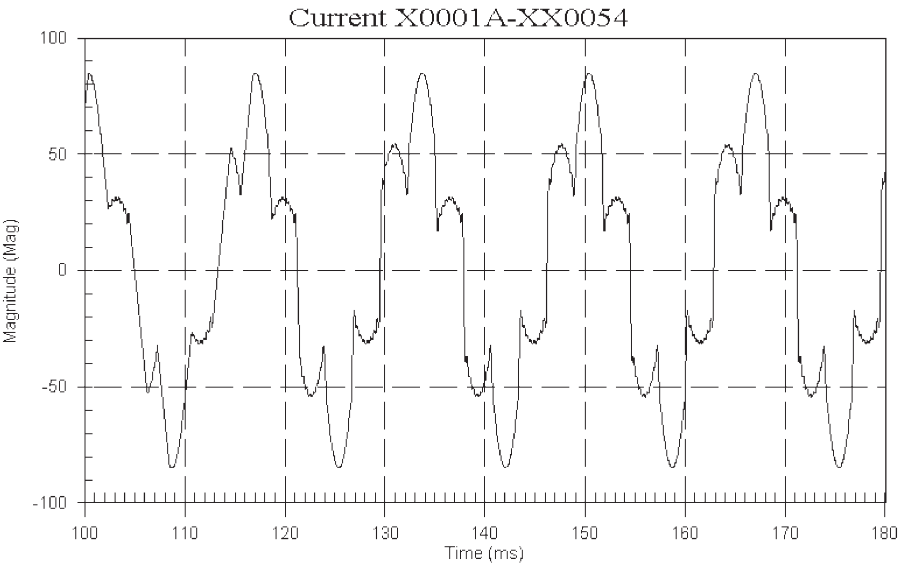

Fig. 2 *Waveforms. Current due to ASD.*

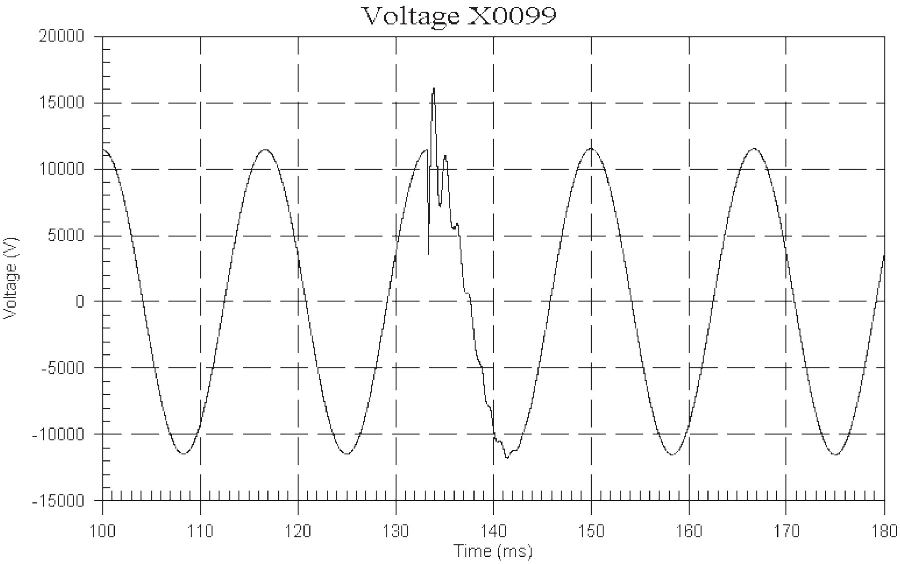

Fig. 3 *Waveforms. Energising of utility capacitor.*

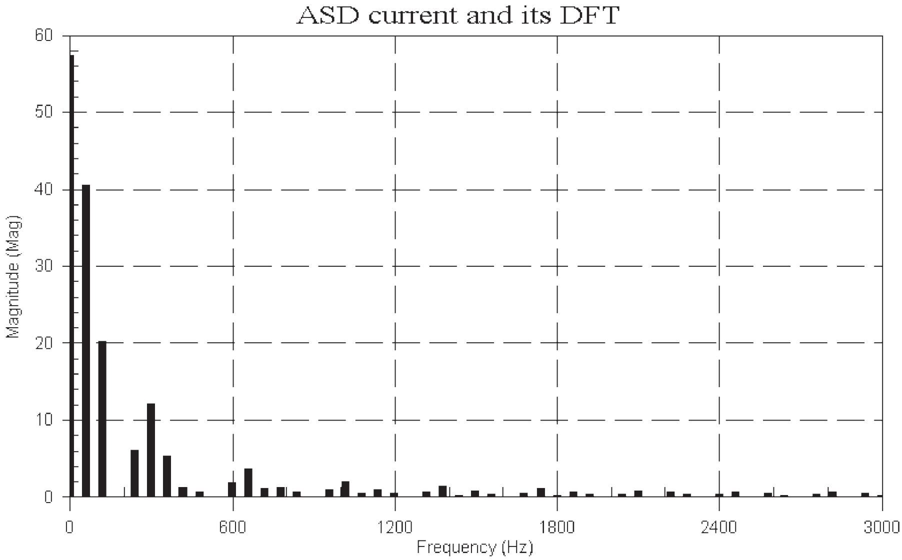

Fig. 4 *Discrete Fourier Transform. Current due to ASD.*

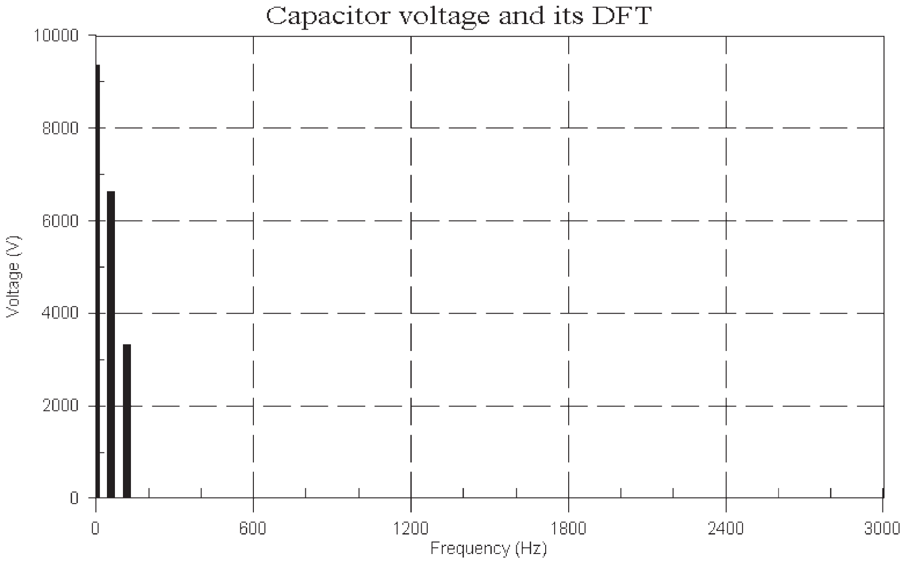

Fig. 5 *Discrete Fourier Transform. Energising of utility capacitor.*

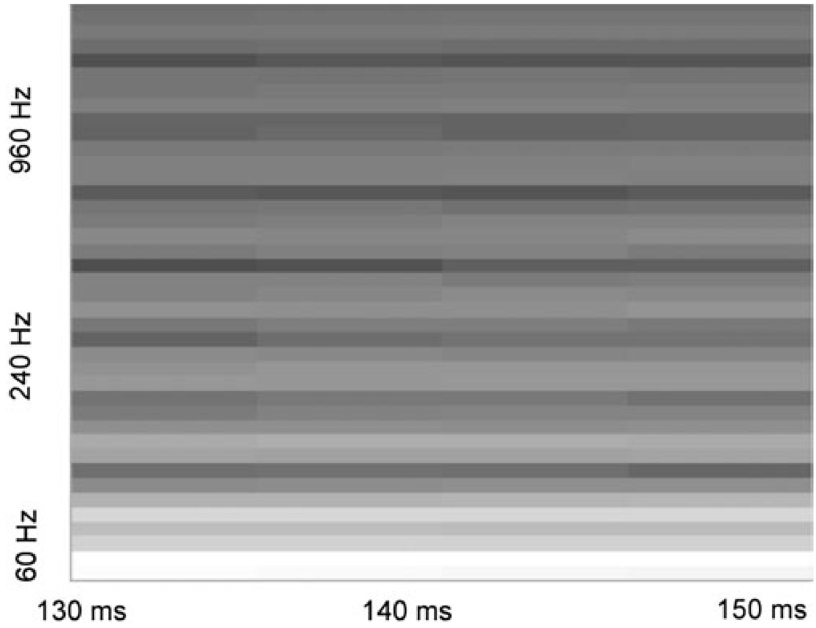

Fig. 6 *Outputs from discrete STFT. Current due to ASD.*

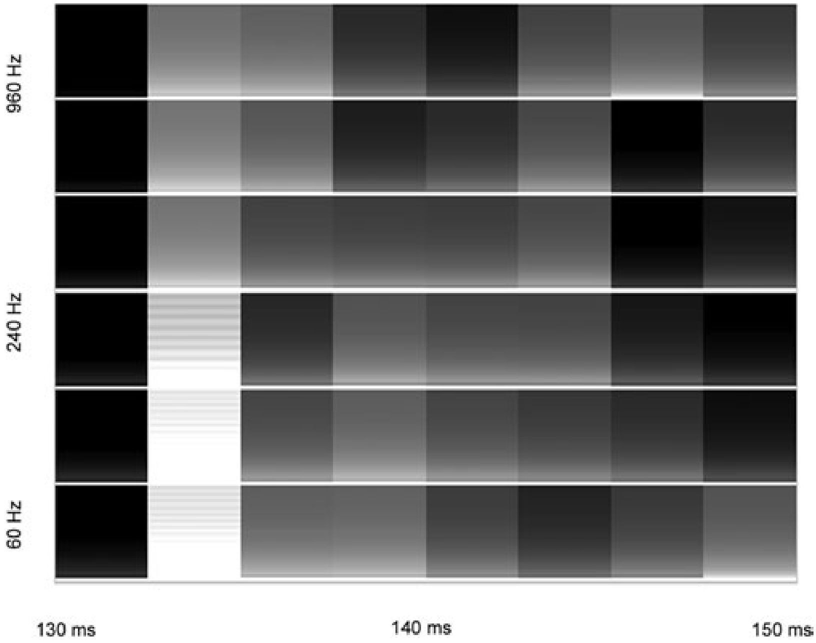

Fig. 7 *Outputs from discrete STFT. Energising of utility capacitor.*

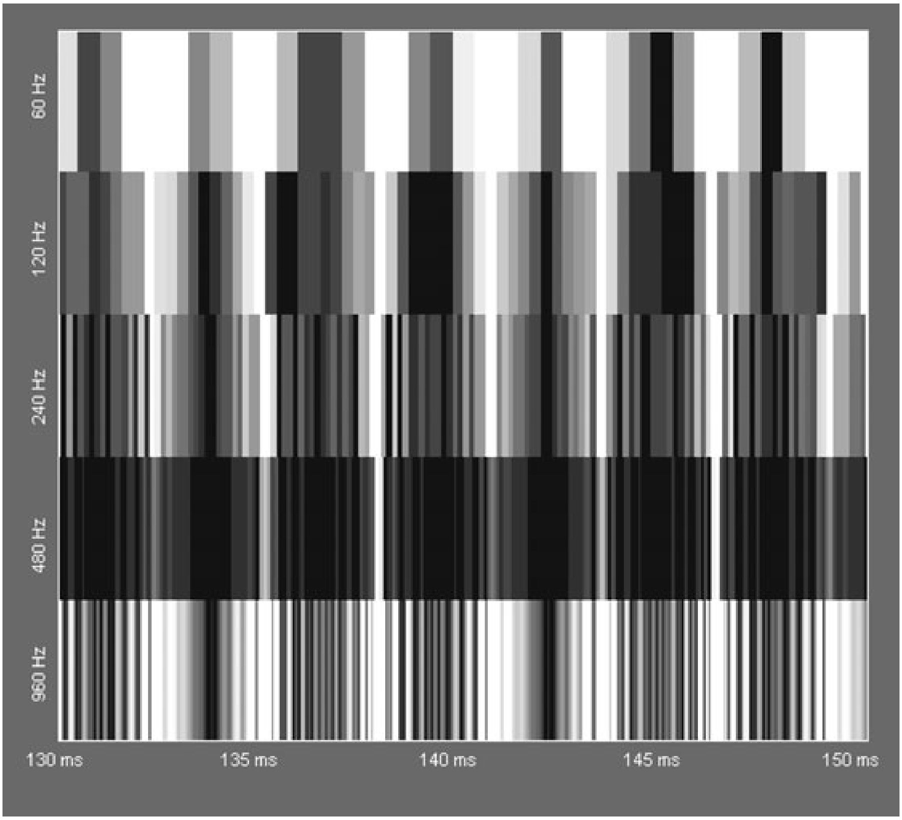

Fig. 8 *Outputs from wavelet. Current due to ASD.*

By applying dyadic Daubechies wavelets, the time-frequency diagram of the individual waveforms is obtained, as shown in Figs 8 and 9 for frequency components from 60 to 960 Hz. As indicated for the discrete STFT, a larger harmonic component is represented by a brighter area. Observation of these figures reveals the most significant harmonics compared with others.[31] These diagrams can be used for filter design in order to suppress unwanted distortion. In addition, they are also beneficial for making decisions. Figures 6–9 were obtained using MATLAB.[32]

Case 2

The transient overvoltage of a capacitor switching event frequently causes protection equipment to operate to disconnect the customer load. ASDs tend to be particularly susceptible to this problem because overvoltage protection thresholds are lower than in other customer equipment to protect the semiconductor components.

The general circuit illustrated in Fig. 10 is used to illustrate this concern and to evaluate the various parameters which affect the DC overvoltage the occurs during capacitor switching. The base conditions for this analysis are as follows:

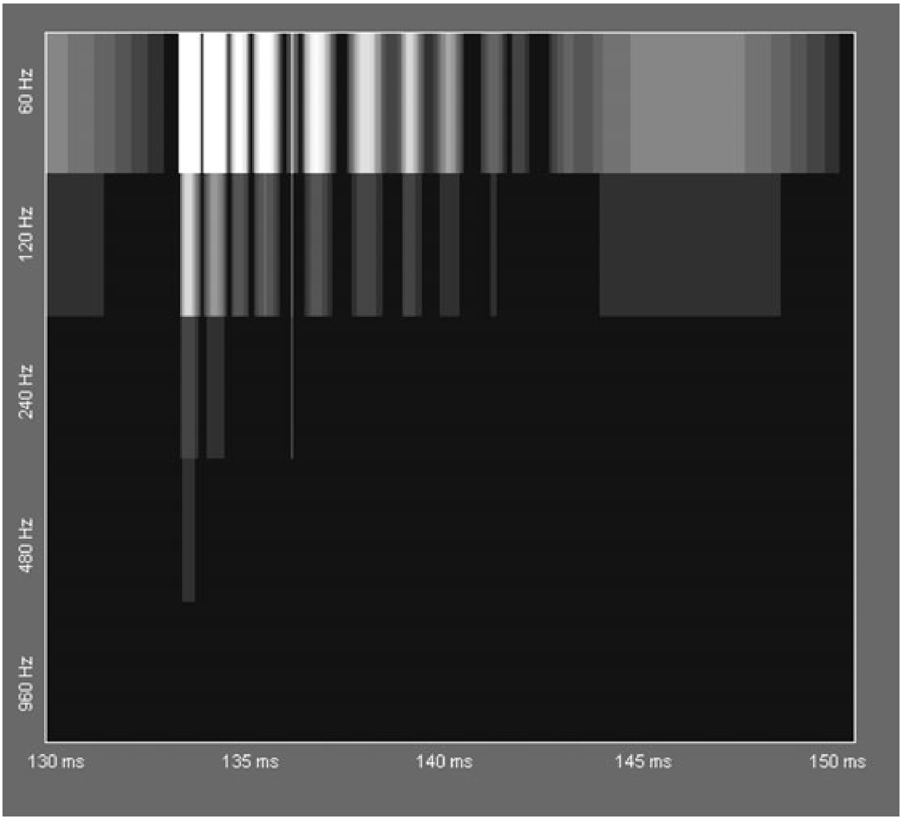

Fig. 9 *Outputs from wavelet. Energising of utility capacitor.*

System source strength at the substation = 200 MVA
Switched capacitor bank size = 3 Mvar
Total feeder load = 5 MW
Customer transformer size = 1500 kVA (6% impedance)
Customer power factor correction = 0 kvar
Customer resistive load = 200 kW
DC capacitor size = 400 μF
ASD choke size = 0.5 mH

The circuit in Fig. 10 is the basis for the EMTP model. Figures 11 and 12 provide typical waveforms for the base case conditions, which illustrate the concerns about transient overvoltage on the DC link. Figure 11 shows the transient current on the DC side. Note that the transient lasts for only one half cycle of the oscillation frequency (300–800 Hz). This is because the transient current charges up the DC bus (Fig. 12) and the diodes in the rectifier front end cannot conduct again until the DC voltage decays.

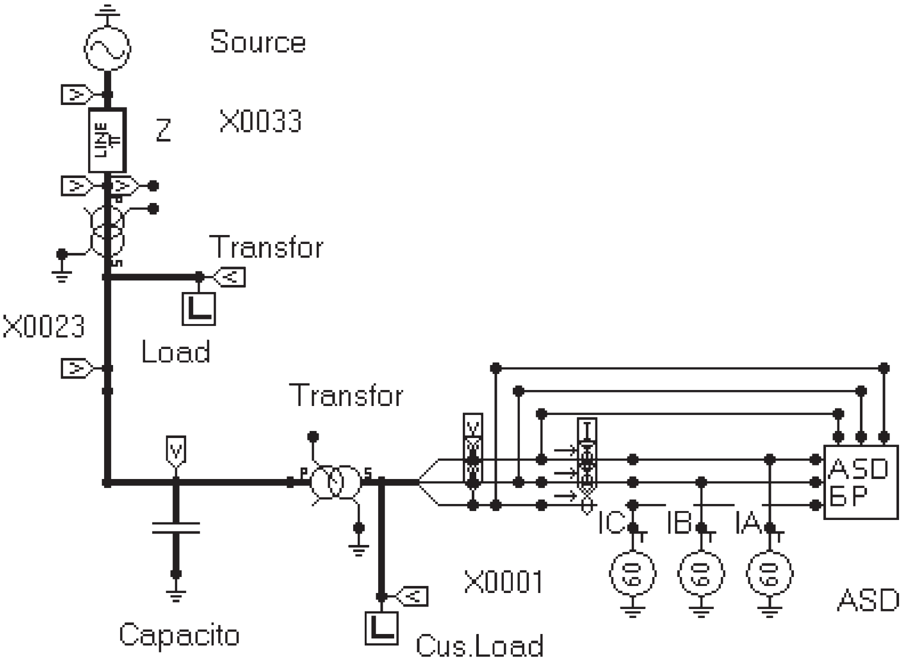

Fig. 10 *Diagram of Case 2.*

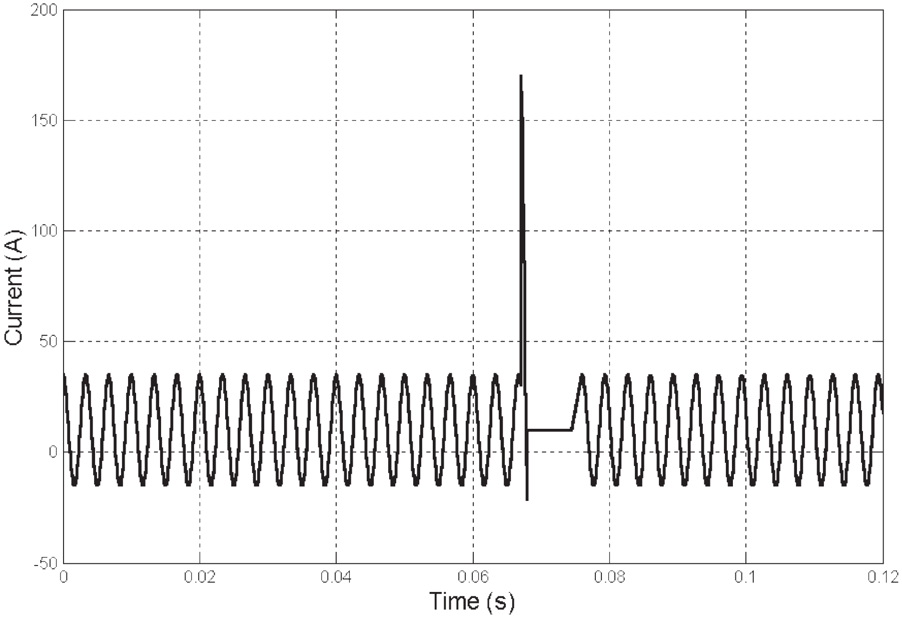

Fig. 11 *ASD DC output current.*

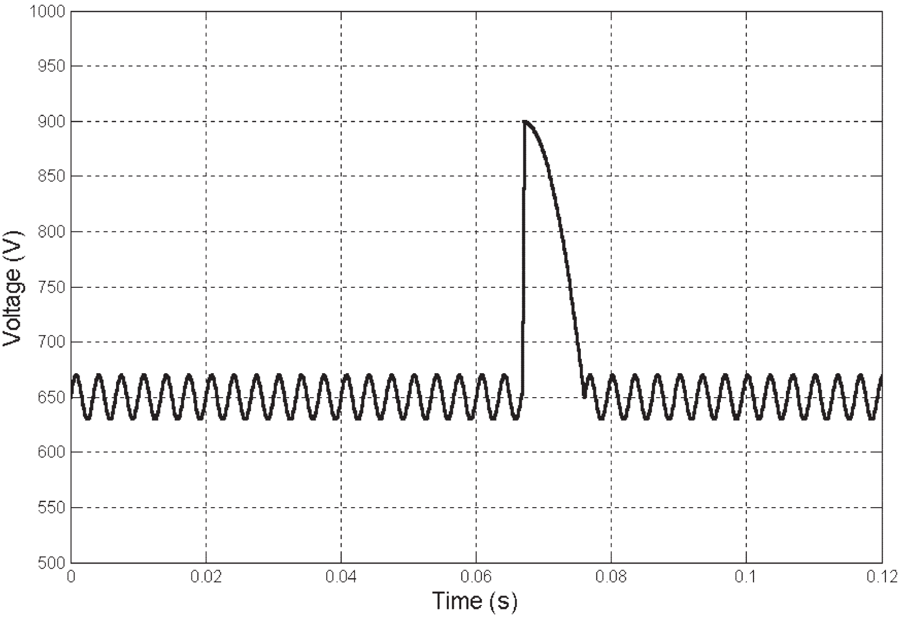

Fig. 12 *ASD DC link voltage.*

By employing wavelets, the time-frequency diagram of the individual waveforms can be obtained, as shown in Figs 13 and 14.

Outcomes and assessment

While the students were provided with harmonics and their impact on distribution systems, they were also given the opportunity to renegotiate the scope or project task at any time. Students were told to consider themselves to be employees of a company. Individual initiative in identifying and formulating alternative approaches or tasks which address the general problem was rewarded.

Some of the knowledge, tools and components used in these design projects were not available a few years ago. The design projects use the same tools and methods currently used in industry, e.g. TOP and EMTP, to address realistic and emerging challenges for the electric power industry. The authors have used these tools to teach a group of 40 graduates learning signal processing theory and power quality concepts.

To determine how these tools and techniques were being used, students were asked to answer several questionnaires throughout the term. The questionnaire included a question on the student expectation of the use of these tools. Students feedback indicates that theoretical developments in lectures on power systems were only appreciated after the uses of these tools.

Several students indicated in their answers that the theory made a lot more sense

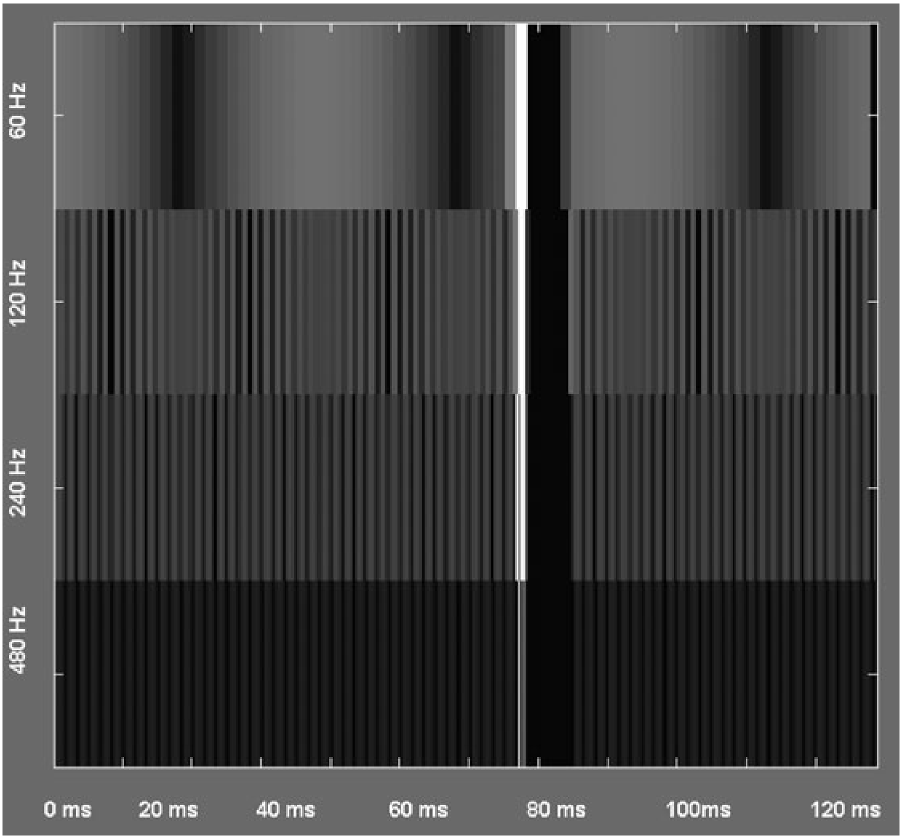

Fig. 13 *Outputs from wavelet. ASD DC output current.*

after using these techniques. The students liked the use of signal processing tools and felt that they provided insight into how the methods could be applied to more complex industrial applications.

Conclusions

The objectives of this course are straightforward. First and foremost, students who complete the course should be able to use and understand the signal processing tools. This means that the students must have a fundamental understanding of time and frequency domain analysis.

The course described in this paper has been well received by students, as evidenced by both the increasing embolients and quarterly course evaluations. The authors of this paper have found this course to offer fertile ground for introducing new topics into the electric power curriculum while stimulating students enthusiasm by using innovative teaching techniques, using industry grade tools, addressing con-

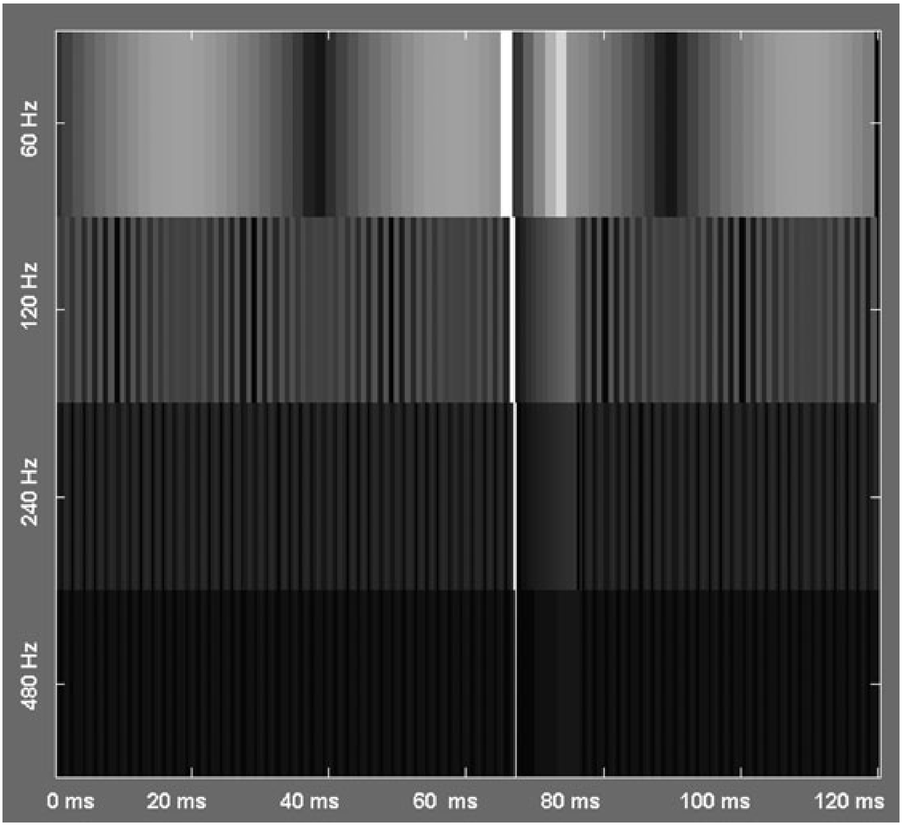

Fig. 14 *Outputs from wavelet. ASD DC link voltage.*

temporary issues in electric power, and promoting efficient communication in a team setting. With this course, electrical engineering curricula offer hands-on experience in application signal processing tools and power quality.

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