Information extraction from acoustic signals by optical fibre interferometry techniques based on chromatic modulation

D. TOMTSIS
TEI of West Macedonia,
Koila, Kozani
GR-50100
GREECE

V. KODOGIANNIS*,
* Dept of Computer Science
University of Westminster
London, HA1 3TP
UNITED KINGDOM

Abstract: - A technique for interpreting acoustic signals is presented based on an extension of the chromatic analysis used successfully in the optical domain. To illustrate the potential of this interpretation technique it was applied to monitoring power switchgear because of the inherent complexity of the various phenomena involved and their interaction with each other. In particular, we present a technique for analysing acoustic vibration data that provides extended information about the frequency content of a signal, requires little processing and data storage overhead and which can easily be adapted to a wide range of applications. The proposed technique is based on chromatic sensing which has been widely applied in the optics field and its advantages over Fourier Transformation are well demonstrated through experimental tests.

Keywords: - Chromatic modulation, interferometry, vibration signals.

1 Introduction

Diagnosis of faults, imperfections, and defects in many mechanical systems is accomplished in a number of applications by the use of vibration signals whereby an acoustic sensor attached to an appropriate point on the system provides a record of the intensity of vibration as a function of time, a signal which in many cases is complex. Post-processing methods are then used to extract useful information from these records by studying time or frequency domain signal characteristics [1]. In the time domain, the appearance of unusual peaks or the amplitude of the vibration could be used to provide an indication of coarse changes if the system generates a repetitive acoustic output, while noise can be reduced using filtering techniques. Statistical techniques can also be used to provide an early indication of component degradation. Alternatively, in the frequency domain, a number of quantities can be identified such as resonance peaks, unusual spectral components and shifts in the balance of the spectral information [2]. Information can be obtained from the signals by performing a Fourier transform and examining the frequency content of the signal. However, these signals are generally complex and the changes that occur may be subtle and distributed over the entire frequency range covered by the signal. In such cases, traditional techniques can hardly quantify the signal changes in a concise manner.

The most promising technique for sensing optical and acoustical parameters involves phase modulation, which has to be decoded by conversion to intensity modulation. Decoding phase modulation involves exploiting interference patterns arising from phase differences. This technique is known as interferometry and there are several different methods of implementation. The system that is considered in this research is the fibre dyne interferometer, which is constructed from multimode fibre and involves phase modulation within the optical fibres themselves [3]. The technique utilises the modal noise or speckle produced from this fibre, an interference pattern that consists of a random array of speckles both in the near and far field. When the optical fibre is disturbed by a mechanical signal, the distribution of speckles is altered. However, the integrated intensity change in the speckle pattern in the far field is negligible, hence spatial filtering is therefore required to facilitate examination of a small proportion of the far field pattern in which intensity variations will take place.

In general, when the optical fibre carrying the coherent light is perturbed, the distribution of the speckle intensities is seen to change with the perturbation [4]. An analysis of the changes in the speckle pattern output from the optical fibre can then be used to obtain information about the perturbations of the fibre. This research investigates the processing of acoustic signals and it is related to optical chromatic sensing and the signals are produced from a fibre homodyne interferometer. The proposed method is based upon chromatic modulation techniques and other common forms of optical and acoustical technology for analysing vibration data. However, it can be easily adapted to a wide range of applications in both the optical and in the acoustical domains [5].

In this paper, a method of monitoring signals from acoustic sensors is presented which is based on acoustic and chromatic sensing. To illustrate the potential of the technique it has been used to monitoring the vibrations produced during the operation of a 145 KV high voltage SF_6 puffer circuit breaker. A circuit breaker is required to control electrical power networks by turning on circuits, by carrying load and by disconnecting circuits under manual or automatic supervision. Such a system is able to carry out its function of controlling any current that may flow in the circuit of which it constitutes a part of the conductor system, by possessing two stable conditions:

(a) "***close***", where it has ideally zero and in practice a very small impedance, and (b) "***open***" where it has ideally an infinite and practically an extremely high impedance. In many cases, circuit breakers consist of a fixed and a movable contact located in a chamber. When the contacts are separated an arc is formed which is extinguished by the sulfer hexafluride (SF_6) ionised gas depending on the construction of the circuit braker. Circuit breaker monitoring is a situation where conventional analysis techniques normally experience problems since the circuit breaker event lasts only for a short time period, operates infrequently, and electromagnetic emissions during operation make the use of conventional acoustic monitors impractical.

2 Chromatic Modulation Theory

The essence of chromatic modulation - an integrated form of spectral monitoring - is the utilisation of polychromatic light for sensing spectral changes by monitoring the total profile of an optical signal within a spectral power distribution. Chromatic changes can be monitored by a number (*n*) of detectors with overlapping spectral responses. The output of each detector may then be expressed as

$$V_n = \int P(\lambda) R_n(\lambda) d\lambda \qquad (1)$$

where $P(\lambda)$ is the spectral power distribution in the optical signal and $R_n(\lambda)$ is the wavelength responsivity of the n^{th} detector and λ is the wavelength [6]. The colour model representing this mathematical formalism is generally called RGB and it is widely used in self-luminous display technologies. Each detector output may also be intensity normalised according to:

$$u_n = \frac{V_n}{\sum_n V_T} \qquad (2)$$

where chromaticity maps may be formed in terms of the coordinates u_1, u_2, … $u_{(n-1)}$. The case of n=3 leads to a two-dimensional chromaticity map (u_1:u_2) on which changes in optical signals may be traced. The special case when $R_1(\lambda)$, $R_2(\lambda)$, $R_3(\lambda)$ correspond to the responsi-vities of the human eye leads to the chromaticity map reducing to the CIE diagram of colour science [7]. The colour model representing this mathematical formalism is called L_{XY} and provides the relative magnitudes of the tri-stimulus values (i.e. $X=u_1$; $Y=u_2$; $Z=u_3$). However, this method of displaying chromatic information does not easily lead to the identification of signal changes in terms of fundamental signal properties. An alternative approach to the processing of the signals from such chromatic detectors overcomes this limitation. For the tri-stimulus case (n=3) this approach utilises three chromatic parameters, namely dominant wavelength (H), intensity (L) and degree of monochromaticity or spectral width (S) which are defined as follows:

$$H = 120\left[m_i + \left(\frac{V_i - V_{\min}}{V_i + V_j - 2V_{\min}} \right) \right] \qquad (3)$$

with

$m_i=0$ for $i=1$, $j=2$, $V_{min}=V_3$,

$m_i=1$ for $i=2$, $j=3$, $V_{min}=V_1$,

$m_i=2$ for $i=3$, $j=1$, $V_{min}=V_2$

$$L = 100\left[\frac{V_{\max} + V_{\min}}{2} \right] \qquad (4)$$

$$S = 100\left[\frac{V_{\max} - V_{\min}}{200m_2 - m_3(V_{\max} + V_{\min})} \right] \qquad (5)$$

with $m_2=0$, $m_3=-1$ for $L \le 50$ and $m_2=m_3=1$ for $L>50$. V_{min} and V_{max} are the minimum and maximum detector outputs [8].

3 Experimental Apparatus

The monitoring system, shown in Fig. 1, consisted of a fibre dyne interferometer, which was wound around the plant being monitored or directly exposed to an acoustic source for calibration. The fibre dyne interferometer consisted of a 10 mW optical power output HeNe laser which was focused by a microscope objective lens into a length of 400 μm diameter hard clad silica multimode fibre. The light from the output of the fibre was subjected to spatial filtering and exhibited a two dimensional speckle pattern, which was susceptible to small vibrations of the optical fibre. The output from the spatial filter was projected onto a BPX65 photodiode and the resulting electrical signal was amplified. An oscilloscope was also used to display the output of the system. The acoustic monitoring system was calibrated with the fibre dyne interferometer wound around the outside surface of a metal tube in which a loudspeaker was placed. A signal generator was also used to artificially generate and apply to the system pure sinusoid signals at different frequencies.

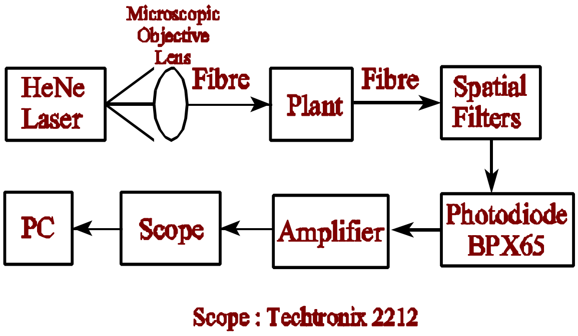


Fig.1: Schematic configuration of the acoustic monitoring system

After calibration, the acoustic monitoring system was used to study the vibrations produced during the operation of a high voltage SF_6 puffer circuit breaker, a schematic diagram of which is shown in Fig. 2.

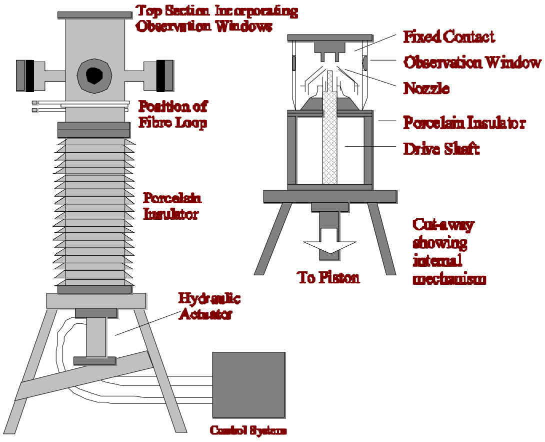


Fig. 2: Schematic diagram of a high voltage SF6 puffer circuit breaker

The fibre dyne interferometer was wound around the exterior of the circuit breaker's nozzle, which was initially in contact with the fixed electrode, so current could pass through. When the circuit breaker was in operation, the hydraulic actuator pulled the nozzle away from the fixed contact causing an arc to form, which was then extinguished by a jet of gas. The acoustic signal produced from the operation of the circuit breaker was then monitored over a range of conditions.

4 Experimental Method

The output from most optical or acoustical sensors is usually represented as a variation of intensity with time, which through Fourier Transformation, can be converted into a frequency spectrum. The same analysis can be performed when time windows are defined for covering a quantum of information, but in this case a frequency spectrum is required for every window of the time varying signal.

4.1 Chromatic Processing Based On FFT Techniques

The spectral information contained within an optical signal can be approximated in practice using a chromatic monitoring system with three detectors of Gaussian responsivity, covering the desired frequency range. Multiplication and then integration of the spectrum by each of these detectors over the detector width provides three outputs, each of which represents the amount of optical energy contained within the frequency range of the Gaussian detector.

4.2 Direct Chromatic Processing

The above mentioned method is based on the acquisition of a spectrum, hence requires the application of the Fourier Transform as well as a number of integrations, operations which are slow to perform and computationally intensive. Furthermore, in the acoustical domain, when the signal frequencies are comparable to monitoring times, the extent of a measurement window requires careful consideration. These processing limitations can be overcome or significantly reduced by considering the output from each Gaussian detector as a measure of the energy in the region of the spectrum covered by a filter. Hence, this information can be obtained by applying Gaussian band-pass filters directly to the time varying signal. Although the chromatic processing approach was used, as shown in Fig. 3, as part of a sequence for compressing spectral information, this method does not rely upon the intermediate step of acquiring a spectrum on which to operate.

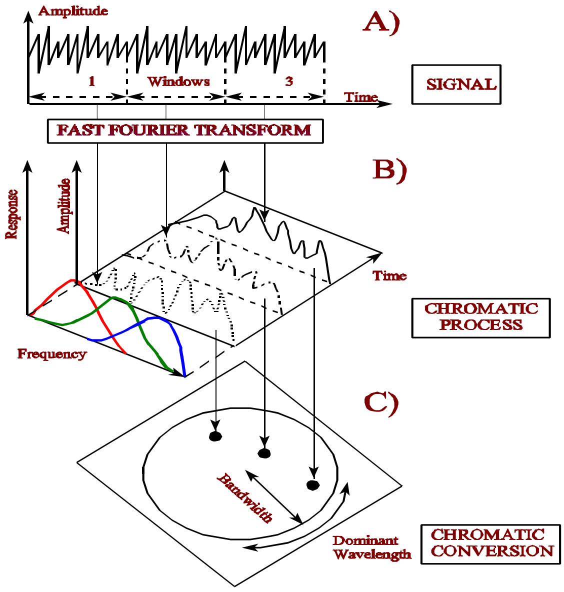


Fig. 3: Chromatic processing based on FFT techniques. This figure illustrates graphically how information compression can be achieved by chromatic modulation methods. A) Signal to be processed. B) Chromatic processing of each time window by a set of three Gaussian detectors. C) Conversion to HLS system or any other chromatic representation system.

Acoustical signals are chromatically processed and monitored directly, hence bypassing the need for handling large quantities of data and intensive data processing. This method requires little processing and data storage overhead and can be adapted to a wide range of applications. The small number of detectors used allows the data to be more easily analysed with many chromatic representation methods for tri-stimulus systems, such as those described in previous sections.

5 Calibration

The calibration of the acoustic monitoring system was performed by applying the homodyne interferometer to the outside surface of a metal tube in which a loudspeaker was placed. The loudspeaker was excited over the range

1 KHz to 5 KHz, in 1 KHz steps. Fig. 4 shows a typical homodyne interferometer output as a function of time with the corresponding Fourier Transform shown in Fig. 5.

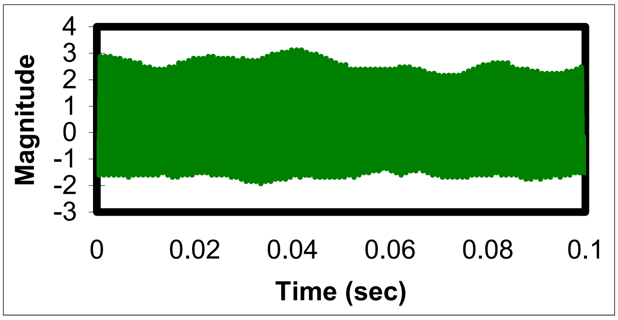


Fig. 4: Typical homodyne interferometer output as a function of time

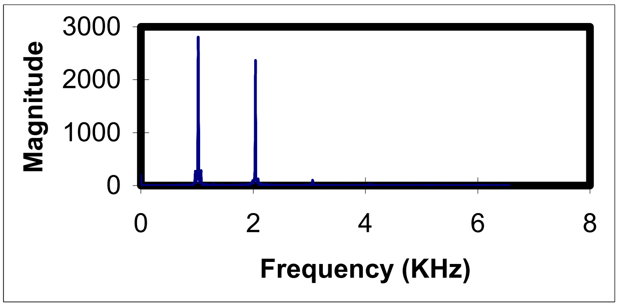


Fig. 5: FT of the signal illustrated in Fig. 4

To calibrate the system, such outputs from the sensor as a function of time were then applied to

- a set of three detectors, the Gaussian responses of which are illustrated in Fig 6 with their peak values obtained at 3, 5 and 7 KHz approximately for the *blue*, *green* and *red* detector respectively.

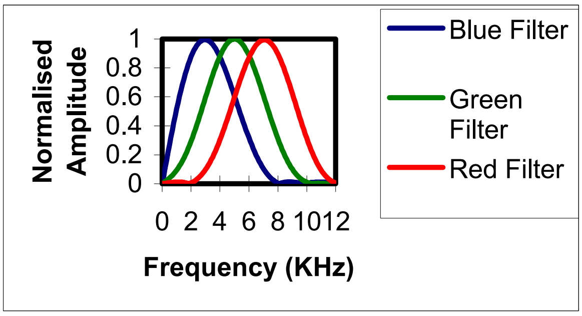


Fig. 6: The Gaussian responses of detectors

  Each test was performed with the Chromatic Method Based on FFT Techniques in order to calculate the X and Y chromatic parameters in the L_{XY} chromatic system.

- a set of three digital band pass filters. The Gaussian responses of the 14th order FIR (Finite Impulse Response) digital filters are shown in Fig. 7, with their peak values obtained at 3, 5 and 7 KHz approximately for the *blue*, *green* and *red* filter respectively. Each test was performed with the Direct Chromatic Processing Method to obtain the same chromatic parameters.

In both cases, the calibration tests were repeated several times to assure the repeatability of the acoustic system output.

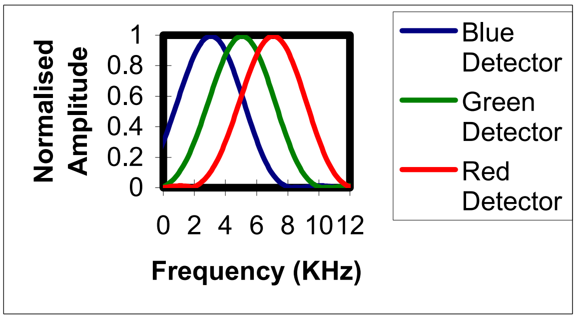


Fig. 7: The 14^{th} order FIR filter responses

The results from the system calibration procedure are shown in Figs. 8 & 9 for both the FFT Based and Direct Chromatic Processing Methods respectively. These figures show in XY space the variation of the X and Y chromatic coordinates calculated from the homodyne interferometer output.

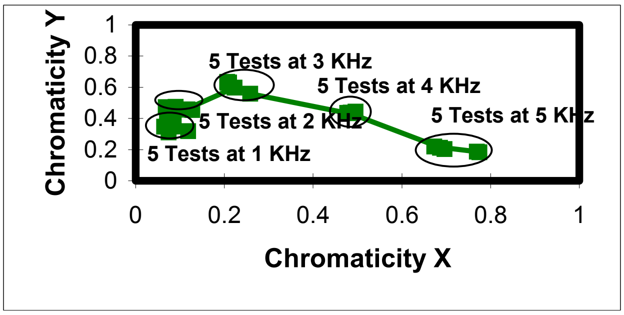


Fig. 8: Calibration of the acoustic monitoring system with the FFT based chromatic processing method

The L_{XY} chromaticity results produced from both methods are very similar since the shape of the Gaussian detector responses is very close to those of the digital band pass filters.

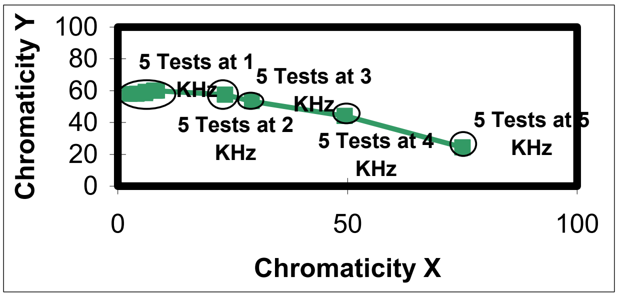


Fig. 9: Calibration of the acoustic monitoring system. This figure shows the FIR filter outputs when a number of sine waves at different frequencies were applied to the system.

The advantage of the Direct Chromatic Processing Method over the FFT Based Method is the increased repeatability of the system output, since no analogue to digital conversion errors are involved (such as time jitter and quantisation errors). In addition an increased speed of data processing due to the fact there is no need to obtain a spectrum on which to operate.

Fig. 10 illustrates the measured variation in the acoustical Hue in the HLS chromatic system, calculated from both the homodyne interferometer output and the pure sinusoids when the Direct Processing Method was used. The Hue angle graph presents a monotonic relationship between Hue angle and frequency in the frequency range of 1 to 5 KHz as well as a good repeatability of the experimental results since each test was repeated five times and the same hue angle value was obtained in most cases.

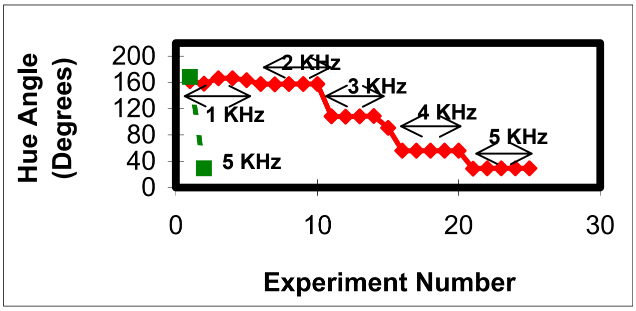


Fig. 10: Calibration of the acoustic monitoring system. This figure shows the measured variation in the acoustical Hue when the Direct Chromatic Processing Method is used. Full Line: Homodyne Interferometer output, Dashed Line: Pure Sinusoid.

6 Experimental Results

After calibration, the acoustic system was utilised to monitor the vibrations produced from a power circuit breaker, where its operation involves three phases:

- Phase 1: Quiescent state prior to operation
- Phase 2: Contact in motion during which an arc was formed
- Phase 3: Contact motion arrested by a buffer

Fig. 11 shows the major part of a circuit breaker signal as an intensity record against time. The three phases of the circuit breaker operation correspond to the following signal time intervals:

- Phase 1, prior to operation, from 0 to 0.015 sec.
- Phase 2, the arc period, from 0.015 to 0.06 sec and
- Phase 3, the buffer period, from 0.06 to 0.15 sec.

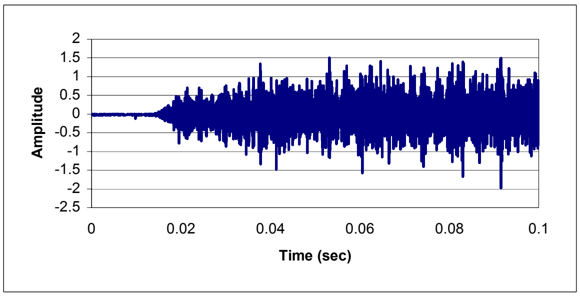
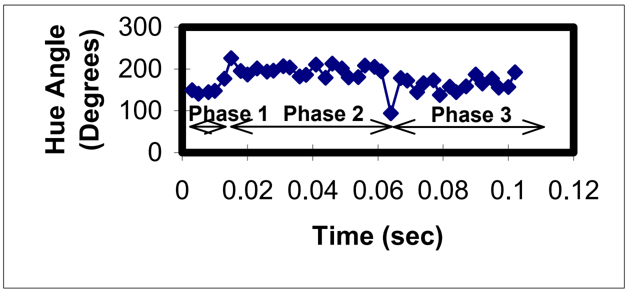
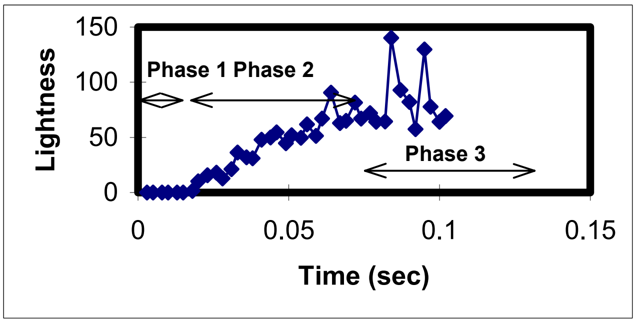


Fig. 11: Typical SF6 circuit breaker signal

Identification of important characteristics or trends from this signal would obviously be difficult or impossible due to its complex form. The variation of the characteristics of the acoustic signal was then investigated between each of the phases of the circuit breaker operation.

Fig. 12 shows a sequence of H, L and S values taken throughout the same operational period. From this data it is possible to easily identify the three operational phases; the hue value varies considerably between the three stages and there are peaks in the lightness and saturation traces when the contact travel begins and when it reaches the buffer. The reduced storage requirement, only three values need to be recorded per sample, allowed the spectral content of an acoustic signal to be monitored over extended periods. Interpretation of the acoustic signal is simplified as only three parameters have to be analysed, trends in each of these parameters; Hue, lightness and saturation can be easily identified.





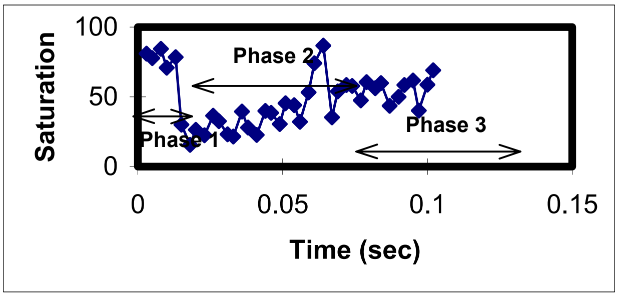


Fig. 12: The vibration signature of the circuit breaker's acoustic signal in the HLS chromatic system

7 Conclusion

Two different methods of monitoring vibration signals have been presented. The first method is based on the FFT and the chromatic modulation approach to process the energy content of an acoustic signal with three broadband detectors to derive Hue, Lightness and Saturation values. In the second one, we process directly the time domain acoustic signature with three FIR filters to produce the equivalent Hue, Lightness and Saturation values. The conversion between the time varying signal and the chromatic parameters can be performed using simple band pass filters; hence very little computation and data storage is required. The small number of filters used allows the data to be more easily analysed. Experimental results have shown that the usage of this technique offers easier data analysis, less intensive calculations and data storage as well as easier identification of trends between physical parameters and measured chromatic data. Although this work was based on monitoring power switchgear, the developed chromatic techniques are applicable to any acoustic signal. The simplification in the identification of trends illustrates the potential of this technique and is an indication that the proposed approach can be used in general terms as a pre-processing stage to an artificial intelligence based monitoring system.

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