172 *Journal of Electrical Engineering & Technology, Vol. 2, No. 2, pp. 172~177, 2007*

Protection Assessment using Reduced Power System Fault Data

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Abstract - Wavelet transforms provide basis functions for time-frequency analysis and have properties that are particularly useful for the compression of analogue point on wave transient and disturbance power system signals. This paper evaluates the compression properties of the discrete wavelet transform using actual power system data. The results presented in the paper indicate that reduction ratios up to 10:1 with acceptable distortion are achievable. The paper discusses the application of the reduction method for expedient fault analysis and protection assessment.

Keywords: Wavelets, Protection, Fault Analysis, Data Compression

1. Introduction

Power system networks are subject to faults which give rise to transients and disturbances on the power network. Fault events, monitored by distributed digital fault recording instrumentation or protection relays (with fault recording), are generally stored as composite analogue and digital time-tagged records and typically transferred over communications links to a utility control centre for fault reporting, analysis and archival. The records provide useful information for fault analysis, and importantly protection assessment. The prospect of gaining rapid access to remote composite data provides obvious practical benefits for accurate protection assessment and adjustment. A prime constraint of remote retrieval is the bandwidth limitation imposed by communications links. Records can be large (> 500 kBytes) and the communications link can present a 'bottleneck' if it is limited by bandwidth or peripheral modem speed. The problem is further compounded if site monitoring involves a number of recording units.

In theory, installing a secure broadband link could solve many of problems associated with bandwidth, though this would require extensive replacement of capital infrastructure to implement. Legacy systems tend to use modem and RF links for supervisory control and data acquisition (SCADA) and substation communications. In the short term, however, a more pragmatic solution for existing systems and one that would potentially enhance broadband upgrading would involve reducing the record data using a compression method. The essential criteria for compression are that the storage occupancy of source data is sufficiently reduced and apparent integrity of the data is not adversely affected by the reduction method. By identifying redundancy in a data it is possible to reduce effective size. One such method that has evolved in recent years is *wavelet compression* [1, 4].

Wavelet transforms provide effective techniques for the compression of analogue data with provision for rapid retrieval using multiresolution compaction of large data sets. Wavelet compression involves signal pre-processing to alter the statistical bias of the data to improve compressibility. The transform analyses raw signal data to identify redundancy prior to loss-less compression. This method is generally known as *transform compression.* Purely loss-less reduction techniques have been applied to power system data in the past, with modest compression ratios (< 5:1), [6]. However, transform methods have rarely been used due mainly to limited acquisition system hardware resources, and cumbersome and often unsuitable transforms.

Transform compression and coding has evolved from applications in speech and image coding [1, 3]. Data compression algorithms contained in MP3, MPEG, and JPEG formats for music, video, and still image compression, respectively, each rely on *lossy* transform pre-processing to extract information content, prior to loss-less compression by a symbolic coding algorithm. The analysing transform yields a vector of coefficient amplitudes determined by expansion across the transform domain. The vector is scalar quantised, to assign more bits to higher amplitude transform coefficients and fewer bits to lower amplitudes. The quantised coefficients are symbolically compressed using loss-less entropy or a dictionary based coding scheme, such as arithmetic coding. When symbolically coded the output sequence is generally shorter than the original signal, containing only the information which best matched the analysing transform.

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Received 19 July, 2006; Accepted 9 February, 2007

The basis of transform compression is that sparse transform coefficients are themselves more easily compressed, rather than the original signal samples.

In this paper, wavelet time-frequency properties are considered in conjunction with a proposed scheme for data reduction. Section II and III briefly review wavelet theory and a proposed compression scheme, respectively. In section IV an application of the scheme for protection assessment is provided using actual power system data.

2. Wavelet Theory

Wavelets, as the name implies, are waves of a short duration with particular properties suitable for the representation of localised and short-term signals features, Fig. 1. A discrete wavelet transform (DWT) expands a signal using the translation (shift in time) and dilation (compression in time) of a particular wavelet function. If the wavelet function is chosen correctly, the transform will yield an expansion that is localised in time and frequency yielding wavelet coefficients at different scales, [2, 3].

The wavelet expansion contrasts with the Fourier transform where the analysing basis function is a fixed trigonometric polynomial and the expansion of the signal is normally restricted to frequency localisation with a loss of time reference (although this limitation can be minimised using a window). The dual time-frequency localisation property at different scales gives the wavelet transform much greater compact support for the analysis of signals with short term transient components and also means that more energetic wavelet coefficients are localised and therefore sparse, in the transform domain, thus providing a basis for data reduction.

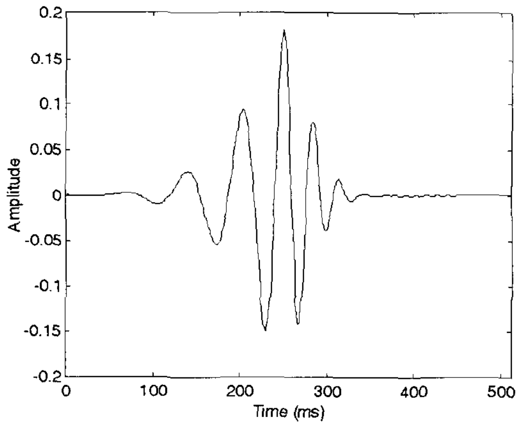


Fig. 1. A typical wavelet function

Wavelet analysis provides *scale* rather than frequency decomposition. This method of analysis is generally referred to as *multiresolution analysis* and a range of wavelet functions has been mathematically derived for the purpose of such analysis. Scale analysis in this context facilitates dual time and frequency localisation. The multiresolution analysis yields *approximation* and *detail* coefficients, $S_{j,k}$ and $D_{j,k}$, respectively, by convolution of the signal with low-pass filter coefficients, h(n), and high-pass filter coefficients, g(n), derived from the chosen wavelet function, [4].

Scale analysis of a signal, S(n), by the wavelet function, φ(n), is achieved by iterative analysis of S(n), parameterised as $S_{j,k}$, where j and k represent translation and dilation, respectively. If it is assumed that S(n) already represents an approximation at a scale $j = 0$, the starting point for the analysis is the primitive function:

$$f(n) = \sum_{k} S_{0,k}\varphi(n-k) \tag{1}$$

The analysis proceeds by convolution of $S_{0,k}$ with h(n) and g(n) to generate a contiguous vector of coefficients $S_{j,k}$ and $D_{j,k}$ at each decomposition scale:

$$S_{j,k} = \sum_{n} \bar{h}_{n-2k} S_{j+1,n} \tag{2}$$

$$D_{j,k} = \sum_{n} \bar{g}_{n-2k} S_{j+1,n} \tag{3}$$

At each scale the contiguous $S_{j,k}$ and $D_{j,k}$ coefficients are decimated following application of (2) and (3) thereby down-sampling the previous vector, [3, 4].

The discrete wavelet transform has an efficient implementation using finite impulse response filters arranged in the form of a quadrature mirror filter (QMF). The QMF creates a series of decomposition levels at different scales with coefficients concatenated at each level. The expansion will generally create vectors of sparse coefficients thereby capturing information content using a reduced number of 'energetic' coefficients. The maximum number of scaled 'levels' of $S(n)$ is defined by $l = \log_2 N$ where N is the signal length.

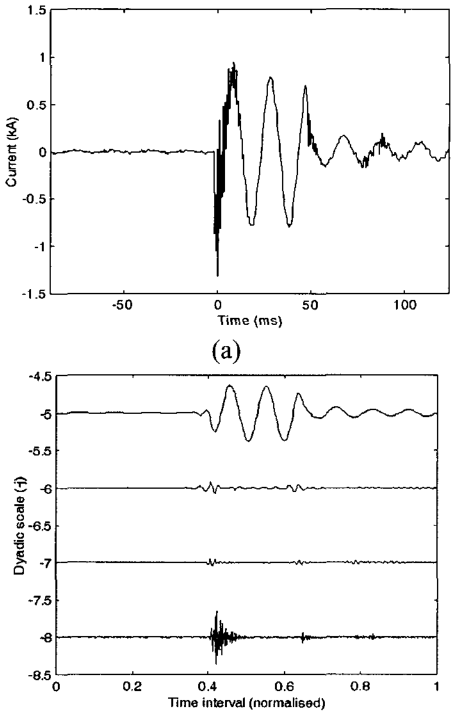
If an *orthonormal* wavelet function is used for signal analysis, a synthesised reconstruction is possible, provided the wavelet function has *biorthogonal* properties, using the expression:

$$S_{j+1,k} = 2\sum_{n\in Z} h_{k-2n} S_{j,n} + 2\sum_{n\in Z} g_{k-2n} D_{j,n} \tag{4}$$

The signal may be directly reconstructed from the wavelet coefficients using the same QMF topology and filter coefficients, h(n) and g(n), by interpolating and upsampling the coefficients at each level. Wavelet multiresolution properties provide a robust basis for time-frequency analysis and synthesis without degeneracy. Such properties are highly desirable for signal filtering and compression. For a given signal, the analysis yields coefficient vectors at different scales. If the vectors are individually reconstructed, the synthesized signals represent filtered 'components' of the original signal, Fig 2. This method of analysis is useful for de-noising [8]. By sorting the high-energy coefficients from those that contribute little to the signal, the coefficients may be compressed using a coding algorithm to reduce the effective size of the data.

3. Data Reduction

A data reduction scheme using the DWT was developed. The scheme was established by loss-less coding of the wavelet coefficients. As many of the low–energy coefficients contribute little to the signal *information*, a threshold T may be applied to eliminate small value coefficients setting to zero those below T, Fig. 3. Thus a loss-less coding algorithm can exploit the high number of zero-order coefficients to compress the coefficients. A detailed description of this method of compression is contained in [1, 4, 8].



(a)

(b)

Fig. 2. (a) Phase to earth fault neutral current; (b) Multiresolution analysis separates the components of (a) using scale decomposition

The compression ratio was defined by $C_r = N / K_e$ where K_e is the number of absolute *energetic* coefficients retained at a specific scale, i.e. $|K_e| \geq T$, and N the total number of signal samples, Fig. 3. The quantised coefficient vectors were compressed using the loss-less Lempel-Ziv-Welch (LZW) algorithm. The LZW algorithm is widely used for loss-less compression of different types of data, including image and text, [7].

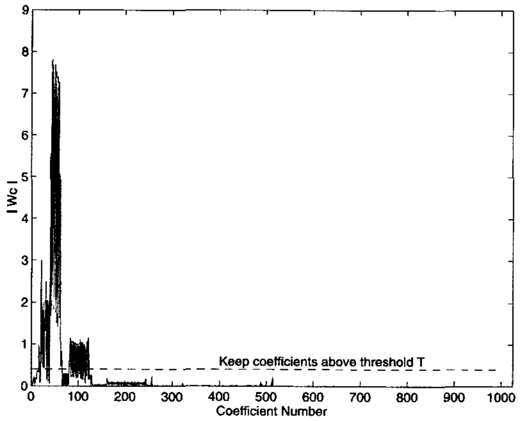


Fig. 3. Threshold selection of coefficients

The compressed signals were subsequently decompressed using the inverse LZW algorithm, and reconstructions obtained from the coefficient vectors using the inverse DWT transform. Signal distortion was assessed by evaluation of the signal to noise ratio (SNR), and percentage root mean square (PRD) error.

4. Protection Assessment

One area of interest in this research has been evaluation of the proposed reduction method for rapid transfer of fault data. This method involves the reduction of point on wave fault records so that the data might be used in conjunction with remote terminal unit data from SCADA systems to aid protection assessment in near real-time. Although measurement and recording systems provide local measurements of voltage and current, among other parameters, in general the measurements are normally restricted to RMS or instantaneous values from regular polling of acquisition units, [5]. In the event of a fault or mal-operation, however, the ability to visualise a sequence of time-tagged events across a wide number of circuits would enable a protection engineer to provide an informed response to an incident using the additional information derived from fault records. The target application for the proposed reduction scheme would be as part of an embedded acquisition system used to record faults. If records can be locally compressed without loss of feature integrity, and transferred across a communication link within acceptable time, they may be used to remove uncertainty in protection decision processes.

Two applications of the proposed scheme are presented in the following exemplars. The first example describes the reduction of a voltage signal derived from a distribution level cable fault with protection intervention. The second example illustrates the reduction of a complete fault record from a transmission level conductor-clashing incident with protection operation.

4.1 33 kV Cable Fault

In particular applications a low-resolution signal with reduced SNR may be tolerable if data is urgently required. The signal in this example provides an instance where reduced SNR is perhaps tolerable. The signal was obtained from a 33 kV cable fault from a digital fault recorder installed at the supply intake point (132 kV) of a distribution substation, Fig. 4. The fault was established as cable damage caused by contractor's mechanical equipment, which caused a voltage dip from 33 kV to 7.8 kV with fault clearance by local protection within 100 ms.

The signal was compressed using a *Symmlet* 10-point wavelet function and five applied threshold values, (C_r = 2:1, 4:1, 10:1, 20:1), reconstructed, and plotted in ascending order with an SNR measure computed in each case, Fig. 5. In this example, the particular area of interest was the depth and duration of the voltage dip.

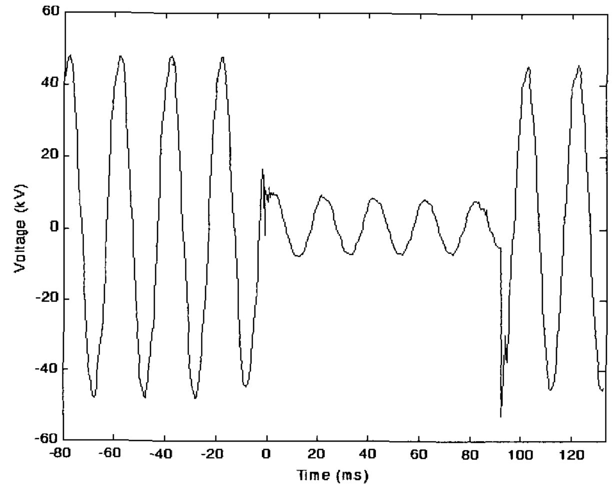


Fig. 4. Cable fault signal from a 33 kV distribution feeder

The reconstructions show that sinusoidal structure, localised transients, and general signal integrity were preserved by the DWT compression, down to a threshold of C_r = 10:1, with SNR = 25.4 dB. At C_r = 20:1, the signal was significantly distorted and would be unsuitable for accurate measurement. However, of particular interest was the observation that the respective points of fault inception, protection intervention, and clearance could be easily identified, with the preservation of timing and in most cases amplitude information. Thus, despite lossy compression of the original signal, it was apparent that accurate information for fault and protection assessment could be gleaned from a significantly reduced data set.

4.2 400kV Conductor Clashing

A complete 8-channel record, Fig. 6, from a 400kV conductor incident was compressed by the proposed method. The record size was 65536 bytes and was analysed using a *Daubechies*-12 wavelet function with coefficients compressed by the LZW algorithm.

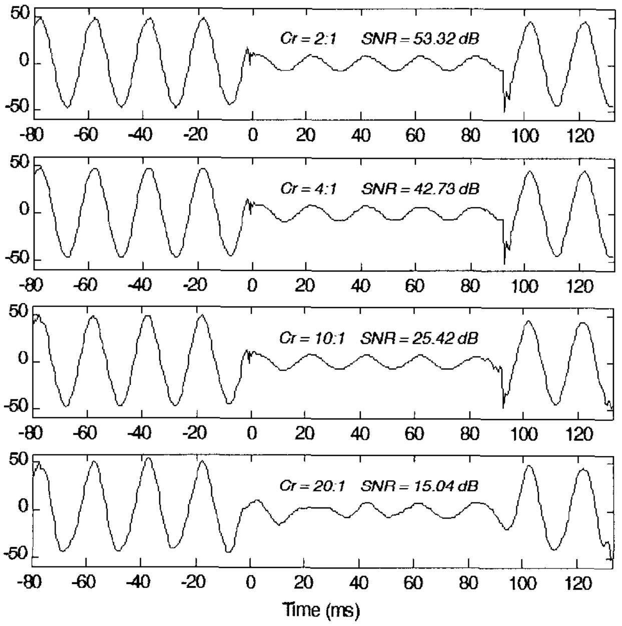


Fig. 5. Reconstruction with different compression ratios

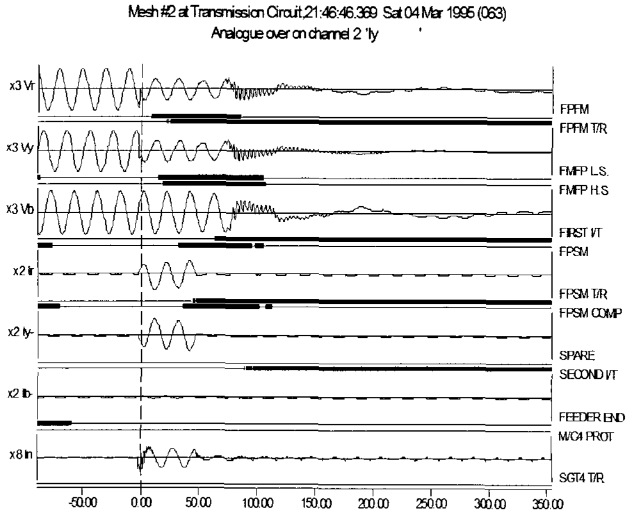


Fig. 6. Fault record from conductor clashing incident

The compressed record was encoded by a modem algorithm (Shannon-Fano encoder) and transmitted over a simulated public switched telephone line using XMODEM 1K protocol at 19200 baud. The simulated line efficiency was set to 0.75 with 10 bits/byte asynchronous transmission. The compressed record was reconstructed at the receiving end.

As a test of wavelet reduction, each record channel was directly compressed using the LZW algorithm. The original and LZW compressed records were also transferred over the same line for comparison, Table 1. The PRD figures represent the distortion introduced by wavelet analysis. The results indicate that wavelet analysis significantly reduces channel size, with compression of signals to < 10% of original size and minimal distortion in most cases. As anticipated, the PRD figures show that channels with the highest distortion were those with lower dynamic range and reduced SNR.

The resultant size of the LZW and DWT + LZW compressed files was 26724 bytes and 5560 bytes, respectively. The transfer time for the original, LZW and DWT + LZW records was measured and tabulated, Table 2. The transfer results reflect data transfer times only, ignoring modem connect and disconnect sequence times. The transfer times show that the DWT + LZW record was transferred across the PSTN line approximately 12 times faster than the original record.

Table 1. Compressed file size and PRD distortion

Channel	LZW	DWT + LZW	PRD
Ir	31%	7.5%	1.17%
Iy	30.7%	7.6%	1.03%
Ib	29.8%	8.6%	7.9%
In	26%	8.5%	8%
Vr	59%	8.8%	4.8%
Vy	48.2%	8.8%	2.8%
Vn	60.9%	8.7%	3.7%
In	39.9%	9%	7.7%

Table 2. Transfer time at 19200 baud for a typical SCADA RTU modem

Original	LZW	WPT + LZW
45.5 s	18.5 s	3.8 s

Both examples illustrate the reduction of point on wave data derived from fault records using wavelet *pre-conditioning*. The pre-conditioner reduces the number of wavelets coefficients through a selection process. In the examples provided an energy threshold was used to sort the coefficients, though other methods exist to perform sorting [8]. A significant merit of the proposed pre-conditioner is the robust ability of the wavelet function and transforms to accurately capture time-frequency structure, preserving the true statistical 'information' in a signal, and exposing redundancy. Thus, as actual signal information is represented by fewer coefficients, the signal has in effect been reduced. Hence a loss-loss coding algorithm can exploit the reduction and compress the data.

In practice, digital data derived from the protection system operating contacts would be compressed separately, typically using a loss-less LZW algorithm, and packaged with the coded analogue data to create a composite (and reduced) record envelope. A telemetry driven system could therefore feasibly dispatch the record envelope over a low-bandwidth communications link for decompression and visual assessment, [9]. The subsequent reduction in communications time for remote retrieval means that the proposed method would be potentially useful for near real-time applications in protection telemetry and assessment in single-ended, and perhaps more importantly, differential protection schemes.

5. Conclusions

This paper has proposed the integration of wavelets in a transform compression scheme to reduce the volume of point on wave data generated by power system network faults. The intended scheme would improve the scope of information available for protection system assessment. The scheme indicates that a loss-less compression algorithm can exploit redundancy inherent in the wavelet coefficients derived from signal transformation. Further research is required to establish the viability of the scheme in differential protection systems, and to determine criteria for selection of wavelet functions to best characterise the range of features in fault signatures.

The results indicate that compression ratios up to 10:1 with acceptable distortion are achievable. Although the proposed scheme is lossy, the results confirm that in certain instances minimal distortion may be acceptable if rapid access is required. The purpose of using the scheme is to reduce the communications burden across existing low-bandwidth serial and modem links to provide greater information access for protection assessment. This paper forms part of on-going research in the area of intelligent protection systems and instrumentation.

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