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A NEW PROTECTION RELAY BASED ON FAULT TRANSIENT ANALYSIS USING WAVELET TRANSFORM

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The paper presents novel approach in distribution protection technic of fault line selection based on analysis of generated transient. Advantages of discrete wavelet transform for signal analysis are discused. The potential of using discrete wavelet transform in protective relay is examined and model of relay using transient phenomena to fault line selection in distribution system is proposed and next integrated into ATP simulation program. Detailed model of distribution system was made in ATPDraw with connected relay through CT model for consideration of possible saturation effect. Simulations were performed for algorithm evaluation with included detailed model of arc fault or high impedance ground fault and results show excellent discrimination function under various operating conditions.

K e y w o r d s: digital relay model, discrete wavelet transform, fault transient, arc model

1 INTRODUCTION

The development of microprocessor based protection relays has started in 70's and lasts till present. From that moment, there has been a great research progress in the development of digital protection techniques. Moreover, the digital protection algorithm has been applied to almost every area of power system protection [1, 3]. The development in the area of power transmission system protection has been primarily concerned with the protection of transmission line systems. On the other side, there has been minor achievement in the distribution system protection [7, 9, 11]. It could appear that the distribution system is not so important compared with the transmission system in term of protection. In fact, the problems involved in the development of new digital techniques for distribution systems is far greater than that for transmission. One of the reasons is that the configuration of distribution systems is much more complicated than that of transmission systems. Due to the interaction between all the components, an overall approach is required to take care the whole network rather than an individual feeder. Furthermore, there is no convenient voltage instrument transformer available in many distribution systems. Most of the new developed digital algorithms are based on the measurement of voltage and current signals, such as impedance algorithms and travelling wave directional algorithms [5, 6].

With the development of micro-electronic technology, the computational power of microprocessors and Digital Signal Processors (DSP) has been greatly increased and the costs have reduced. It is now realised that the time for the development of cost effective protection for the distribution system is coming. At the same time, recent developments in power system protection have provided new relaying principles suitable for distribution system protection [8]. In particular, the newly developed transient directional relay [11] and transient directional comparison scheme do not require the voltage transducer. It will be a great step in distribution system protection if the techniques can be successfully applied in this area [12].

Signal analysis tools, currently used in the digital relays, have shown that are very useful and efficient in power system steady state analysis. Among these are Kalman filtering based algorithms, fourier analysis based algorithms, least squares methods based algorithms and FIR filtering based protection [2]. However in presence of non-stationary signals, the performance of these techniques is limited. A more recent solution to the problem is the wavelet transform. F Jiang states that the wavelet analysis has the capability of providing accurate transient information in both time and frequency domain [11]. The current and voltage signals obtained from a line when a fault occurs have long duration low frequency components and short duration high frequency components. Wavelet transforms appear to offer the right characteristics to analyze the information contained in these signals for the purpose of line protection. Wavelet transform has a special feature of variable time-frequency localization, which is very different from windowed Fourier transform. This feature can be explored as an alternative to the methods mentioned above.

Conventional FFT spectral estimation is based on a Fourier series model of the data, that is the process assumed to be composed of a set of harmonically related sinusoids. This approach to spectrum analysis is computationally efficient and produces reasonable results for a large class of signal processes. In spite of these advantages there are several inherent performance limitations of the

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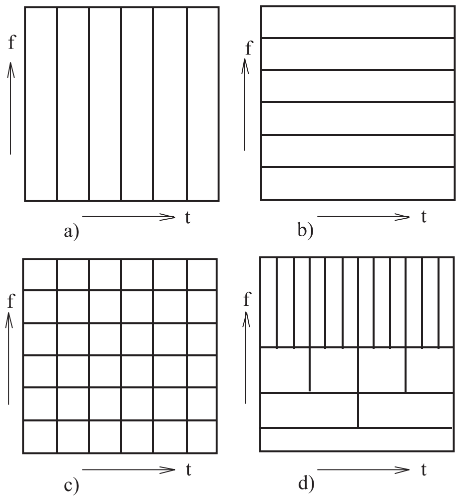

Fig. 1. The time-frequency tilling a) time domain (Shannon), b) frequency domain (Fourier), c) STFT (Gabor), d.) DWT.

FFT approach. The most prominent limitation is that of frequency resolution, i.e. the ability to distinguish the spectral responses of two or more signals. Because of some invalid assumptions (zero data or repetitive data outside the duration of observation) made in this methods, the estimated spectrum can be a smeared version of the true spectrum. A second limitation is due to windowing of the data, that occurs when processing with the FFT. Windowing manifests itself as leakage in the spectral domain — energy in the main lobe of a spectral response leaks into the side-lobs, obscuring and distorting other spectral responses that are present. These two performance limitations of the FFT approach are particularly troublesome when analyzing short data records. Short data records occur frequently in practice, because many measured processes are brief in duration or have slowly time-varying spectra, that can be considered constant only for short record lengths. In an attempt to alleviate the limitations of the FFT approach, many alternative spectral estimation procedures have been proposed within the last 4–5 decades. In the case of a non-stationary signal, any change of the signal causes a continuous spectrum which spread out over the whole frequency axis. Therefore other methods of analysis are needed, to get a two-dimensional timefrequency representation $S(t,\omega)$ of the investigated signal. First, Gabor has adapted the Fourier Transform to define the $S(t,\omega)$, assuming that the signal is stationary when seen through a window of limited extent. This yields the Short-Time Fourier Transform (STFT). The time varying spectra of non-stationary time series commonly used are spectrograms, from the STFT. If a signal is composed of small bursts of components, then each type of component can be analyzed with good time resolution or frequency resolution, but not both. To overcome the resolution limitation, the Wavelet Transform (WT) has been developed [10, 11, 12]. Wavelet Transform provides a unified framework for a number of methods, which have been developed independently for various signal processing applications. In contrast to the STFT, the WT uses short windows at high frequencies and long windows for low frequencies as is shown in Fig. 1. Using the WT, the time-varying spectra of non-stationary signals can also been obtained in form of scalograms. Scalogram is defined as the squared modulus of the WT. In contrast to the spectrogram the energy of the signal is here distributed with different resolutions.

2 DISCRETE WAVELET TRANSFORM

The Wavelet Transform provides a time-frequency representation of the signal. It was developed to overcome the short coming of the Short Time Fourier Transform (STFT), which can also be used to analyze non-stationary signals. While STFT gives a constant resolution at all frequencies, the Wavelet Transform uses multi-resolution technique by which different frequency spectrums are analyzed with different resolutions [10].

A wave is an oscillating function of time or space and is periodic. In contrast, wavelets are localized waves see Fig.2. They have their energy concentrated in time or space and are suited to analysis of transient signals. While Fourier Transform and STFT use waves to analyze signals, the Wavelet Transform uses wavelets of finite energy.

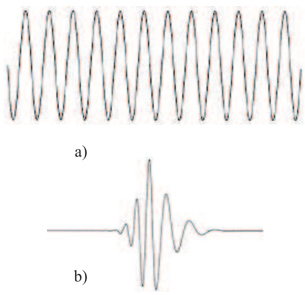

Fig. 2. Demonstration of a) a wave and b) a wavelet.

The wavelet analysis is done similar to the STFT analysis. The signal to be analyzed is multiplied with a wavelet function just as it is multiplied with a window function in STFT, and then the transform is computed for each segment generated. However, unlike STFT, in Wavelet Transform, the width of the wavelet function changes with each spectral component. The Wavelet Transform, at high frequencies, gives good time resolution and poor frequency resolution, while at low frequencies, the Wavelet Transform gives good frequency resolution and poor time resolution.

The wavelet transform is a recently developed mathematical tool for signal analysis. It has become a very important tool for research in the field of mathematics, physics and engineering. It transforms a time domain signal to time-scale domain. This process of transformation is called signal decomposition because a signal is decomposed into several other signals with different level of resolution. Wavelet transform is a linear transform but with

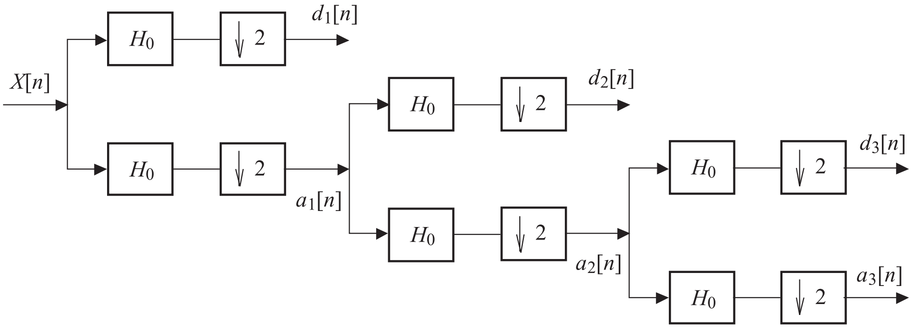

Fig. 3. Three-level wavelet decomposition tree.

the special property: it has time location as well as frequency location at the same time and higher frequency according to shorter duration, vice versa. Such multiresolution property is particularly suited for analyzing transient signals. For the analysis of the transient signal the dyadic wavelet transform is the most suitable and useful wavelet transform in all wavelet transforms for the purpose. Another important reason that wavelet transform is attractive for engineers is there are fast calculation algorithms which are based on filter bank.

The discrete wavelet transform (DWT) given by (1) is one of the three forms of wavelet transform.

$$DWT\,x(m,n) = a_0^{-m/2}\Bigg(\sum_n X[n]\Psi^*\Big[\frac{k - na_0^m b_0}{a_0^m}\Big]\Bigg) \quad (1)$$

Ψ is the *mother* wavelet, the asterisk in (1) denotes a complex conjugate, a_0^m, $na_0^m b_0$ are the scaling and shifting parameters respectively, $k, m, n \in Z$ (Z is the set of positive integers).

It moves a time domain discritized signal into its corresponding wavelet domain. This is done through a process called "sub-band codification", which is done through digital filter techniques. In the signal processing theory, to filter a given signal $X[n]$ means to make a convolution of this signal. This is illustrated in Fig. 3, the $X[n]$ signal is passed through a low-pass digital filter (G_0) and a high-pass digital filter (H_0). After that, half of the signal samples are eliminated. Basically, the DWT evaluation has two stages.

The first consists on the wavelet coefficients determination. These coefficients represent the given signal in the wavelet domain. From these coefficients, the second stage is achieved with the calculation of both the approximated and the detailed version of the original signal, in different levels of resolutions, in the time domain. At the end of the first level of signal decomposition (as illustrated in Fig. 3), the resulting vectors $d_1[n]$ and $a_1[n]$ will be, respectively, the level 1 wavelet coefficients of approximation and of detail. In fact, for the first level, these wavelet coefficients are called $a_1[n]$ and $d_1[n]$, respectively, as stated bellow (2):

$$\begin{aligned} a_1[n] &= \sum_n X[n]G_0(k-2n)\,, \\ d_1[n] &= \sum_n X[n]H_0(k-2n)\,. \end{aligned} \quad (2)$$

Next, in the same way, the calculation of the approximated ($a_2[n]$) and the detailed ($d_2[n]$) version associated to the level 2 is based on the level 1 wavelet coefficient of approximation ($a_1[n]$). The process goes on, always adopting the "$n-1$" wavelet coefficient of approximation to calculate the "n" approximated and detailed wavelet coefficients. Once all the wavelet coefficients are known, the discrete wavelet transform in the time domain can be determined. This is achieved by "rebuilding" the corresponding wavelet coefficients, along the different resolution levels. This procedure will provide the approximated ($a_j[n]$) and the detailed ($d_j[n]$) version of the original signal as well as the corresponding wavelet spectrum Fig. 4.

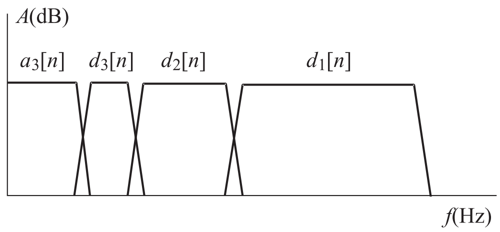

Fig. 4. Example of covering the finite spectrum with the spectra of dilated wavelets for three-level wavelet decomposition.

3 PRINCIPLE OF FAULT LINE SELECTION

A fault in a power system generates transient current with wide frequency spectra. The transient current will travel outward from the faulty point along the lines. When the current wave meets a discontinuity point in the system, such as a busbar, part of the current wave will be reflected back while some of the current will continue to travel along the connected circuits. A busbar is usually connected to many power apparatuses such as power transformers and generating units, the characteristics of these apparatuses will determine the busbar to earth impedance that is normally conductive in nature. However, the capacitance and capacitive coupling become the dominant factor in the busbar impedance at significant high frequencies. Therefore, a substantial amount of the transient current, particularly the higher frequency components, will be routed to the earth through the busbar capacitance. This fact is the key factor of developing the transient current based protection scheme on which the fault line selection is based. The relay principle can

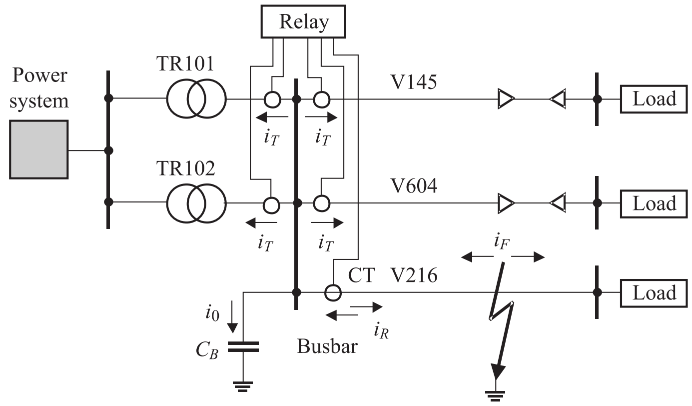

Fig. 5. A multi-section line system.

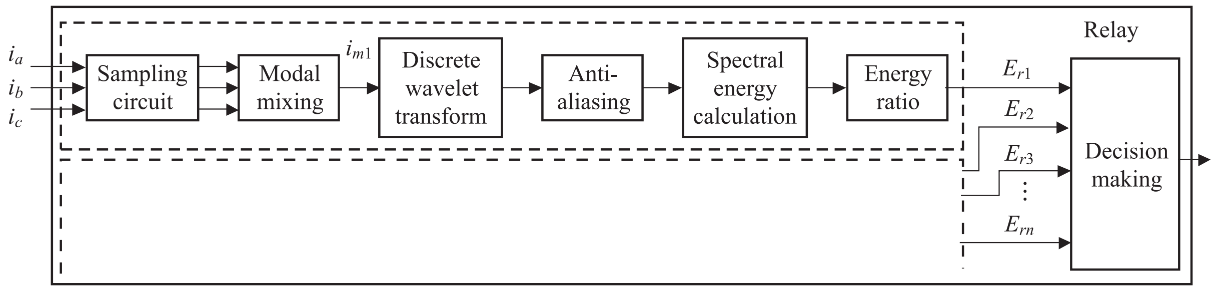

Fig. 6. Block diagram of the proposed relay unit.

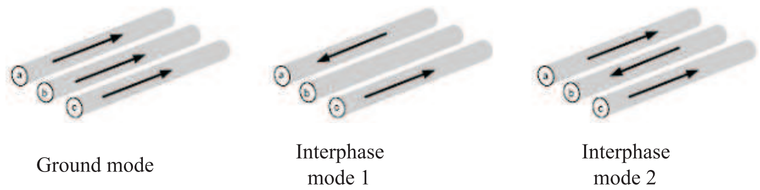

Fig. 7. Natural modes of a three-phase power line.

be illustrated with the power system shown in Fig. 5. If a fault occurs in the system, a transient current i_F, which contains wide-band frequency components, will be initiated towards busbar. When the current wave arrives at busbar R, a portion of the current, i_T, will continue to travel into other outlets and portion will be reflected back to the line i_R. However, part of the current, i_0, will be shunted by the capacitance at busbar. As a result, the fault transient currents i_T, detected by relay at healty outlets will be attenuated in comparison with the initial current i_F.

It is clear that, a higher frequency component will be more significantly attenuated than a lower frequency component since the equivalent admittance of a busbar to earth increases with the increasing of the frequency. As a result, the fault transient of faulty line will contain more high frequency component than that of an healty line. Consequently, a ratio of a high frequency component to a low frequency component can be used to determine what line is faulty. To implement this concept, the frequency components of the fault transient signal need to be analysed.

4 RELAY MODEL DESIGN

Principle of proposed relay is graphicaly described in block diagram on Fig. 6.

Because of mutual inductances of three phases, the fault currents in three phases are hard to be analyzed. In power line transient analyses, a single real transformation matrix can be used to obtain exact modes. The new algorithm use model components instead of phase components. The result of every model component is uncoupling. On three phase transmission line the transients can be considered to propagate as independent modes. The modal voltages v_m and modal currents i_m are related to the phase voltage v_{ph} and current i_{ph} by:

$$\begin{aligned} [v_m] &= \left[S^{-1}\right]\left[v_{ph}\right], \\ [i_m] &= \left[Q^{-1}\right]\left[i_{ph}\right] \end{aligned} \tag{3}$$

where $[S]$ and $[Q]$ are the modal voltage and current transformation matricies respectively. The modal components comprise of one ground mode and two aerial modes are on Fig. 7.

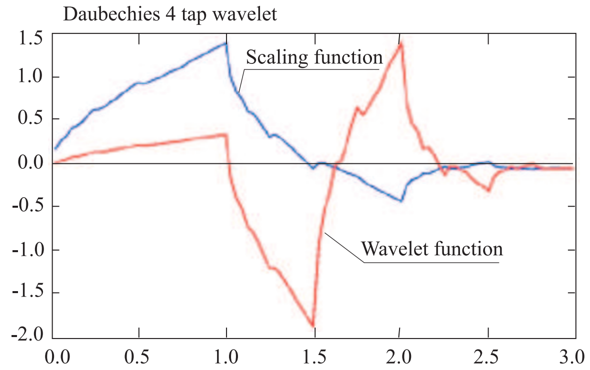

Fig. 8. Daubechies 4 mother wavelet.

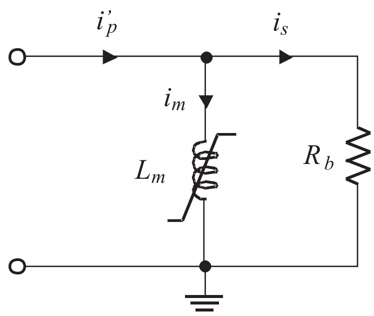

Fig. 9. CT modeling for the relay transient studies.

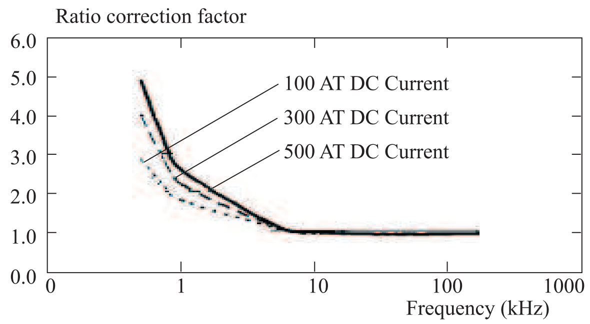

Fig. 10. Ratio correction factor vs frequency current transformer with DC saturation current.

To a good approximation the aerial modes have low attenuation and a constant propagation velocity and can reliably be used in protection schemes.

$$[S] = [Q] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & -2 \\ 1 & -1 & 1 \end{bmatrix} \tag{4}$$

Also, since the power lines and substation busbars are reasonably balanced, very little modal mixing occurs at the busbar. Each mode is therefore independent of the other modes and behaves the same as for the single phase case. Thus each aerial mode can be used to give direction information at the substation busbar. Other interesting characteristics of this matrix transformation are: frequency independent, line parameter independent, identical for voltage and current determination.

As can be seen in Fig. 5, the relay is interfaced to the CTs on every line emanating from the substation busbar. The modal mixing block receives the sampled signals from the three phase CTs and combines the three phases to form Mode 2 signal. The main part of the relay is the discrete wavelet transform. The outputs of the modal mixing circuit are then passed to the discrete wavelet transform decomposition. For the protection relaying purposes the wavelet should have properties like availability of discrete transform, compact support, FIR filter implementation, fast algorithm and orthogonal or biorthogonal analysis. For real time relaying purposes the speed of algorithm and easy computation are very important. Since the wavelets, Mexican hat, Morlet and Meyer do not have discrete transform and fast algorithm implementation, so they were not considered. The wavelets designed by Daubechies have the properties required so they were investigated. Daubechies wavelets are the most popular wavelets. They represent the foundations of wavelet signal processing and are used in numerous applications. These are also called maxflat wavelets as their frequency responses have maximum flatness at frequencies 0 and π. For short and fast transient disturbances, such as the case of this study, db4 are better, while for slow transient disturbances, db8 are particularly good. The mother wavelet used in this study is db4 shown in Fig. 8.

The Daubechies D4 transform has four wavelet and scaling function coefficients. The scaling function coefficients are:

$$\begin{aligned} h_0 &= \frac{1+\sqrt{3}}{4\sqrt{2}}\,, & h_1 &= \frac{3+\sqrt{3}}{4\sqrt{2}}\,, \\ h_2 &= \frac{3-\sqrt{3}}{4\sqrt{2}}\,, & h_3 &= \frac{1-\sqrt{3}}{4\sqrt{2}}\,. \end{aligned} \tag{5}$$

The wavelet function coefficient values are:

$$g_0 = h_3\,,\ g_1 = -h_2\,,\ g_2 = h_1\,,\ g_3 = -h_0\,. \tag{6}$$

The scaling and wavelet functions are calculated by taking the inner product of the coefficients and four data values. The equations are shown below:

$$\begin{aligned} a_i &= h_0 s_i + h_1 s_{i+1} + h_2 s_{i+2} + h_3 s_{i+3}\,, \\ d_i &= g_0 s_i + g_1 s_{i+1} + g_2 s_{i+2} + g_3 s_{i+3}\,. \end{aligned} \tag{7}$$

Before energy integral computation for higher accuracy details and approximation of DWT are resampled and anti-aliased by digital low-pass filters tuned to top frequency of each detail. The protection scheme based on this technique is to extract the windowed average energy spectrum of fault generated transients. The relay consists of wavelet multi-channel filter banks which are designed to capture two wanted signal components, *ie* d_1 and d_2. Then the spectral energies of two extracted signals, Ed_1 and Ed_2, can be represented by the area covered by the d_i^2 curve and so as to be found by the integral as shown below

$$ED_i(n\Delta T) = \sum_{k=n-M}^{n} d_i^2[k\Delta T]\Delta T \tag{8}$$

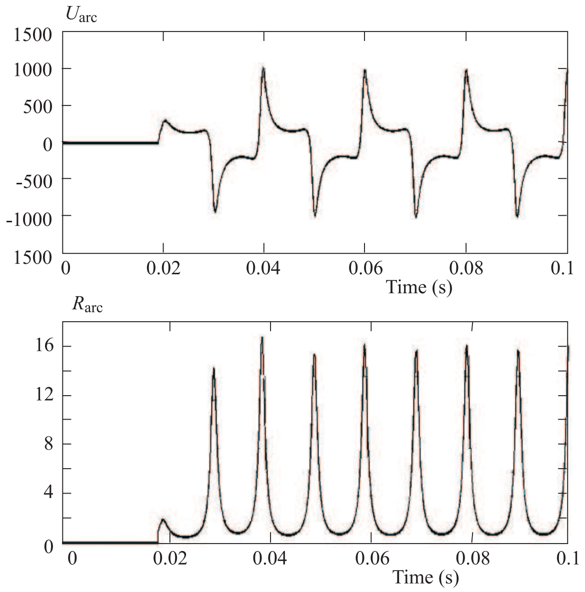

Fig. 11. Example of arc fault voltage and resistance time behaviours.

where Ed_i — energy in i-th DWT detail, d_i — DWT detail, ΔT — sampling time step, M — number of samples in the window.

The ratio of a lower frequency energy signal, E_1, to a higher frequency energy signal, E_2, determining fault line selection to the protected zone, is given in (9). Where a delay is introduced for the high frequency signal to compensate the running time difference between different frequency filters. $E_{ri} = Ed_1 \big/ delay(Ed_2)$. Energy ratios from all busbar outlets are sent to decision making unit where fault line selection is realised. With this arrangement, the response of the scheme is not affected by the power frequency short-circuit level at the terminating busbars or the precise configuration of the source side networks. The sampling frequency of sampling circuit used is 143 kHz and resulting cut-off frequencies of WT filter bank are in Tab. 1.

Table 1. Table of WT detail frequency bandwidth.

detail no.	f_L [Hz]	f_H [Hz]
1	35714.29	71428.57
2	17857.14	35714.29
3	8928.57	17857.14
4	4464.29	8928.57

4 RELAY FUNCTION VALIDATION

The power system was modeled in ATP-Draw according to fig.5 with various fault scenarios and fault types as metallic fault, arcing fault and high impedance fault.

CT model

For the relay transient studies simplified equivalent CT model is used as shown in Fig. 9. The magnetizing branch L_m is a non-linear element determined from CT V-I characteristic. The $R_b = R_S + R_1$ is the CT secondary winding resistance together with burden resistance including lead resistance.

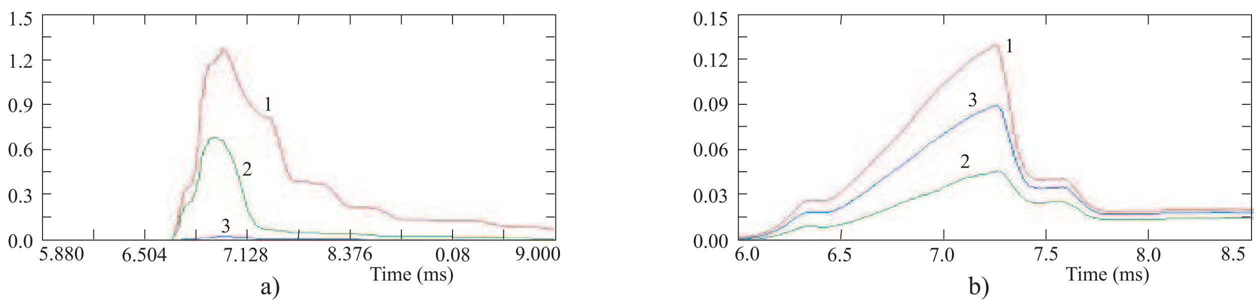

Fig. 12. Time behaviour of 1st and 4th WT detail energy ratio in unloaded compensated 22 kV distribution system with 25 % of cables for a.) 1 phase to ground arc fault, b.) 1 phase to ground 100 kΩ fault.

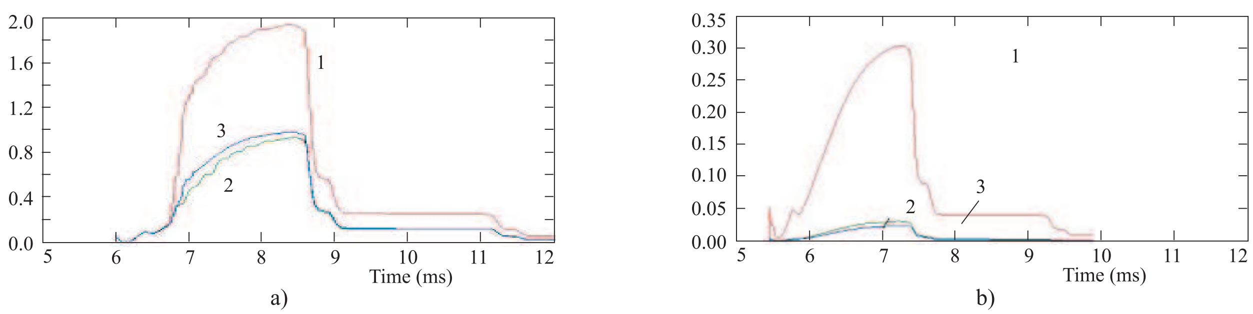

Fig. 13. Time behaviour of 1st and 4th WT detail energy ratio in max. loaded compensated 22 kV distribution system with 25 % of cables for a.) 1 phase to ground arc fault, b.) 1 phase to ground 100 kΩ fault.

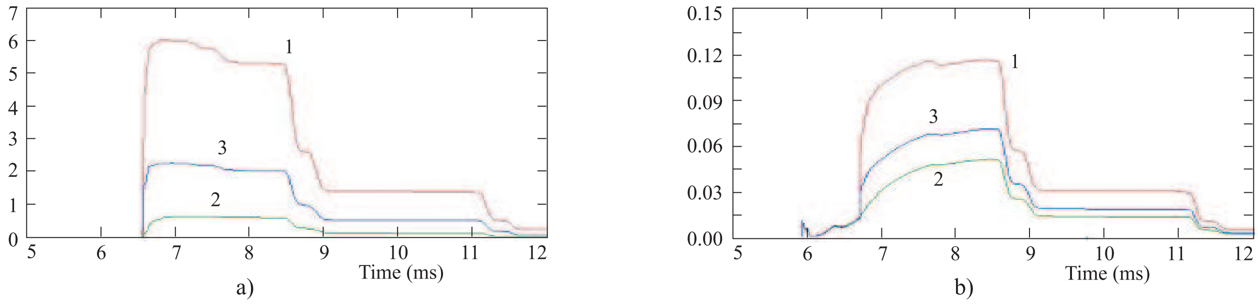

Fig. 14. Time behaviour of 1st and 4th WT detail energy ratio in unloaded compensated 22 kV distribution system without cables for a.) 1 phase to ground arc fault, b.) 1 phase to ground $100\,\mathrm{k\Omega}$ fault.

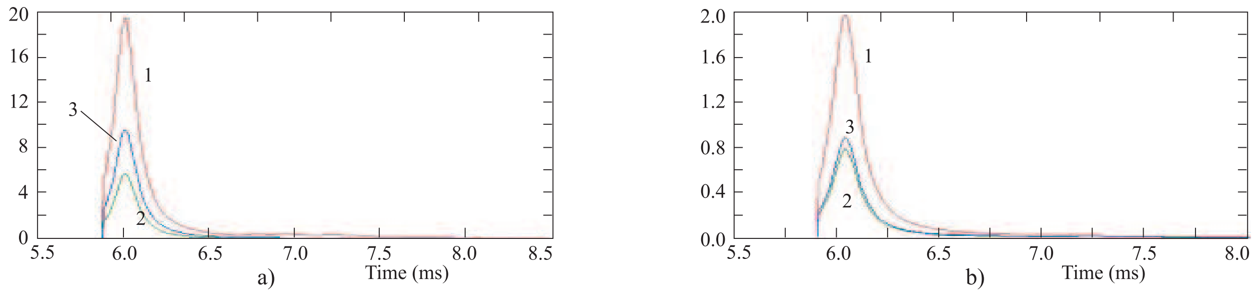

Fig. 15. Time behaviour of 1st and 4th WT detail energy ratio in max. loaded compensated 22 kV distribution system without cables for a.) 1 phase to ground arc fault, b.) 1 phase to ground $100\,\mathrm{k\Omega}$ fault.

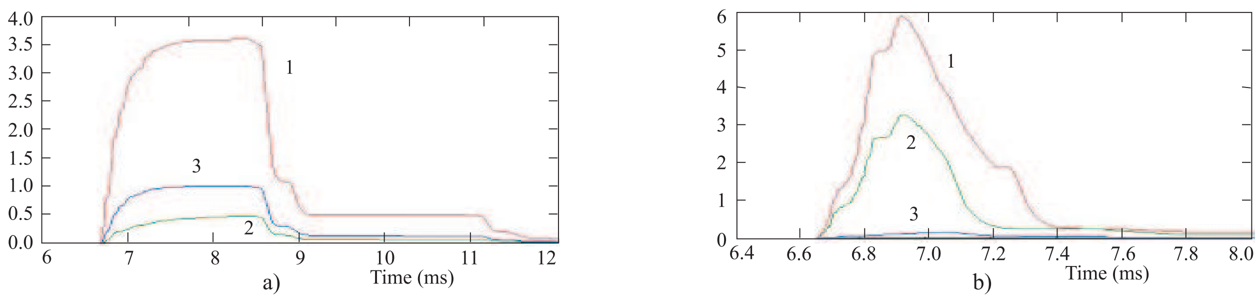

Fig. 16. Time behaviour of 1st and 4th WT detail energy ratio in compensated 22 kV distribution system with 25 % of cables for a.) double phase to ground short in max. loaded system, b.) three fhase to ground short in unloaded system.

The magnetizing branch is connected on CT secondary because V-I curve measurements are regularly performed from CT secondary side. Hysteresis representation is not necessary in the most relay studies.

Current transformer saturation has been shown to degrade the transformer action, but this is found to be restricted to frequencies lower than 7 kHz. For all distribution current transformers similar characteristic as shown on Fig. 10 is valid. For this reason, relay protection scheme uses WT details with higher frequencies than 7 kHz to be resistent from CT saturation.

Arc model

This model takes into account real interaction of the arc and the electromagnetic transient in the line during the arcing process correctly, since sudden changes in the arcing conditions arise following a partial arc extinction. The arc can be represented by a Type-91 TACS/MODELS controlled resistance in the ATP. When solving the differential equation (10) in the s domain by using MODELS's LAPLACE function, the time varying arc conductance g can be obtained as:

$$g(t) = \frac{1}{1+\tau s} G(t)\,, \tag{10}$$

$$G = \frac{|i_{arc}|}{(u_0 + r_0|i_{arc}|)l_{arc}(t)} \tag{11}$$

where τ is the time constant of the arc, g is instantaneous arc conductance, G is stationary arc conductance, l_{arc} id instantaneous arc length, u_0 is characteristic arc voltage, r_0 is characteristic arc resistance.

Chosen simulation results of energy ratio calculated by relay are shown on Fig. 12 to Fig. 16 for system configurations with pure overhead lines and with 25 % of cables for 1 phase to ground arcing or high ohmic fault in loaded and unloaded states. Also double and three phase short circuit faults are documented to show correct fault line selection of relay. This few results are very small part from hundreds simulations that were carried to verify correct function of this relay directional discrimination. In all cases fault was on line "1" behaviour marked with "2" corresponds to healty line and "3" is healthy feeder.

Figure 17 documents the effect of bus capacitance. Y axis is difference between maximum value in energy ratio of faulted line and maximum value in energy ratio of most significant outlet from healty outlets in p.u.

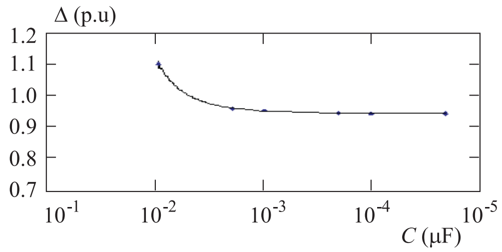

Fig. 17. The effect of bus capacitance.

5 CONCLUSION

The principle of relay direction discrimination based on decomposition of fault transient by wavelet transform was examined above. The relay responses with respect to different fault and system conditions were examined. Results show that the proposed technique is able to give correct responses in all cases. The technique also offers many other advantages, such as insensitivity to fault type, fault position, fault path resistance and fault inception angle. It is also resistent to CT saturation and system short-circuit levels. When the fault occurs at a voltage zero point, the scheme relies on the high frequency signals generated by the fault arc because the travelling waves are virtually non-existent for this type of fault.

Acknowledgement

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