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Investigations of Influence on Power Quality of Superconducting Fault Current Limiter

***Abstract**. Waveforms obtained from a superconducting Fault Current Limiter are investigated using the Prony modelling technique. Comparable measurements with the use of standard tools of spectral analysis (like FFT) fail because of short data available and low levels of higher spectral components.*

***Streszczenie.** W pracy przedstawiono wyniki analizy widmowej prądów i napięć zarejestrowanych w obwodach z nadprzewodzącym dławikiem przetężeniowym. Zastosowano metodę parametrycznego modelowania za pomocą metody Prony. Klasyczne metody oparte na FFT zawodzą w tym przypadku z powodu krótkich sekwencji danych, niestacjonarności przebiegów i niskiego poziomu wyższych harmonicznych.*

Keywords: Prony method, Superconducting Fault Current Limiter, harmonic analysis, power quality.
Słowa kluczowe: metoda Prony, nadprzewodzący dławik przetężeniowy, analiza widmowa, jakość energii.

Introduction

The quality of voltage waveforms is nowadays an issue of the utmost importance for power utilities, electric energy consumers and also for the manufactures of electric and electronic equipment. The voltage waveform is expected to be a pure sinusoidal with a given frequency and amplitude. Modern electric apparatus generate a wide spectrum of components which can deteriorate the quality of the delivered energy, increase the energy losses as well as decrease the reliability of a power system. Investigated signals contain multiple harmonic components and present often non-stationary behaviour [1].

The standard method for studying time-varying signals is short-time Fourier transform (STFT) where the Fourier transform is applied to a windowed signal to obtain the energy distribution along the frequency direction at the time corresponding to the centre of the window. The crucial drawback of this method is that the length of the window is related to the frequency resolution. Increasing the window length leads to improving frequency resolution but it means that the non-stationarities occurring during this interval will be smeared in time and frequency. This inherent relationship between time and frequency resolution becomes more important when one is dealing with signals whose frequency content is changing. [2]

In this paper the time-varying characteristics of power system signal components are estimated using the Prony model [3].

Prony method is a technique for modeling sampled data as a linear combination of exponentials [4]. Although it is not a spectral estimation technique, Prony method has a close relationship to the least squares linear prediction algorithms used for AR and ARMA parameter estimation. Prony method seeks to fit a deterministic exponential model to the data in contrast to AR and ARMA methods that seek to fit a random model to the second-order data statistics. The paper [3] presents a new method of real-time measurement of power system frequency based on Prony model.

The paper contains detailed analysis of the fundamental component waveforms of the currents and higher harmonic analysis of the voltages recorded at the test setup with a superconducting Fault Current Limiter (FCL) using the Prony method, recalled below.

Fault Current Limiter

For the large-scale power system, the development of FCLs for suppressing the over fault currents is strongly desired. FCLs with diverse principles, which apply superconducting techniques, have been proposed, such as: resistive, inductive, magnetic shielding and saturated core FCLs, etc [5]. The structure of a prototype saturated core FCL incorporating the DC HTS (High Temperature Superconductor) bias winding is shown in Fig. 1.

Because of the nonlinear influence of the saturated magnetic core, it is expected that the currents and voltages measured from the testing circuit shown in Fig. 2 can show a certain level of harmonic and interharmonics components as well as non-characteristic components.

The DC bias winding for FCL is expected to use HT superconductors, which will drive the core into saturation with a low DC power supply voltage. In this case of investigated Saturated Core High Temperature Superconducting Fault Current Limiter (FCL) [5] the spectral contents of the currents and voltages and, therefore, periodicity intervals are unknown. Detection of additional frequency components can be used for assessment of the impact of such devices on the quality of energy and for fault identification.

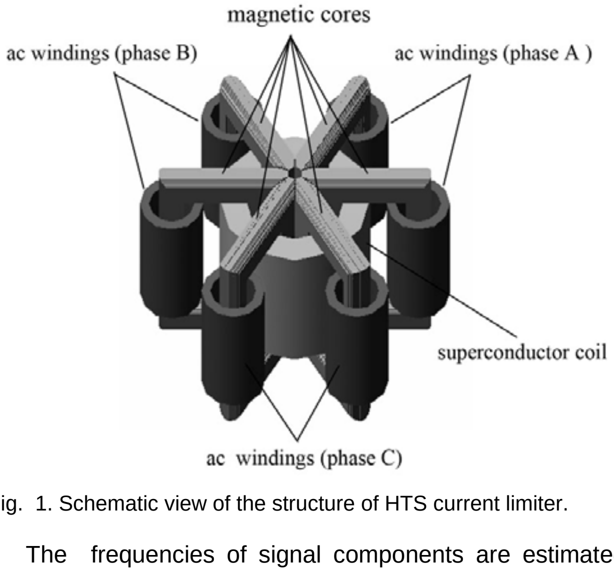

Fig. 1. Schematic view of the structure of HTS current limiter.

The frequencies of signal components are estimated using the Prony model. Prony method is a technique for modelling sampled data as a linear combination of exponentials. Although it is not a spectral estimation technique, Prony method has a close relationship to the least squares linear prediction algorithms used for AR and ARMA parameter estimation. Prony method seeks to fit a deterministic exponential model to the data in contrast to AR and ARMA methods that seek to fit a random model to the second-order data statistics [6] .

Prony Method

Assuming the M data samples $[x_1,\ x_2,\ \ldots\ x_M]$ the investigated function can be approximated by p exponential functions:

$$y[n]=\sum_{k=1}^{p}A_k e^{(\alpha_k+j\omega_k)(n-1)T_s+j\psi_k} \tag{1}$$

where $n=1,2,\ldots,M$

T_s – sampling period, A_k – amplitude,

α_k – damping factor, ω_k – angular velocity,

ψ_k – initial phase.

The following vectors can be defined :

$$\mathbf{x}_{w0}=\begin{bmatrix}x_p & x_{p-1} & \cdots & x_1\end{bmatrix} \tag{2}$$

$$\mathbf{x}_{k0}=\begin{bmatrix}x_p & x_{p+1} & \cdots & x_{M-1}\end{bmatrix}^T \tag{3}$$

$$\mathbf{x}_{k1}=\begin{bmatrix}-x_{p+1} & -x_{p+2} & \cdots & -x_M\end{bmatrix}^T \tag{4}$$

$$\mathbf{x}_{k2}=\begin{bmatrix}x_1 & x_2 & \cdots & x_p\end{bmatrix}^T \tag{5}$$

where p is the assumed number of exponential components, which can approximate the investigated signal.

The Toeplitz matrix:

$$\mathbf{t}=\begin{bmatrix}x_p & x_{p-1} & \cdots & x_1\\ x_{p+1} & x_p & \cdots & x_2\\ \vdots & \vdots & & \vdots\\ x_{M-1} & x_{M-2} & \cdots & x_{M-p}\end{bmatrix} \tag{6}$$

created from (2) and (3), makes it possible to determine the vector of coefficients **a** of the characteristic polynomial:

$$\mathbf{t}\cdot\mathbf{a}=\mathbf{x}_{k1}\ , \tag{7}$$

where:

$$\mathbf{a}=\begin{bmatrix}a_1 & a_2 & \cdots & a_p\end{bmatrix}^T \tag{8}$$

The roots of the characteristic polynomial:

$$z^p+a_1z^{p-1}+\ldots a_{p-1}z+a_p=0 \tag{9}$$

written in a vector form:

$$\mathbf{z}=\begin{bmatrix}\mathbf{z}_1 & \mathbf{z}_2 & \cdots & \mathbf{z}_p\end{bmatrix}^T \tag{10}$$

define a Vandermonde matrix:

$$\mathbf{v}=\begin{bmatrix}\mathbf{z}_1^0 & \cdots & \mathbf{z}_{p-1}^0 & \mathbf{z}_p^0\\ \mathbf{z}_1^1 & \cdots & \mathbf{z}_{p-1}^1 & \mathbf{z}_p^1\\ \vdots & \vdots & \vdots & \vdots\\ \mathbf{z}_1^{p-1} & \cdots & \mathbf{z}_{p-1}^{p-1} & \mathbf{z}_p^{p-1}\end{bmatrix}. \tag{11}$$

Vector of complex values **h** can be calculated from (5) and (11) solving the system of equations:

$$\mathbf{v}\cdot\mathbf{h}=\mathbf{x}_{k2} \tag{12}$$

where:

$$\mathbf{h}=\begin{bmatrix}\mathbf{h}_1 & \mathbf{h}_2 & \cdots & \mathbf{h}_p\end{bmatrix}^T. \tag{13}$$

Using the equations (10) and (13), parameters of exponential components for $k=1,\ 2\ ,\ldots\ ,p$ can be calculated from:

(14) $A_k=|\mathbf{h}_k|$ amplitude,

(15) $\phi_k=\arg(\mathbf{h}_k)$ initial phase,

(16) $\alpha_k=f_p\cdot\ln|\mathbf{z}_k|$ damping factor,

(17) $\omega_k=f_p\cdot\arg(\mathbf{z}_k)$ angular velocity.

Investigation results and discussion

Because of the short data records available (two periods of the fundamental component of 50 Hz), only limited extent of investigations was possible. The measurement setup is shown in Fig. 2. The signals under investigation were phase load currents sampled at the frequency of 5 kHz.

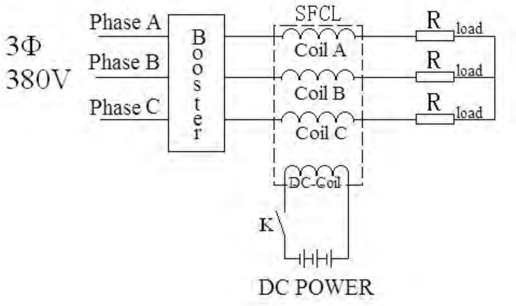

Fig. 2. Test measurement setup with FCL.

Initial investigations included the computation of current spectra using classical Welch spectrum. As expected, the presence of 3rd 5th and 11th harmonic was detected. Some additional basic results are presented in Table 1.

Table 1. Parameters of phase currents

	without FCL			with FCL		
phase	A	B	C	A	B	C
I_{RMS} [A]	39,7	35,0	34,7	38,3	34,3	33,9
THD %	9,87	6,20	5,65	10,69	5,94	5,66

Above presented results suggest a slight increase of harmonic distortion in the circuit with FCL and quite strong asymmetry between phases.

In the next step the analysis of fundamental frequency (50 Hz) was performed using the Prony method.

Fig. 3 shows the current in the circuit without FCL and Fig. 4. – current with FCL. Figures represent the fluctuations in time of frequency and of amplitude of the fundamental component of the current.

There is quite a strong evidence that FCL causes important fluctuations of parameters of the fundamental component. Nature of these fluctuations is periodical (when comparing results without FCL where fluctuations are lower and of stochastic nature with results with FCL- where fluctuations are much stronger and periodical.

When roughly comparing the fluctuations (over 2 periods) it appears that FCL causes 2.2 Hz and 1.016 (pu) of fluctuations compared to 1.3 Hz and 1.0086 pu without FCL. Results based on shorter data sequences (not reported in this paper) show higher values although these results can be less accurate and more affected more by noise.

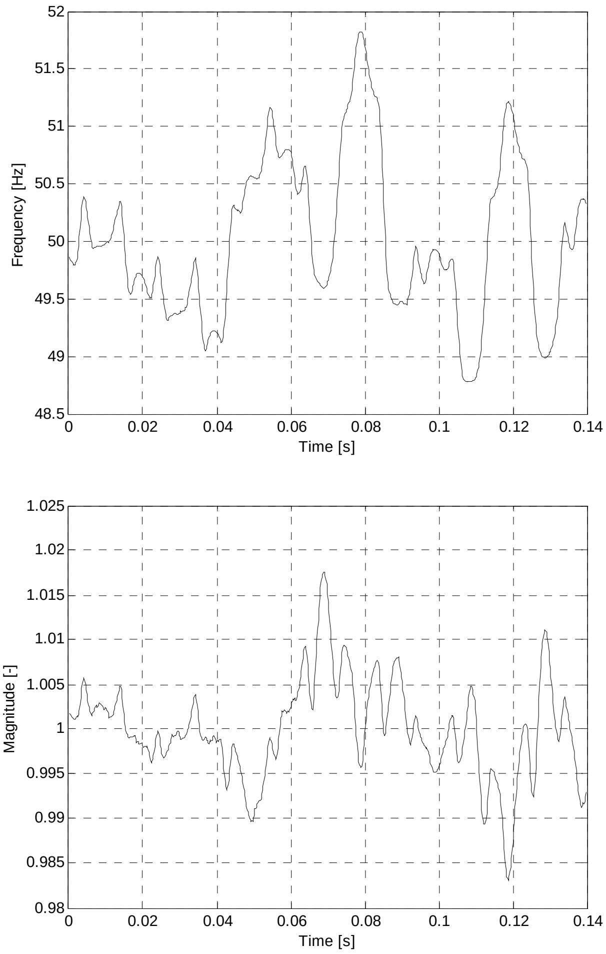

Fig. 3. Analysis of fundamental frequency of the current without FCL (50 Hz) using Prony method. (Upper –frequency, Lower-Magnitude).

In the next step the voltages recorded during tests with FCL were investigated. The Fig. 5 shows the voltage waveform in phase B with superposed approximated waveform using parameters obtained using the Prony method.

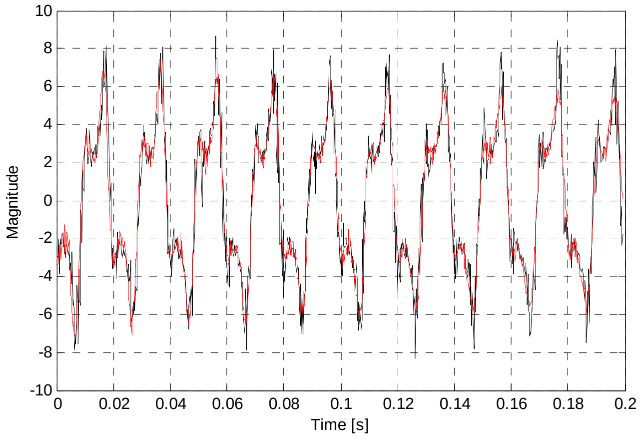

Fig. 4. Original (black) and approximated (using Prony method) (red) waveform of the voltage in phase B.

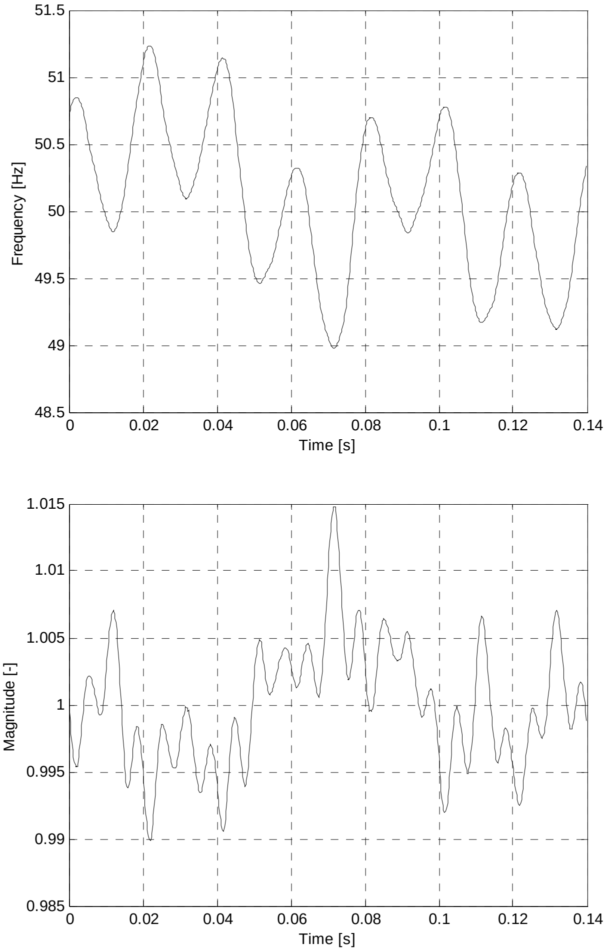

Fig. 5. Analysis of fundamental frequency of the current with FCL (50 Hz) using Prony method. (Upper –frequency, Lower-Magnitude).

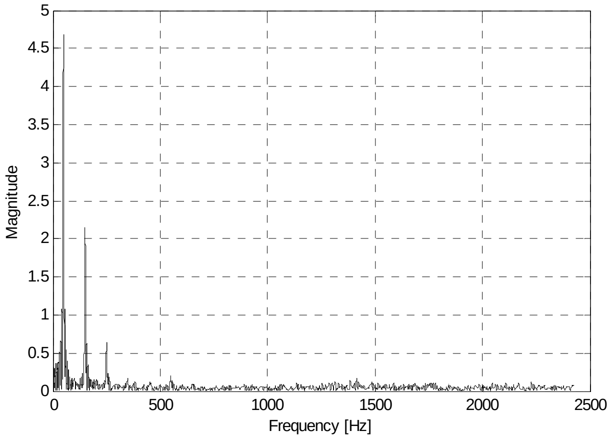

Fig. 6. Spectrum FFT of the voltage waveform.

The spectra of voltage waveforms are shown in Figs. 6 and 7. The FFT spectrum shows the presence of 3 harmonic components (fundamental, third and fifth harmonic) which is confirmed by Prony parameter estimation which yields the values of main spectral components as: 49,95Hz, 149,8Hz and 248,4Hz. It was also observed an expressed asymmetry between phases which needs further investigations.

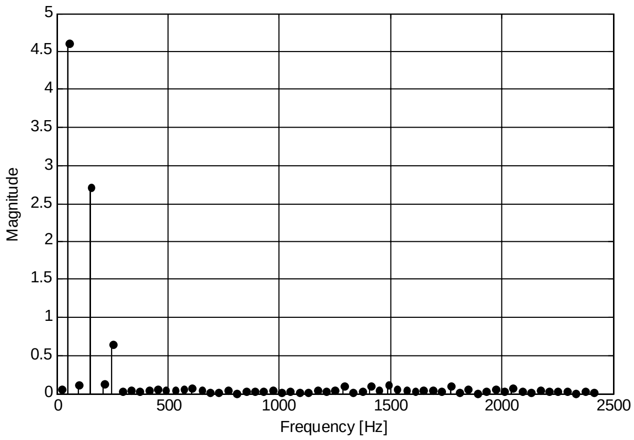

Fig. 7. Estimated spectral components of the voltage using Prony method.

Conclusions

Higher harmonics generated within the circuits with non-linear devices (such as Fault Current Limiter) can affect the power quality and disturb the function of connected apparatus. Therefore it is important to accurately know the spectral contents of investigated waveforms. The investigations show the advantages of parametric modelling using the Prony model, which delivers highly accurate results, even for short data records.

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