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A New Method for Fundamental Signal Extraction Based on Wavelet Transform

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Original scientific paper

In this paper, a new method is proposed for improving the fundamental extraction by wavelet transform. This method uses the discrete wavelet transform (DWT), FIR filter and inverse discrete wavelet transform (IDWT). In the proposed method, frequency interference is allowed to occur at the extracted frequency bands by DWT. DWT output signal is filtered by FIR then the IDWT is used to reconstruct the filtered signal. This process improves the quality of extracted fundamental component and transient response. To verify the validity of the proposed method, the electric distribution system of electric arc furnaces (EAFs) of Mobarakeh Steel Company is simulated in MATLAB software. Finally the fundamental component of the voltage of point of common coupling (PCC) is extracted by proposed method and DWT and IDWT method.

Key words: Fundamental component, Wavelet transform, FIR filter, EAF

Nova metoda izoliranja osnovne komponente signala zasnovana na transformaciji elementarnog vala. U radu je predložena nova metoda za unaprjeđenje određivanja osnovne komponente signala korištenjem transformacije elementarnog vala. Metoda koristi diskretnu transformaciju elementarnog vala (DWT), FIR filter i inverznu iskretnu transformaciju elementarnog vala (IDWT). Metoda dopušta interferenciju s DWT u frekvencijskom rasponu osnovne komponente. Izlazni DWT signal filtriran je pomoću FIR-a, a zatim se primjenjuje IDWT za rekonstrukciju filtriranog signala. Ovaj proces poboljšava kvalitetu određene osnovne komponente i odziva prijelazne pojave. Za provjeru vjerodostojnosti predložene metode, u MATLAB programu simuliran je sustav za elektrodistribuciju elektrolučne peći (EAF) za poduzeće Mobarakeh Steel Company. Konačno, osnovna komponenta napona točke zajedničkog spoja (PCC) određena je predloženom metodom uz DWT i IDWT.

Ključne riječi: Osnovna komponenta, transformacija elementarnog vala (valića), FIR filter, EAF

1 INTRODUCTION

Nowadays, with increasing the use of power electronic devices, EAFs (AC and DC), and induction furnaces, voltage and current harmonics are injected into the power systems [1-4]. These harmonics cause some problems such as decreasing capacity of transmission lines and increasing losses in power systems[5, 6]. Active power filters with various control algorithms are usually employed to remove the effects of harmonics from the power systems [7-9]. One of the very important issues in the active power filter algorithms is extraction the fundamental component of voltage and current signals.

Fourier-based methods are widely used for fundamental extraction. These methods have very good performance, but they are not suitable for the analysis of non-stationary signals. So, the wavelet transform based method has been proposed to resolve this problem and analysis of non-stationary signals [10-13]. In this method, the input signal is decomposed into several frequency bands by DWT and then the desired frequency band which contains the fundamental component is reconstructed by IDWT. In the DWT and IDWT method, the input signal is decomposed so that there is only one harmonic in each extracted frequency band. This process is used to prevent frequency interference.

In addition to the power quality, the most popular wavelet transform applications in power systems are power system transients, load forecasting, partial discharges, power system measurement and power system protection [14] that in all of them, the fundamental component extraction is necessary. Among the above mentioned applications, the fast response of the wavelet transform is a critical issue in the power quality, power system transients, power system measurement and power system protection. So, the aim of this paper is to propose a new method for improving the transient response of the fundamental extraction by wavelet transform.

To achieve the above objective, the fundamental extraction by DWT and IDWT is improved by FIR filter so that the output signal quality and the transient response will be improved. For this propose, the input signal is firstly decomposed by DWT, so that the extracted frequency band width is twice that of the DWT and IDWT method and the frequency interference is allowed to occur. Then a FIR filter is used and finally, the filtered signal by FIR filter is reconstructed by IDWT.

To verify validity of the proposed method and made a comparative study with the DWT and IDWT method, the electric distribution system of electric arc furnaces (EAFs) of Mobarakeh Steel Company is simulated in MATLAB software. The results confirm the superiority of the proposed method.This document is a template for Microsoft Word versions 6.0 or later.

2 WAVELET TRANSFORM

The wavelet transform is concluded in two discrete and continues forms. These forms are introduced in the next subsections.

2.1 Continues wavelet transform

Wavelet transform of continues signal is described by Eq. (1) [15].

$$W_f(a,\tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t)\psi^*\left(\frac{t-\tau}{a}\right) dt, \qquad (1)$$

where $\psi^*(t)$ is the complex conjugate of mother wavelet $\psi(t)$, τ is the phase shift and a is the scale. Mother wavelet is a function with limited period and zero average. Decomposition of a continuous signal by WT is [15]:

$$x(t) = \frac{1}{C_\psi} \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \frac{1}{a^2} W_f(a,\tau)\psi\left(\frac{t-\tau}{a}\right) da\, d\tau, \quad (2)$$

where

$$C_\psi = \int_{-\infty}^{+\infty} \frac{|\psi(\omega)|^2}{\omega} d\omega < \infty. \qquad (3)$$

2.2 Discrete wavelet transform

Three different methods have been proposed for implementation of DWT. These methods consist of multi-resolution analysis (MRA), windowed wavelet transform (WWT) and lifting wavelet transform (LWT).

2.2.1 MRA

In 1989, S.Mallat introduced MRA in the wavelet theory for implementation of DWT and unified the structure of wavelet orthogonal basis [16]. He proposed that discrete signals could be decomposed and reconstructed according to the wavelet transform. In the MRA, the input signal is firstly passed through high-pass ($g(z)$) and low-pass ($h(z)$) filters and then the results are down sampled by a factor 2 This process decomposes the input signal into Detail and Approximation where contain low and high frequency components, respectively. Figure 1 shows the one-level MRA structure. For increasing the MRA levels, several series of Fig. 1 are used.

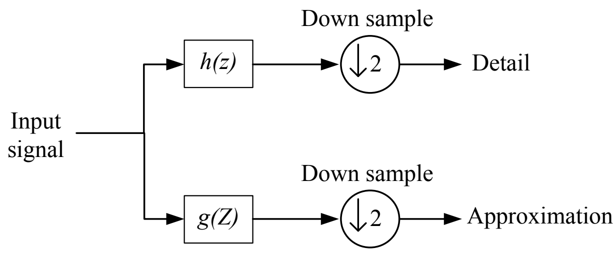

Fig. 1. One level multi-resolution analysis

The relationship between sampling frequency (f_s) and upper limit of the lowest frequency band (f_u) in the MRA can be expressed by [17]:

$$f_u = \frac{f_s}{2^{J+1}}, \qquad (4)$$

where J is the total number of MRA levels.

2.2.2 WWT

WWT is the same as MRA, but in WWT, the input signal must be windowed as a multiple of 2^N, where N is the number of MRA levels.

2.2.3 LWT

In the MRA, the input signal is passed through low-pass and high-pass filters and then is down sampled by 2. In other words, the whole data is firstly analyzed, and then the half of it is removed. This process increases the computational cost. For decreasing the computational cost in the LWT, the up sample is done after filtering. Moreover, it has been proven for long length filters that LWT can reduce the number of computations by half [18].

For obtaining the LWT, the FIR filters in MRA methods are divided into odd and even FIR filters that can be shown as (5). It is proven that, always exist Laurent polynomials

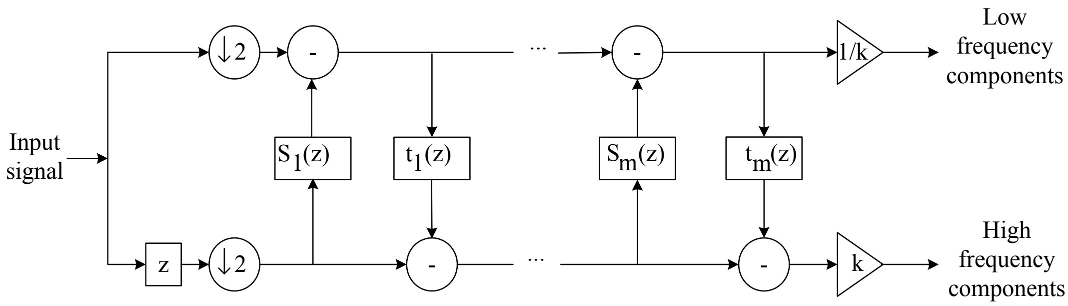

Fig. 2. Block diagram of LWT Proposed method

$s_i(z)$ and $t_i(z)$ for $1 \leq i \leq m$ and a non-zero constant k, so that $P(z)$ matrix can be written as (6) [19]:

$$P(z) = \begin{bmatrix} h_e(z) & g_e(z) \\ h_o(z) & g_o(z) \end{bmatrix}, \tag{5}$$

$$P(z) = \prod_{i=1}^{m} \begin{bmatrix} 1 & s_i(z) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ t_i(z) & 1 \end{bmatrix} \begin{bmatrix} k & 0 \\ 0 & 1/k \end{bmatrix}. \tag{6}$$

According to (5), the block diagram of LWT can be drawn as Fig. 2.

3 PROPOSED METHOD

In previous works, the using of DWT and IDWT has been proposed for extraction the fundamental component by wavelet transform. In this method, the frequency band width is selected so that there is only one harmonic in each frequency band. This is done to avoid frequency interference. In the proposed method, the extracted frequency band width is considered twice of DWT and IDWT method and the frequency interference is allowed to occur. Then, a FIR filter is used. The obtained signal is applied to the lowest frequency band of IDWT to reconstruct the fundamental component. This process improves transient response and quality of fundamental extraction. The proposed method is shown in Fig. 3.

4 SIMULATION RESULTS

To evaluate the proposed method, the electric distribution system of EAFs of Mobarakeh Steel Company is simulated in MATLAB software. This network is shown in Fig. 4-a. The EAF is connected to the PCC through the cable, furnace transformer (T_F) and main transformer (T_S). The T_F is used to change the active input power of the arc furnace via a tap changer which is located at the secondary winding.

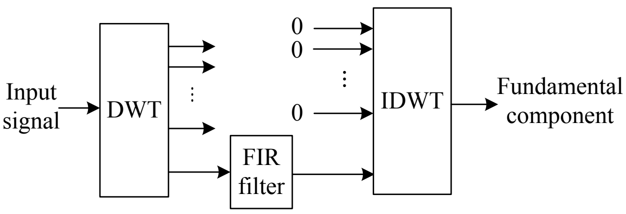

Fig. 3. Proposed method

The simplified model of simulated network is shown in Fig. 4-b. In this figure, all of impedances have been transferred into the secondary of T_F. Where X'_{LSC} and R'_{LSC} are short circuit reactance and resistance at bus PCC, respectively. X_t and R_t are the equivalent reactance and resistance of cable, T_F and T_S. Electrical specifications of the supplying network are given in Appendix.

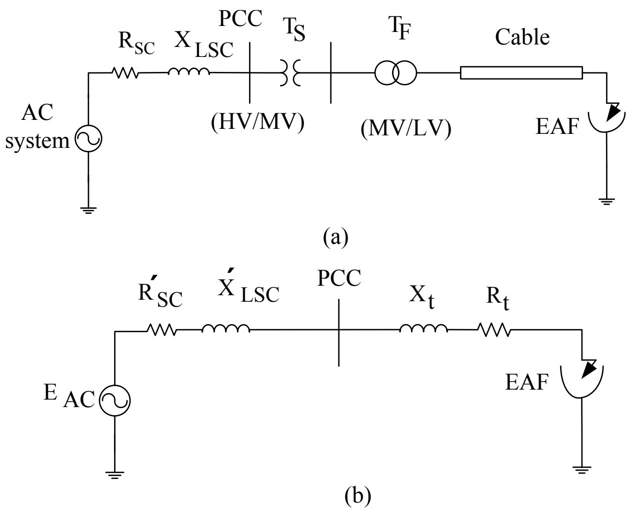

Fig. 4. Supplying network of EAF: (a) Single-line diagram, (b) simplified model

4.1 EAF model

In this paper, proposed model in [1] is used for modeling the EAF. This model is a combination of hyperbolic and exponential models and defined as follows:

$$V_{arc}(I_{arc}) = \begin{cases} \left(V_T + \frac{C_i}{D_i+|I_{arc}|}\right)\text{sign}(I_{arc}) & \frac{dI_{arc}}{dt} \geq 0 \\ \left(V_T + \frac{C_d}{D_d+|I_{arc}|}\right)\text{sign}(I_{arc}) & \frac{dI_{arc}}{dt} < 0 \end{cases}, \quad (7)$$

where V_{arc} is the arc voltage, I_{arc} is the arc current, V_T is the magnitude of the voltage threshold to which the voltage approaches as the current increases, I_0 is the current steepness constant and C and D are corresponding to the arc power and arc current respectively. These parameters are shown in Appendix.

4.2 Fundamental extraction

The voltage of PCC bus and its frequency spectrum are shown in Fig. 5-a and Fig. 5-b, respectively. As shown in this figure, the V_{PCC} has both odd and even harmonics but the amplitude of even harmonics are very low and can be neglected.

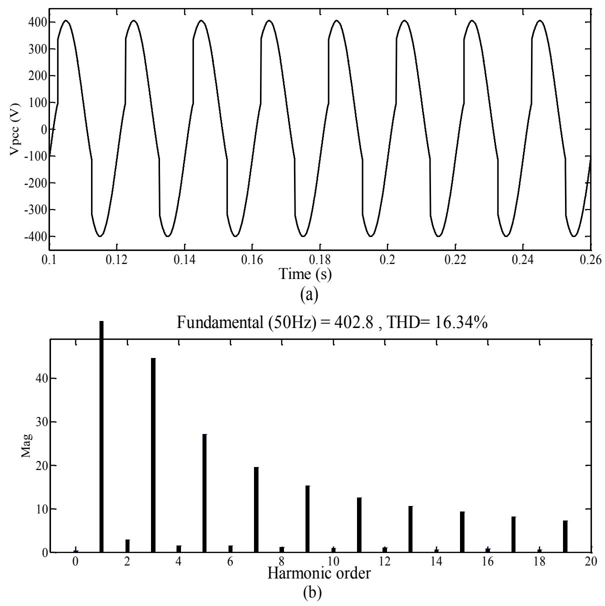

Fig. 5. V_{PCC} and its frequency spectrum: (a) V_{PCC} , (b) frequency spectrum

The extracted fundamental component of V_{PCC} by two methods is shown in Fig. 6. According to this figure, the proposed method improves the THD of extracted signal from 2.28% to 1.10%; moreover the transient response is 2 ms faster than the DWT and IDWT method. In the other words, the overall time delay in the DWT and IDWT method and the proposed method are 12 ms and 10 ms, respectively.

For obtaining the results of Fig. 6, in the proposed method, V_{PCC} is sampled by 3200 Hz, then 3 decomposition levels by Haar mother wavelet, third order FIR filter

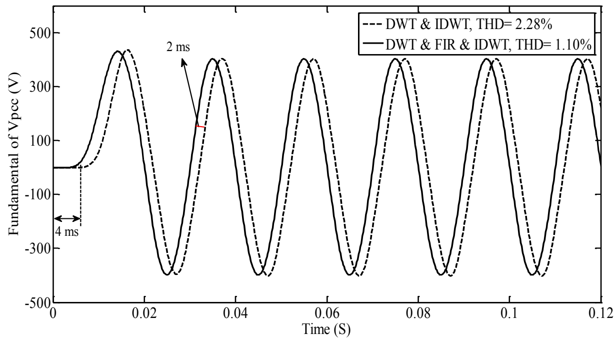

Fig. 6. Fundamental of V_{PCC}

and 5 reconstruction levels by db8 mother wavelet have been utilized. Meanwhile, in the case of DWT and IDWT, V_{PCC} is sampled by 3200 Hz and 4 decomposition levels by Haar mother wavelet and 5 reconstruction levels by db8 mother wavelet have been utilized. In this section, LWT has been used for implementation of DWT and IDWT.

If the decomposition levels decreases in the DWT and IDWT method, the transient response time will be improved and the output signal THD will be increased. To examine this issue, the V_{PCC} fundamental component is extracted again. But in this case, the decomposition levels are decreased to 3 in the DWT and IDWT method. The obtained results are shown in Fig. 7. According to this figure, the THD of extracted signal by DWT and IDWT method is increased to 14.43% due to the frequency interference. But its transient response is 3.4 ms faster than the proposed method.

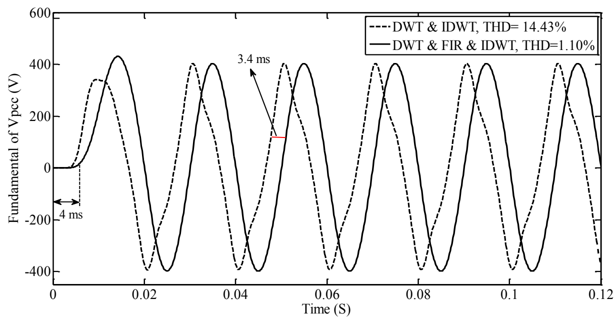

Fig. 7. Fundamental of V_{PCC}

4.3 Effect of FIR filter order

As previously mentioned, the FIR filter is used to improve the decomposed signal. Order of FIR filter is an important factor that can affect the quality of the extracted signal. So, the effect of FIR filter order is studied in terms of extracted signal quality and transient response time in this subsection.

The corresponding delay time and the output signal THD of different FIR filter order are shown in Table 1. According to this table, increasing the FIR filter order, increases the delay time and improves the output signal THD. Hence, the FIR filter order must be selected according to the application. In the next section, the third order FIR filter will be used. The transfer functions of FIR filters are provided in the Appendix.

Table 1. Effect of FIR filter order

Order	**1st**	**2nd**	**3rd**	**4th**	**5th**
THD (%)	6	2.53	1.1	0.53	0.3
Delay time (ms)	7.6	8.8	10	11.2	12.4

4.4 Comparison of different types of DWT

In earlier sections, three different methods were introduced for implementation of DWT. To evaluate the effect of each implementation method, the fundamental component of V_{PCC} is extracted by three introduced methods. The results are shown in Fig. 8. It can be observed that the response of LWT and MRA are overlapped and the LWT response is 2.5 ms faster than the WWT response, but THD of the output signal is the same in all implementation methods. The simulation conditions are the same as previous.

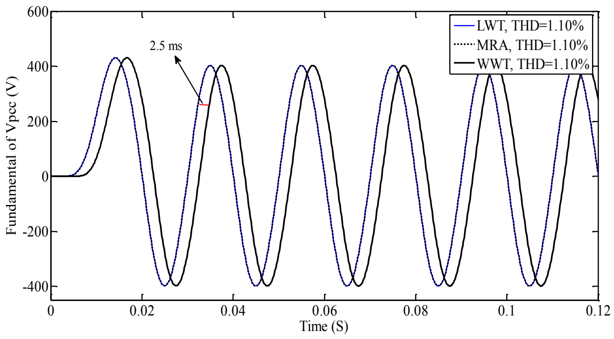

Fig. 8. V_{PCC} fundamental extracted by LWT, MRA and WWT

Taking into consideration the results represented in Fig. 8, performance of LWT and MRA are better than WWT. On the other hand, LWT is more efficient than the MRA. Thus the LWT is chosen here.

5 CONCLUSION

A new method is proposed for fundamental signal extraction based on DWT, FIR filter and IDWT. In this method, the frequency interference is allowed to occur at the output of DWT, and then the FIR filter and IDWT are used. This process improves the transient response and the THD of extracted signal. To evaluate the proposed method, the electric distribution system of electric arc furnace (EAF) of Mobarakeh Steel Company is simulated in MATLAB software and the obtained results are compared with the DWT and IDWT method. The results showed the superiority of the proposed method. Hence, the proposed method can be used instead of DWT and IDWT method because of its ability to improve the transient response and the extracted signal THD.

APPENDIX A APPENDIX SECTION

This appendix describes the parameters used in simulations as shown in Fig. 3 and Fig. 4.

Table 2. Specifications of the supplying network of EAF of Mobarakeh Steel Company

$\mathbf{E}_{AC}$ (V)	f (Hz)	$\mathbf{R}'_{SC}$ (mΩ)	$\mathbf{X}'_{SC}$ (mΩ)	$\mathbf{R}_t$ (mΩ)	$\mathbf{X}_t$ (mΩ)
586	50	0.8524	7.976	1.899	7.867

Table 3. The EAF parameters at early stage of charging

C	D	I_0	V_T
190000	5000	10	200

Table 4. Transfer function of different FIR filter order

1st order	$1 - z^{-1}$
2nd order	$(1 - z^{-1})^2$
3rd order	$(1 - z^{-1})^3$
4th order	$(1 - z^{-1})^4$
5th order	$(1 - z^{-1})^5$

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