Postprint: Application of Empirical Mode Decomposition to EAST Superconducting Coil Voltage Signal Analysis

Authors: Chen Yuanyang, Bao Xiaohua, Gao Ge, Zhou Yang

Date: 2019-03-05T00:00:00+00:00

Abstract

When a quench occurs in the poloidal field superconducting coils of the Experimental Advanced Superconducting Tokamak (EAST), the weak voltage signal variation resulting from the resistance change of the superconducting coil is overwhelmed by strong noise. To address this issue, Fast Fourier Transform is employed to analyze the time-frequency characteristics of the coil voltage signals. Based on the analysis results, the Empirical Mode Decomposition (EMD) method is proposed for analyzing the voltage signals across the superconducting coil, yielding several Intrinsic Mode Functions and a residual component, and it is revealed that the energy of the weak signal is predominantly distributed in the residual component. This method can mitigate environmental effects and detect weak variations in the voltage signal.

Full Text

Application of Empirical Mode Decomposition in Analyzing Voltage Signals of EAST Superconducting Coils

Chen Yuanyang[1], Bao Xiaohua[1], Gao Ge[2], Zhou Yang[1]
(1. School of Electrical Engineering and Automation, Hefei University of Technology, Hefei 230009, China
2. Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China)

Biographies: Chen Yuanyang (born 1993) is a Ph.D. candidate whose research focuses on superconducting magnet power supply and optimization for tokamak devices. Bao Xiaohua (born 1972) is a professor and doctoral supervisor whose research interests include motor noise and vibration theory and control technology.

Abstract

In the Experimental Advanced Superconducting Tokamak (EAST) device, the weak voltage signal variations caused by resistance changes in poloidal field superconducting coils during quench events are submerged in strong background noise. To address this problem, we first analyze the time-frequency characteristics of coil voltage signals using fast Fourier transform. Based on the analysis results, we propose applying the Empirical Mode Decomposition (EMD) method to analyze the voltage signals across the superconducting coils. This approach yields several intrinsic mode function components and a remainder, revealing that the energy of weak signals is primarily distributed in the remainder. This method can effectively eliminate environmental influences and detect weak variations in voltage signals.

Keywords: Weak signal, empirical mode decomposition, coil voltage, remainder

1 Introduction

The Experimental Advanced Superconducting Tokamak (EAST) is a fully superconducting, large-scale, non-circular cross-section tokamak device independently designed by China. Its poloidal field magnet system consists of 14 superconducting coils that must provide sufficiently large alternating currents and extremely rapid magnetic flux changes to control plasma breakdown and configuration [1-4]. To ensure safe operation of the device, it is essential to detect the weak voltage signal variations caused by resistance changes in the superconducting coils at the early stages of quench events.

Quench is a critical phenomenon in superconductor operation. The poloidal field coils are constructed using CICC (Cable-In-Conduit Conductor) conductors. When quench occurs, resistance suddenly appears in the superconducting coil and gradually increases. Since resistance changes directly cause voltage changes, voltage detection is more direct and rapid than many other quench detection methods. However, poloidal field superconducting coils operate in extremely complex and variable electromagnetic environments. The coupled voltage across the coil terminals is very strong, and the voltage variation caused by resistance changes is drowned in coupled noise voltage. Therefore, eliminating voltage signal noise and accurately detecting voltage trends are crucial for quench signal detection.

Over the past decades, domestic and international experts have conducted extensive research on weak signal detection. Traditional techniques such as curve fitting and smoothing, lock-in amplification, statistical averaging of discrete quantities, correlation detection, and adaptive noise cancellation have been joined by emerging methods including stochastic resonance, chaotic oscillators, empirical mode decomposition, and blind source separation. Advances in computer technology and modern power electronics have created the material conditions for implementing these methods [5-6]. Reference [7] introduces curve fitting principles; reference [8] compares several different smoothing and denoising methods; reference [9] constructs a lock-in amplifier and applies it to multi-frequency time-varying signal processing, eliminating low-frequency noise effects and improving output signal-to-noise ratio; reference [10] discusses the principles of sampling integration in detail; reference [11] proposes an optimal segmentation method for time-domain averaging to eliminate period truncation errors; reference [12] introduces the use of autocorrelation functions to suppress noise and extract weak periodic signals; references [13-14] apply cross-correlation detection to analyze echo signals in laser ranging and gear crack fault signals, respectively, effectively improving the success rate and accuracy of weak signal extraction; reference [15] proposes a variable step-size adaptive filtering algorithm; and reference [16] presents an improved energy detection algorithm for generalized Gaussian noise backgrounds, with simulation results demonstrating significantly reduced error probability under low signal-to-noise ratio conditions.

This paper employs the Empirical Mode Decomposition (EMD) algorithm to process voltage signals across superconducting coils before and after adding quench signals, obtaining intrinsic characteristic functions and a remainder at different frequencies. Through Hilbert-Huang transform, we calculate the spectra and marginal spectra of each component to obtain the time-frequency distribution of signals. Analysis reveals that weak voltage variations can be effectively reflected in the remainder of EMD decomposition.

2 EMD Algorithm

2.1 Principles of Empirical Mode Decomposition

The Empirical Mode Decomposition algorithm, proposed by Norden E. Huang et al., is based on the concept of Intrinsic Mode Functions (IMF) and decomposes arbitrary signals into several IMF components. Each IMF component represents local characteristics of the original signal, and instantaneous frequencies can be obtained by deriving the phase of their analytic signals. Compared with Fourier transform, its adaptive time-frequency analysis feature allows component frequency characteristics to vary with time, making it more suitable for analyzing non-stationary, non-linear signals. However, the EMD algorithm also has limitations, specifically: (1) End effect phenomenon: When using spline functions to process extreme points, fitting errors occur at endpoints, and error accumulation can "pollute" the entire sequence; (2) Envelope fitting problems: Cubic spline functions exhibit overshoot and undershoot phenomena when fitting data; (3) Mode mixing: Abnormal signal variations cause multiple different characteristic time scales to exist in one mode component after decomposition, causing IMF components to lose specific physical meaning.

2.2 EMD Algorithm Steps

The EMD algorithm proceeds as follows: (1) Identify all maxima and minima of the original signal, then fit the upper and lower envelope curves using cubic spline interpolation; (2) Calculate the mean of the upper and lower envelopes and subtract this mean from the original signal to obtain a new sequence; (3) Determine whether this sequence meets the two criteria of an intrinsic mode function. If satisfied, it can be used as an IMF; otherwise, treat it as the original signal and repeat the first two steps until the first IMF component is obtained; (4) Calculate the residual signal and use it as a new signal, repeating steps (1) and (2) until all IMF components are extracted.

The original signal can be expressed as:

$$x(t) = c_i(t) + r_n(t)$$

where $c_i(t)$ represents the i-th intrinsic mode function and $r_n(t)$ represents the remainder.

3 Voltage Signal Characteristics of Superconducting Coils

3.1 Generation of Superconducting Coil Voltage

The poloidal field power supply is one of the subsystems of the tokamak device, playing a crucial role in plasma current generation and control. It consists of 12 sub-power supply systems, each comprising corresponding control, measurement, protection, and drive components. By controlling current changes, it provides extremely rapid magnetic flux variations to maintain plasma current magnitude and configuration. The structure of each power supply system is shown in [Figure 1: see original paper].

During each operation cycle, the current in the coils goes through a rising phase, flat-top phase, and feedback stage for plasma current control. The voltage and current across the coils are measured by Hall sensors and transmitted to a Windows platform. [Figure 2: see original paper] shows the voltage signals collected by Hall voltage sensors and current signals collected by Hall current sensors during a normal discharge experiment, with a sampling frequency of 10 kHz and 230,000 sampling points. The figure shows that the coupled voltage across the coil terminals reaches up to 300 V, while the voltage variation during the initial quench stage is only a few volts, with the detected trend change accounting for only about 1% of the noise voltage.

For superconducting coils, due to their zero-resistance characteristic, if current is applied without interference, the voltage across the terminals is nearly zero, allowing rapid determination of quench status through voltage amplitude monitoring. However, in the poloidal field power supply system, 14 parallel superconducting coils exist with magnetic flux coupling between them. Plasma current during generation or disruption phases produces interfering magnetic fields, and induced eddy currents in the device shell create magnetic flux coupling interference. Consequently, during device operation, substantial coupled voltages exist across superconducting coil terminals, which pose significant interference for quench signal detection, as quench-induced voltage variations are drowned in interference voltages.

3.2 Amplitude-Frequency Characteristics of Voltage Signals

To understand the amplitude-frequency characteristics of voltage signals and quench signals, we performed analysis using fast Fourier transform. The results, shown in [Figure 3: see original paper], indicate that the voltage signal contains six large-amplitude frequency components corresponding to significant harmonic components in the rectifier bridge output current, along with numerous stray components, particularly abundant in the low-frequency band.

4 EMD Analysis of Voltage Signals

Fourier analysis reveals that the voltage signals across the coils have a wide frequency band with rich low-frequency components, representing a non-stationary signal. During quench events, coil resistance increases linearly, and quench events can occur at any time during device operation. To simulate quench phenomena, we selected data from the 5-7 second time period and added artificially constructed quench signals to the original voltage signals–specifically, the resistance value multiplied by the real-time current value. Taking the quench occurrence moment as time zero, the resulting quench signal is shown in [Figure 4: see original paper]. The quench signal is non-periodic, approximately resembling a ramp signal with amplitude gradually increasing from 0 V to 5 V, linearly superimposed on the original signal.

Following the procedure described in Section 2, we performed EMD analysis on the voltage signals before and after adding quench signals to extract IMF components and trend terms at different frequencies. [Figure 5: see original paper] shows the EMD decomposition results before and after adding quench signals. [Figure 5a: see original paper] shows that the original signal is decomposed into 11 IMF components, with slight frequency aliasing effects in low-frequency components caused by abrupt points in the voltage signal, but this does not affect trend term extraction. [Figure 5b: see original paper] shows that after adding quench signals, the voltage is decomposed into 12 IMF components, indicating that the added signal energy is not entirely concentrated in the trend term but partially extracted into components. By subtracting each IMF component from the original signal, we obtained the voltage variation trend. [Figure 6: see original paper] shows the spectra of EMD decomposition results. From the final decomposition layer, under normal conditions, the voltage trend range during the selected time period is 116-118 V, while after adding quench signals, the voltage trend value increases correspondingly, reaching a maximum of 121 V. Comparing the trend term variation with the added quench signal, as shown in [Figure 7: see original paper], the trend term variation extracted through

EMD decomposition can effectively track the quench signal superimposed on the original voltage signal.

5 Conclusion

To address the problem of excessive coupled noise voltage across EAST poloidal field superconducting coils drowning quench signals, we analyzed the time-frequency characteristics of voltage signals and proposed using EMD algorithm to decompose voltage signals and extract voltage variations from the trend term. The analysis yields the following conclusions: (1) The main components of coupled voltage across superconducting coil terminals are distributed in the 0-1,000 Hz range, as determined by fast Fourier analysis. (2) EMD decomposition can extract voltage signals with different frequency characteristics. The spectra of each component generally match the time-frequency analysis of the original signal. The extracted remainder has deviations at endpoints but can adequately reflect voltage trends after adding quench signals.

References

[1] Wang Linsen, Tang Lunjun, Gao Ge, et al. The grounding design of EAST poloidal power supply for EMC[J]. Power Electronics, 2011, 45(12): 101-103.

[2] Yang Yalong, Fu Peng, Zhu Yinfeng. Research on the reliability in power supply control network for the superconducting coils of EAST poloidal field[J]. Cryogenics & Superconductivity, 2012, 40(5): 30-34, 52.

[3] Zheng Rui, Fu Peng, Wang Linsen. Data acquisition system of poloidal field power supply control system of EAST[J]. Microcomputer Information, 2009, 25: 15-17.

[4] Chao Huili, Xiao Bingjia, Ji Zhenshan. Application of plasma current protection in controlling system of EAST Tokamak[J]. Microcomputer Information, 2010, 28: 34-35, 97.

[5] Si Wenrong, Li Junhao, Yuan Peng, et al. Measurement and analysis for pulse sequence of partial discharge signals under DC voltage[J]. Transactions of China Electrotechnical Society, 2010, 25(3): 164-171.

[6] Zhu Wenlong, Zhou Jianzhong, Xiao Jian, et al. An ICA-EMD feature extraction method and its application to vibration signals of hydroelectric generating units[J]. Transactions of the Chinese Society for Agricultural Machinery, 2013, 33(29): 95-101, 14.

[7] Pattanadech N, Yutthagowith P. Fast curve fitting algorithm for parameter evaluation in lightning impulse test technique[J]. IEEE Transactions on Dielectrics & Electrical Insulation, 2015, 22(5): 2715-2724.

[8] Halim E B, Shah S L, Zuo M J, et al. Fault detection of gearbox from vibration signals using time-frequency domain averaging[C]. American Control Conference, 2006.

[9] Peng Jianxue, Ye Yinzhong. New technology of noise elimination in ultra weak signal lock-in amplifier[J]. Control Engineering of China, 2007(S2): 65-67.

[10] Sun Ziqiang, Chen Changzheng, Gu Yanling, et al. Incipient fault diagnosis of large scale wind turbine gearbox based on chaos theory and sampling integral technology[J]. Journal of Vibration & Shock, 2013, 32(9): 113-117.

[11] Zou Jinchun, Qu Lei, Dai Guanghao, et al. An improved algorithm for time domain averaging based on fractional delay filtering[J]. Journal of Mechanical Strength, 2015(5): 793-799.

[12] Ming Anbo, Chu Fulei, Zhang Wei. Compound fault features separation of rolling element bearing based on the wavelet decomposition and spectrum auto-correlation[J]. Journal of Mechanical Engineering, 2013, 49(3): 80-87.

[13] Zhang Zhengyu, Gui Xiaolin. Faint signal digital correlation detection of laser ranging: study and simulation[J]. Chinese Journal of Lasers, 2002, 29(7): 661-665.

[14] Yang Ming, Dong Chuanyang, Xu Dianguo. Review of gear fault diagnosis methods based on motor drive system[J]. Transactions of China Electrotechnical Society, 2016, 31(4): 58-63.

[15] Jiang Han, Jiang Quanyuan. Power system transient stability simulation based on shamanskii-VDHN algorithm with variable step size[J]. Proceedings of the Chinese Society of Electrical Engineering, 2011, 31(34): 105-112.

[16] Zhi Shaolong, Wu Yuquan, Sui Tianyu, et al. Research on an improved algorithm for energy detection of wake-up signal and its application[J]. Technical Acoustics, 2012, 31(2): 162-166.

Note: Figure translations are in progress. See original paper for figures.