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# A Method for Decomposing Dynamic Load Signals and Its Application

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***Abstract* – The current and power signals of high-power nonlinear dynamic load devices exhibit complex, random, fast-changing dynamic characteristics. These dynamic characteristics seriously affect the accurate measurement of smart electricity meters. Therefore, the research on the dynamic characteristic of high-power dynamic load has become an important issue to be solved in the field of error testing of smart electricity meters. Dynamic load signal decomposition is the basis and key issue for analyzing load dynamic characteristics. In this paper, the non-stationary stochastic process modulation model of dynamic load signal is established firstly. A method of least squares empirical mode power decomposition is studied, which divides the signal into quasi-steady-state terms and dynamic terms. Secondly, based on the proposed decomposition method, the actual collected signals of electrified railway traction substation are decomposed, which proves the effectiveness of the proposed model and the decomposition method. The theoretical method of this paper provides theoretical support for the dynamic error test of smart electricity meter.**

***Keywords – Dynamic Load, Empirical Mode Decomposition, Dynamic Error Test***

## I. INTRODUCTION

In recent years, the proportion of nonlinear dynamic load in smart grids has been increasing. The current and power signals of high-power nonlinear dynamic load devices such as electrified railway locomotives (hereinafter referred to as high-power dynamic load) exhibit complex, random, fast-changing dynamic characteristics (hereinafter referred to as dynamic characteristics). These dynamic characteristics will lead to a large tolerance in the electric energy metering of smart electricity meters [1-2], which seriously affect the accuracy of electricity charge. In addition, analysis of the dynamic characteristics of the dynamic load, giving its essential characteristics and characteristic parameters is the focus of establishing dynamic test signals. And the correct and appropriate dynamic test signal is a key issue to realize the dynamic error test of smart electricity meter. Therefore, researching the dynamic characteristics of high-power dynamic load has practical application value and important theoretical value for the accurate measurement of smart electricity meter.

It is a significant thinking method in scientific research to "Decompose and simplify" complex problems into a combination of several typical problems and establish a reasonable and appropriate mathematical model. For the study of dynamic characteristics of high-power dynamic loads, "Decomposition and simplification" can simplify the analysis of huge workload, establish a obvious signal model, and then realize the establishment of dynamic test signals. Therefore, we decomposes the dynamic characteristics of high-power dynamic load. The current and power signals are decomposed into a steady-state part describing the slow-wave characteristics and a dynamic part describing the random fast-wave characteristics.

Regarding the research on dynamic load power decomposition methods, after continuous exploration by domestic and foreign scholars, some progress has been made. It mainly includes harmonic decomposition, instantaneous power decomposition, and three-phase power decomposition. Harmonic decomposition lay a theoretical foundation for determining the harmonic components of the signal, establishing a harmonic steady-state signal model, and researching the influence of harmonics on power quality. Instantaneous power decomposition decomposes the power signal into active power and reactive power, which supports the reactive compensation of electric energy. Three-phase power decomposition is an important basis for analyzing three-phase unbalance and its compensation. The above decomposition method provides key theoretical support for various power quality and power loss problems. However, a publicly reported method has not been seen so far, which decomposes the steady-state part of slow fluctuations and the dynamic part of random fast fluctuations. Therefore, it is necessary to study the method of decomposing the load current and power signal into steady state and dynamic modal signals. And establish a mathematical model of dynamic load stochastic process with a small time scale on the microsecond level. Furthermore, the dynamic error test of smart electricity meter is realized.

## II. MATHEMATICAL MODEL AND DECOMPOSITION METHOD OF QUASI-STEADY-STATE AND DYNAMIC TERMS OF DYNAMIC LOAD SIGNALS

### *A. Mathematical model*

For the sake of brevity, the voltage, current and power signals of high-power dynamic load are collectively called dynamic load signals. Due to the high power dynamic load, the current and power signals have random and fast changing characteristics. We take the dynamic load signal as a random process changing with time t, which is called the dynamic load random signal.

In actual situations, the current and voltage signals are discrete time series acquired at a certain sampling rate. So, we analyze the current and voltage signals of dynamic load as a random time series. $t_n$ stands for discrete time.

The voltage and current signals of dynamic load collected in the field are a non-stationary random process. Therefore, we adopt a comprehensive method based on mechanism and load characteristics, combined with the measured data and random signal theory in digital signal processing to model. Modulation models are commonly used models in non-stationary stochastic process modeling. Instantaneous signal of dynamic load is expressed by the modulation model of non-stationary random process as follows:

$$\tilde{X}(t_n) = \tilde{A}(t_n) \cdot g(t_n), \tag{1}$$

where "~" denotes a random signal. $g(t_n)$ is a determinate signal of the variable $t_n$, which is composed of a single or a plurality of sin or cos signals. And $g(t_n)$ is called an observation signal which changes with time. It is determined by the mechanism of the high-power device. At the point of common coupling, the signal is compensated to exhibit a sinusoidal variation. $\tilde{A}(t_n)$ is a non-stationary random process of random envelopes, which is the time series of random envelopes. It represents the amplitude fluctuation characteristics of the load. Equation (1) has a clear physical meaning, that is, the stationarity is attributed to $g(t_n)$, and the random fast change characteristic is attributed to $\tilde{A}(t_n)$.

Based on the above analysis of the "decomposition" of high-power dynamic load dynamics. We represent $\tilde{A}(t_n)$ as the sum of the quasi-steady-state term and the dynamic term:

$$\tilde{A}(t_n) = \tilde{m}(t_n) + \tilde{v}(t_n), \tag{2}$$

where $\tilde{m}(t_n)$ is the slowly varying quasi-steady-state of current or power signal, and $\tilde{v}(t_n)$ is the stochastic rapidly changing dynamic term of current or power signal. Bringing equation (2) into equation (1), we can get the random time series expression after dynamic load transient signal decomposition:

$$\tilde{X}(t_n) = \left(\tilde{m}(t_n) + \tilde{v}(t_n)\right) \cdot g(t_n), \tag{3}$$

Under the actual working conditions of the power grid, the amplitude fluctuation range of the load voltage signal is small and the speed is slow. The influence of the dynamic error can be neglected, and its amplitude can be expressed by the constant $U_\mathrm{m}$.The amplitude of the load current signal fluctuates widely and changes rapidly in a random manner, and the amplitude is expressed by a random process $\tilde{A}_k^\mathrm{i}(t_n)$. The instantaneous power signal can be obtained by multiplying the instantaneous current by the instantaneous voltage signal. According to the above characteristics, the instantaneous current, voltage and power signals are respectively represented by equation (1). The random time series representations of the signals are as follows:

$$\tilde{\imath}_k(t_n) = \tilde{A}_k^\mathrm{i}(t_n) \cdot I_\mathrm{m}\sin\left(2\pi f_0 t_n + \varphi_k^\mathrm{i}\right), \tag{4}$$

$$u_k(t_n) = U_\mathrm{m}\sin(2\pi f_0 t_n + \varphi_k^\mathrm{u}), \tag{5}$$

$$\tilde{p}_k(t_n) = u_k(t_n) \cdot \tilde{\imath}_k(t_n)$$

$$= \tilde{A}_k^\mathrm{p}(t_n) \cdot P_\mathrm{m}\left\{\cos\psi + \cos\left(4\pi f_0 t_n + \varphi_k^\mathrm{u} + \varphi_k^\mathrm{i}\right)\right\}, \tag{6}$$

where $\tilde{A}_k^\mathrm{i}(t_n)$, $\tilde{A}_k^\mathrm{p}(t_n)=\tilde{A}_k^\mathrm{i}(t_n)$ are non-stationary random time series of instantaneous current and power amplitude envelope. $k$ takes $\mathrm{a,b,c}$, and represents $\mathrm{a,b,c}$ three phases, respectively. $f_0$ is a 50 Hz power frequency. $\varphi_k^\mathrm{i}$ and $\varphi_k^\mathrm{u}$ are the initial phases of instantaneous current and voltage. $\psi=\varphi_k^\mathrm{u}-\varphi_k^\mathrm{i}$ is the phase difference between voltage and current. $I_\mathrm{m}$, $U_\mathrm{m}$ and $P_\mathrm{m}=U_\mathrm{m}I_\mathrm{m}/2$ are the maximum amplitudes of the observation signals of the instantaneous current, voltage, and power signals, respectively.

The current and power $\tilde{A}(t_n)$ of equations (4) and (6) are decomposed by the method of equation (2). The resulting decomposition signals of the instantaneous current and power random sequences are expressed as follows:

$$\tilde{\imath}_k(t_n) = \tilde{I}_k^\mathrm{m}(t_n) \cdot I_\mathrm{m}\sin\left(2\pi f_0 t_n + \varphi_k^\mathrm{i}\right)$$

$$+\tilde{I}_k^\mathrm{v}(t_n) \cdot I_\mathrm{m}\sin\left(2\pi f_0 t_n + \varphi_k^\mathrm{i}\right), \tag{7}$$

$$u_k(t_n) = U_\mathrm{m}\sin(2\pi f_0 t_n + \varphi_k^\mathrm{u}), \tag{8}$$

$$\tilde{p}_k(t_n) = \tilde{P}_k^\mathrm{m}(t_n) \cdot P_\mathrm{m}\left\{\cos\psi + \cos\left(4\pi f_0 t_n + \varphi_k^\mathrm{u} + \varphi_k^\mathrm{i}\right)\right\}$$

$$+\tilde{P}_k^{\mathrm{v}}(t_n)\cdot P_{\mathrm{m}}\{\cos\psi+\cos(4\pi f_0 t_n+\varphi_k^{\mathrm{u}}+\varphi_k^{\mathrm{i}})\}, \quad (9)$$

where $\tilde{I}_k^{\mathrm{m}}(t_n)$ and $\tilde{P}_k^{\mathrm{m}}(t_n)$ respectively represent the quasi-steady-state terms of the load instantaneous current and power. $\tilde{I}_k^{\mathrm{v}}(t_n)$ and $\tilde{P}_k^{\mathrm{v}}(t_n)$ respectively represent dynamic terms of instantaneous current and power. Other parameters have the same meaning as before.

### *B. Decomposition method*

In order to determine the quasi-steady-state term and the dynamic term, the definition of the criterion is performed on the quasi-steady-state signal. The criterion is: within 10 seconds, if the amplitude of the signal is between the adjacent maximum and minimum values, the amplitude fluctuation range is less than 0.2% of the signal rating. It is called a quasi-steady-state signal.

Based on the above analysis and criterion, we proposes a least squares empirical mode decomposition method to decompose the non-stationary sequence of random envelope $\tilde{A}(t_n)$. The quasi-steady-state terms and dynamic terms are obtained respectively. The specific decomposition scheme is as follows.

Step (1) firstly determines the maximum and minimum values of the non-stationary sequence of random envelope $\tilde{A}(t_n)$, and then uses the spline interpolation method for the two extreme points. The two envelopes of the local maximum point and the minimum point of $\tilde{A}(t_n)$ are respectively obtained. Secondly, obtains the average envelope $l_1(t_n)$. $l_1(t_n)$ is the first quasi-steady-state term obtained by the first mode decomposition.

Step (2) because $l_1(t_n)$ still changes rapidly with time. Replace the average envelope $l_1(t_n)$ with $\tilde{A}(t_n)$, repeat the decomposition of the step (1), and obtain the second average envelope $l_2(t_n)$, which is the second quasi-steady-state term obtained by the second mode decomposition. The averaging operation of $l_1(t_n)$ $l_2(t_n)$ is obtained as a non-solid state mode function $l(t_n)$.

$$l(t_n)=\frac{l_1(t_n)+l_2(t_n)}{2}, \quad (10)$$

Step (3) performs a least squares fitting on the non-solid state mode function $l(t_n)$ to find the best fitting function of the data. Taking the fitting function class $\Phi$ as a polynomial function, for the dynamic load signal, using the data point $\{l(t_n),\ n=0,1,\ldots,m\}$ on the non-solid state mode function, the fitting function $f(t_n)\in\Phi$ is obtained, so that the sum of the squares of the errors $E^2$ is minimum.

$$E^2=\sum[f(t_n)-l(t_n)]^2, \quad (11)$$

where the function $f(t)$ is,

$$f(t)=F_k t^k+F_{k-1}t^{k-1}+\cdots+F_1 t+F_0$$
$$=\sum_{i=0}^{k}F_i t^i, \quad (12)$$

In the fitting, starting from the high order, the order $k$ is decremented by one each time to perform the fitting operation until the amplitude dynamic fluctuation range of the fitting function $f(t)$ conforms to the criterion of the quasi-steady-state term signal, and the fitting ends. Get a most reasonable order $k^*$. The fitting function $f(t_n)$ of the non-solid state mode function $l(t_n)$ obtained by this method is a quasi-steady-state term $\tilde{m}(t_n)$.

Step (4) calculates the signal of the dynamic term $\tilde{v}(t_n)$ according to the decomposition of the equation (2), as shown in the following equation:

$$\tilde{v}(t_n)=\tilde{A}(t_n)-f(t_n), \quad (13)$$

The least squares empirical mode decomposition method described above can effectively separate the quasi-steady-state term $f(t_n)$ and the dynamic term $\tilde{v}(t_n)$ of the dynamic load random signal (current or power), and then obtain a dynamic load random signal model as follows:

$$\tilde{\imath}_k(t_n)=f^{\mathrm{i}}(t_n)\cdot I_{\mathrm{m}}\sin(2\pi f_0 t_n+\varphi_k^{\mathrm{i}})$$
$$+\tilde{v}^{\mathrm{i}}(t_n)\cdot I_{\mathrm{m}}\sin(2\pi f_0 t_n+\varphi_k^{\mathrm{i}}), \quad (14)$$

$$\tilde{p}_k(t_n)=f^{\mathrm{p}}(t_n)\cdot P_{\mathrm{m}}\{\cos\psi+\cos(4\pi f_0 t_n+\varphi_k^{\mathrm{u}}+\varphi_k^{\mathrm{i}})\}$$
$$+\tilde{v}^{\mathrm{p}}(t_n)\cdot P_{\mathrm{m}}\{\cos\psi+\cos(4\pi f_0 t_n+\varphi_k^{\mathrm{u}}+\varphi_k^{\mathrm{i}})\}, \quad (15)$$

$$u_k(t_n)=U_{\mathrm{m}}\sin(2\pi f_0 t_n+\varphi_k^{\mathrm{u}}), \quad (16)$$

## III. ANALYSIS AND DISCUSSION ON DECOMPOSITION OF THE ACTUAL ACQUIRED SIGNALS

According to the decomposition method above, the instantaneous current signals collected at the point of common coupling (PCC) of an electrified railway traction substation in Hebei, China were decomposed by Matlab programming. The results are shown in Figures 1-4. The current signal is acquired on the secondary side of the current transformer (CT). For electric energy metering, the harmonic power is small and negligible within the allowable range. Therefore, Figure 1 shows the 2000 second instantaneous current fundamental signal (only phase A current is given).

For the current fundamental envelope signal $\tilde{A}_k^{\mathrm{i}}(t_n)\cdot I_{\mathrm{m}}$ of Fig. 2, according to the least squares empirical mode decomposition method, the quasi-steady-state term envelope are decomposed as shown in Fig. 3. Where, the solid line is the non-solid state mode function $l(t_n)$, and the dotted line is the quasi-steady-state term envelope $f^{i}(t_n)\cdot I_m$. The dynamic term envelope $\tilde{v}^{i}(t_n)\cdot I_m$ is shown in Figure 4.

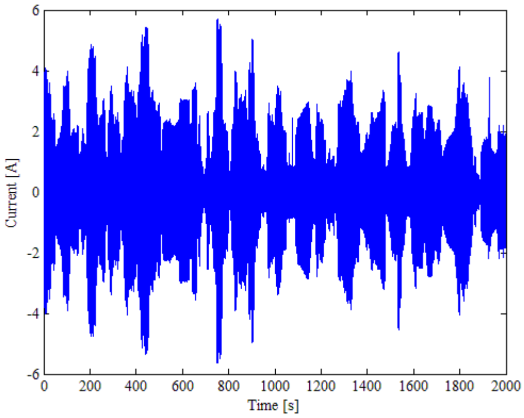


*Fig. 1. The instantaneous current fundamental signal from CT in Traction substation*

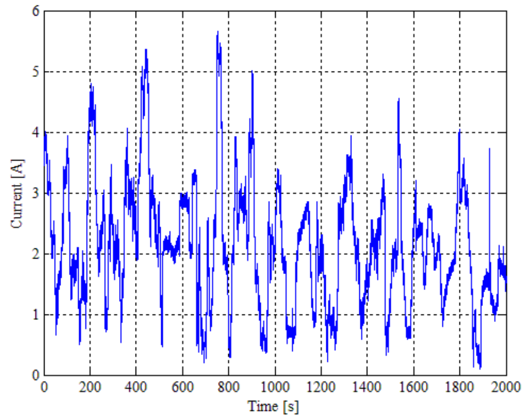


*Fig. 2. The instantaneous current fundamental envelope from CT in Traction substation*

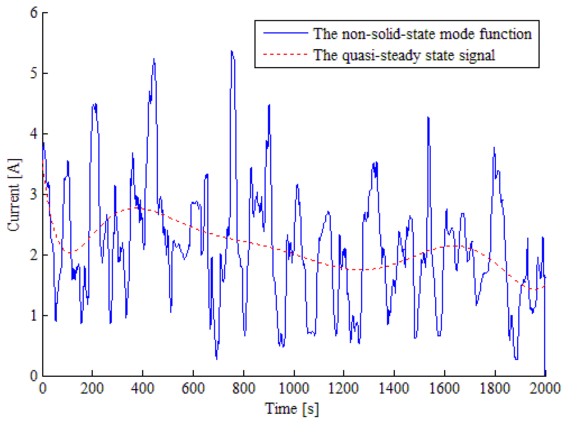


*Fig. 3. The quasi-steady-state signal $f^{i}(t_n)\cdot I_m$ and the non-solid state mode function $l(t_n)$ of current fundamental envelope from CT in Traction substation*

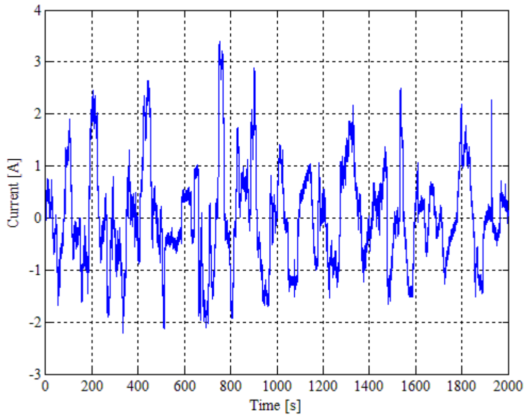


*Fig. 4. The dynamic signal $\tilde{v}^{i}(t_n)\cdot I_m$ of current fundamental envelope from CT in Traction substation*

From the above decomposition results of dynamic load signal can be seen: (1) The quasi-steady-state term has the characteristics of slow fluctuation, strong cyclic fluctuation. And the influence on the error of smart electricity meter can be attributed to the influence of steady-state signals under different conditions. For example, the cyclic period of the quasi-steady-state term can be used to determine the on-off ratio of the OOK test signal. (2) The dynamic term has random fast fluctuation characteristics and strong impact. The model of random dynamic test signal should be used to test its influence on the dynamic error of smart electricity meter. The impulse parameters of the dynamic term can be used to determine the parameters of the random dynamic test signal. The decomposition results also prove the validity of the proposed model and decomposition method.

## IV. CONCLUSIONS

In this paper, a modulation model of dynamic load non-stationary random signal is established, and a least squares empirical mode power decomposition method is proposed. The decomposition results of the actual acquired signals indicate the feasibility of the proposed model and the decomposition method.

## V. ACKNOWLEDGMENT

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