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Analysis of Excitation Current in DC-Biased Transformer by Wavelet Transform

***Abstract**. To analyze the excitation current in DC-Biased Transformer in depth, the thesis deduces the mathematical expression of distortion excitation current, and put forwards the analysis method with wavelet transform principle, which directs at analyzing the boundedness of distortion excitation current using the Fourier Transform. Through sampling the distortion excitation current signal, we resolve its wavelet LF approximation signal and HF detail signal, conclude DC component size of the distortion excitation current, confirm the moment of excitation current waveform distorting, comparatively analyze the results after Fourier Transform, and make clear that the principle is feasibility and superiority. Through analyzing the energy spectrogram in the signal high-frequency band of distortion excitation current and short circuit current are determined. Simulation results show that energy changes in the high frequency band among the different scale. In practice, DC bias can lead to the action of relay protection device, which does harm to the system potentially.*

***Streszczenie.** Przedstawiono metodę analizy składowej stałej podmagnesowującej w prądzie magnesującym transformatora. Do analizy wykorzystuje się transformatę falkową I transformatę Fouriera prądu magnesującego. (**Wykorzystanie transformaty falkowej do analizy prądu magnesującego transformatora podmagnesowanego składową DC**)*

Keywords: transformer; DC magnetic bias; excitation current; wavelet transform; energy spectrogram.
Słowa kluczowe: transformator, transformata falkowa.

Introduction

Power transformer is the extremely important component in the AC electric network, and in the high - voltage power system partial transformer need to be neutral ground directly. Therefore the DC may sneak into the excitation winding in the actual run process, causing the phenomenon of transformer DC magnetic biasing. There are two main sources that produce the interference current. The one is the geomagnetic induced current with the property of a quasi-dc current, which is caused by the magnetic storm [1-2]. The other is the DC, which is produced by the high-voltage DC transmission system running in the way of unipolar earth loop [3-4]. Under DC magnetic biasing, the transformer iron core enters the saturation status rapidly, the work point drifts, the excitation current distortion happens, and the phenomenon of the half-wave saturation appears, which introduce a serial of problems such as the transformer noise, over-heat and so on, even probably cause the transformer breakage and the relay protection faulty action.

The work carried out in allusion to the study of the power transformer DC magnetic biasing phenomenon has included the measurement of the ferromagnetic material characteristic under the DC magnetic biasing, the analysis of the transformer internal electromagnetic characteristic through setting up the magnetic circuit model, and the restraining measure of the DC magnetic biasing[5-7]. However, little reference explores the distortion excitation current in depth. The reference [8] regards the DC biasing as the one of the harmonic problem under ignoring the hysteresis effect condition. The reference[9-11]adopt the common Fourier transform to analysis the distortion excitation current, but harmonic content extracted can be very little when excitation current doesn't distort seriously. At the same time, the Fourier transform can only formulate the relation between the harmonic frequency and the DC biased variable in the frequency domain, which can cause the problem that information of the time and frequency domain can't reach the localization simultaneously.

Yet so far rare reference has analyzed the problem of the distortion exciting current at the time of the Transformer DC Magnetic Biasing using the wavelet transformation principle. Time-Frequency window supplied by the wavelet transformation can adjust on the concrete shape and dynamic of the signal, explore the transient of the excitation current signal effectively, show its frequency element, and satisfy the analysis to the distortion exciting current, which is worth studying in depth.

The thesis defines the magnetic saturated degree coefficient of the transformer iron core, deduces the mathematical expression of distortion exciting current, and analyzes the exciting current signal under the DC magnetic biasing using the wavelet transformation principle. The simulation result shows that the image results gained match with the description of the mathematical expression, meanwhile the method accurately measures the DC component of distortion current, locates the moment of the current distortion accurately, and embodies the tremendous superiority of the Fourier transform. Through analyzing the energy spectrogram in the signal high-frequency band, we draw the conclusion that excitation current under DC bias lead to the protection device action.

The mathematical description of the distortion excitation current

In order to describe it conveniently, the table 1 shows the main sign and its implication that the paper used.

Table 1. The main sign and its implication

Sign	Implication
t_1	The start time of the exciting current distortion
ϕ_M	The maximum magnetic flux in the non-saturated section
I_M	The maximum exciting current in the non-saturated section
I_0	DC inflowing into the transformer winding from the external
ϕ_0	DC magnetic flux caused by DC
k_1	Magnetization curve slope in the non-saturated section
k_2	Magnetization curve slope in the saturated section

Most bulk transformer is three-phase winding type, which is most sensitive to the DC magnetic biasing effect in the different structure transformer [12-13]. Take the single phase transformer of the winding type for example, the Fig.1 shows the relation curve between the iron core magnetic fluxΦ and the excitation current i. The fold line

OAB represents the trace of the single phase transformer's iron core working point, which neglects the hysteresis effect and is approximately indicated by the fold line. The OA and AB separately indicate the non-saturated region and the saturated one of the ferromagnetic material. When the system runs normally, the iron core of the transformer generally operates in the A point nearby, close to the saturated region. After the DC enters the winding through the transformer neutral point, the DC magnetic flux is set up in the transformer, which makes the iron core working point drifts to the high saturated region, and causes the distortion of excitation current to happen, with the phenomenon of the half-wave saturation appearing and further causes the transformer not to work normally [14].

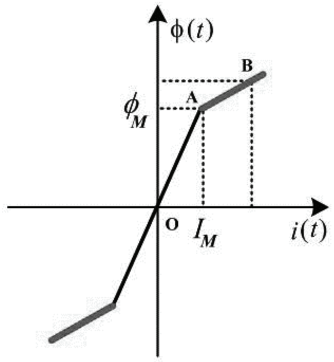

Fig.1. Curve of saturation characteristic

We separately provide the deduction of two stages so as to analyze the variation situation of the exciting current in the whole effective region.

In the normal working hours, that is to say the situation $\phi_o + \phi_m \sin(\omega t) \le \phi_M$:

According to $\phi = k_1 i$, the exciting current is:

(1) $$i = I_0 + i_m \sin(\omega t)$$

In the DC magnetic biasing hours, that's to say the situation $\phi_o + \phi_m \sin(\omega t) > \phi_M$:

According to $\phi = k_2(i - I_M) + \phi_M$, we can see $i = I_M + [\phi_o + \phi_m \sin(\omega t) - \phi_M]/k_2$. Here $K = k_1/k_2$ is defined as the magnetic saturated degree coefficient of the transformer iron core. After we further deal with it, it becomes：

(2) $$i = K[I_0 + i_m \sin(\omega t)] - (K-1) I_M$$

Compare (2) with (1), it becomes;

(3) $$i = I_0 + i_m \sin(\omega t) + (K-1)\left[I_0 + i_m \sin(\omega t) - I_M\right]$$

After the iron core enters into the saturated working region, according to $\phi_o + \phi_m \sin(\omega t) = \phi_M$, the distortion time of the exciting current can be concluded:

(4) $$t_1 = \arcsin\left[\left(\phi_M - \phi_o\right)/\phi_m\right]/\omega = \arcsin\left[\left(I_M - I_o\right)/i_m\right]/\omega$$

Therefore we can conclude the mathematical expression of the exciting current in one cycle $[-\pi, \pi]$ integrating (1) (3) (4). It's as follows:

(5) $$i = \begin{cases} I_0 + i_m \sin(\omega t) & t \in \left[-\frac{\pi}{\omega}, t_1\right) \cup \left(\frac{\pi}{\omega} - t_1, \frac{\pi}{\omega}\right] \\ I_0 + i_m \sin(\omega t) + (K-1)\left[I_0 + i_m \sin(\omega t) - I_M\right] & t \in \left[t_1, \frac{\pi}{\omega} - t_1\right] \end{cases}$$

Obviously, in the time stage $t \in \left[t_1, \frac{\pi}{\omega} - t_1\right]$ of the (5), the transformer iron core enters into the saturated status, and the exciting current distortion happens, increasing the exciting current:

(6) $$\Delta I = (K-1)\left[I_0 + i_m \sin(\omega t) - I_M\right]$$

We can get the DC component $\Delta I_D = \frac{K-1}{2\pi}\left[(\pi - 2\alpha)\left(I_o - I_M\right) + 2\sqrt{i_m^2 - I_M^2 + 2 I_M I_o - I_o^2}\right]$,

Through resolving ΔI , in the distorted exciting current, the summation of the DC component is:

(7) $$I_D = I_o + \Delta I_D$$

From (7) we can conclude that the DC component in the distorted exciting current is greater than that of inflowing into the transformer winding from the external.

The compendium of the wavelet transformation principle

Wavelet transformation is one kind of analysis method of signal time scale (time-frequency), and it has the characteristic of Multi-resolution Analysis. It has the higher frequency resolution and the lower time resolution in the Low Frequency section, and in the High Frequency section the situation is opposite. Also the wavelet transformation is fit for exploring the transient abnormal phenomenon appearing in the normal signal and showing its component. What's more, applying wavelet transformation to the faulty measurement and diagnosis of the dynamical system is effective [15-16].

For the function $\psi(t)$, that is the wavelet function, only its Fourier transform meets the condition $C_\psi = \int_{-\infty}^{+\infty} |\omega|^{-1} |\psi(\omega)|^2 d\omega < \infty$, $\psi(t)$ can it be regarded as the wavelet. And $\psi(\omega)$ is the Fourier transform of $\psi(t)$, which is a signal function with the finite energy. $\psi(t) \in L^2(R), L^2(R)$ is square-integrable square of the real number field. Continuous wavelet transform is defined as $CWT(a,b) = |a|^{-1/2} \int_{-\infty}^{+\infty} f(t) h\left(\frac{t-b}{a}\right) dt$, therein $h(t)$ is the basic wavelet; 'a' is the scale factor, 'b' is the shift factor, and 'a' & 'b' is continuous wavelet transform.

However, because the computer can only process the discrete variable, we need utilize the discrete time wavelet transform to analyze and reconfigure the signal. The wavelet transform discretization aims at the scale factor "a" and the shift factor "b", but actually 'a' and 'b' can only get the discrete data. Command $a = a_0^m$ ($a_0 \ne 1$), $b = n b_0 a_0^m, m, n \in Z$, the discrete wavelet function can be defined as the $\psi_{m,n} = a_0^{-m/2} h\left(a_0^{-m} t - n b_0\right)$. Command the time variable $t = kT(k \in Z)$, T is the cycle and $T = 1$ the signal $f(t)$ quantizes $f(k)$, DTWT is defined as $DWT(m,n) = a_0^{-m/2} \sum_k f(k) h\left(\frac{k - n b_0 a_0^m}{a_0^m}\right)$.

Generally, we assign constant $a_0 = 2, b_0 = 1$, DTWT of is $DWT(m,\ n) = 2^{-m/2} \sum_k f(k) h\left(2^{-m} k - n\right)$.

After decomposing the f (t) signal with the wavelet, we regard the detail signal energy as the scale function and define the detail energy signal function: E (j)=log₂($\sum_{k \in Z} \left|d_{j,k}\right|^2$) according to the wavelet coefficient $d_{j,k}$ of the various scale. There into, 'j' is the scale. The energy distributing in each the high-frequency band is different, that is, the rate of energy changes in the adjacent high-frequency band:

(8) k_i=(E(j+1)-E(j))/((j+1)-(j)) (i=1,2);

Through defining

(9) k=k_1/k_2=(E(j+1)-E(j))/(E(j+2)-E(j+1))

It reflects the energy change condition in the high-frequency band among the different scale.

The simulation analysis of the algorithm examples

The algorithm examples description

The paper takes the single phase saturated transformer with double/triple winding for example, and builds the verification test using the double winding under the condition of DC magnetic biasing. The system wiring figure is shown as Fig.2. The basic value of magnetic flux is the peak value of sine magnetic flux of the transformer primary winding under the unit standard sine voltage value, and the basic value of magnetic linkage is the basic magnetic flux multiplying the turns of the primary winding, selecting the rated capacity and voltage the basic value.

The parameters of the transformer are as follows: the rated capacity is 150MVA, the rated voltage of the primary winding is $500/\sqrt{3}\,KV$, $R_1 = 0.002pu$, $L_1 = 0.08pu$, the rated voltage of the secondary winding is $230/\sqrt{3}KV$, $R_2 = 0.002pu$, $L_2 = 0.08pu$, the iron core saturation characteristic is [0,0; 0.001,1; 1,1.5], and the iron core dissipation is $R_m = 5000pu$.

The power supply is single phase AC with the 50HZ frequency, its peak value voltage is $500\sqrt{2}/\sqrt{3} = 408KV$, the basic value of voltage is $U_{base} = 288KV$, and the basic value of current is $I_{base} = 735A$. It adopts the RLC load, the rated useful power is 150MVA, and the rated voltage is $230/\sqrt{3}\,KV$.

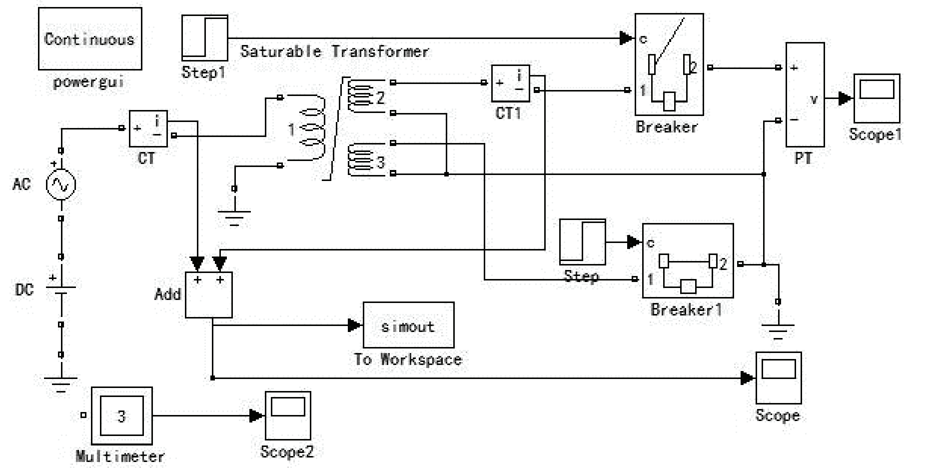

Fig.2. Saturation model of single transformer with two or three winding

Results Analysis

Exciting current under different D.C. bias

Fig.3 and Fig.4 separately show excitation current distorting waveform under different D.C. bias. It shows that establishing flux by DC component causes the iron core working point to drift to the high saturated region, and the distortion of exciting current happens gradually to a certain degree before entering into the stable state. The greater the DC voltage is, the shorter time the current distortion takes, and the more serious degree of distortion is. During one cycle, exciting current distortion only occurred in a period of time within half waveform, and peak current becomes bigger based on the corresponding original exciting current, according with the mathematical expression (5) deduced in section one.

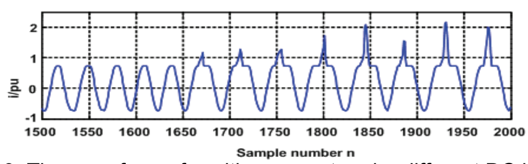

Fig.3. The waveform of exciting current under different DC bias ($U_{DC} = 5V$)

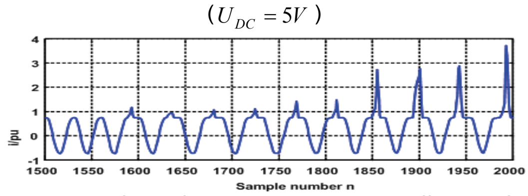

Fig.4. The waveform of exciting current under different DC bias ($U_{DC} = 10V$)

The exciting current signal by wavelet decomposition

The process of exciting current distortion can be considered as transient one, and as is shown in Fig.3, the exciting current waveform meets the conditions of the wavelet transform [17-18].Perform seven -layer wavelet decomposition to the selected signal. Fig.5 shows low-frequency approximation signal a7 sequence decomposed and Figure 6 shows the high-frequency detail signal b1-b4 sequence.

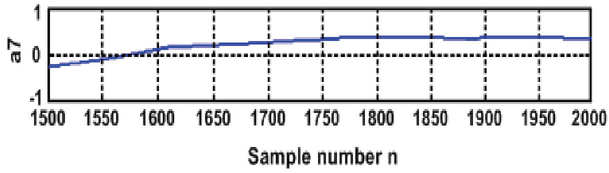

Fig.5. The low -frequency approximation signal by wavelet decomposition

According to Fig.5, a7 sequence has separated out DC component clearly from the distortion exciting current signal. After sample Number1650, wavelet coefficients are basically unchanged with 0.5, but there is a slow increasing process before, which can explain that after joining 5V DC voltage, DC component value contained in the distortion exciting current has increased on the basis of the DC value flowing into the windings from transformer neutral point, according with the mathematical expression (7) deduced in section one.

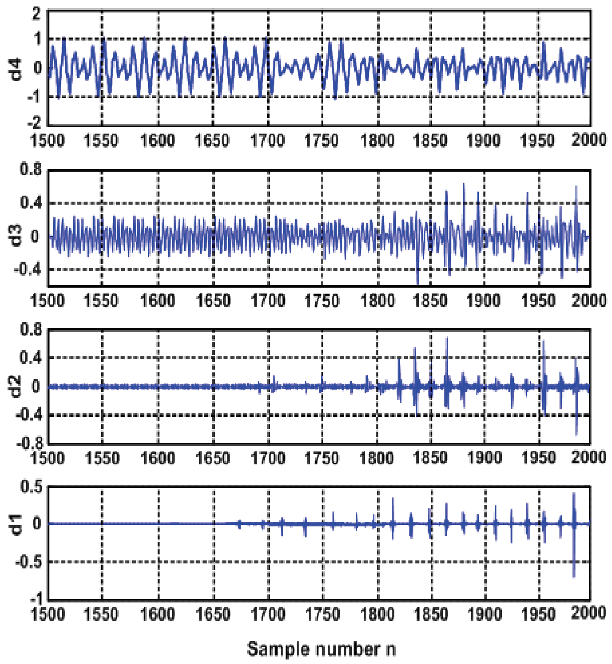

Fig.6. The high-frequency detail signal by wavelet decomposition

We can see from Fig.6 that High-frequency detail signal d1, d2, d3 sequence are associated with the resulting current distortion, d1 sequence component contains more current distortion information than any other component, waveform changes reflect regularity and information the d4 component contains is very weak.

From d1 sequence we can see the distortion location clearly, the sample number 1675 obviously shows the wavelet coefficient augment, that is to say, the exciting current start to distort here, which is consistent to Figure 3, and with the seriousness of the distortion, the wavelet coefficients become very big, between them the wavelet coefficients is 0.This method can locate the moment of the current distortion quickly and accurately.

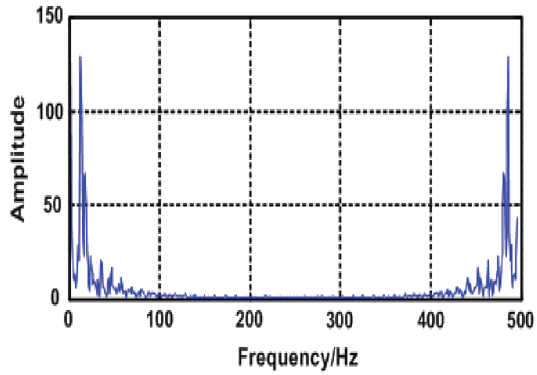

Fig.7. Signal schemes by Fourier transform

By processing the distortion current signal of Fig.3 using Fourier Transform, we can get the image shown in Fig.7 We can see that the signal by Fourier Transform can confirm the frequency value contained in the original signal, but Fourier Transform is unable to determine the moment of the current distortion for the measurement DC component.

The energy spectrogram in the signal high-frequency band

When the short fault happens inside the transformer, the iron core is apt to saturation and its internal turn-to-turn short fault can be equivalent to the third winding one. The paper calculates the turn-to-turn short fault through changing the parameters of the third winding, and analyzes the current under the DC magnetic biasing comparatively.

From the above, we decompose and dispose the high-frequency detail signal of the exciting current under the magnetic biasing and the short current under the internal fault. The figure 8 is the energy spectrogram of the signal.

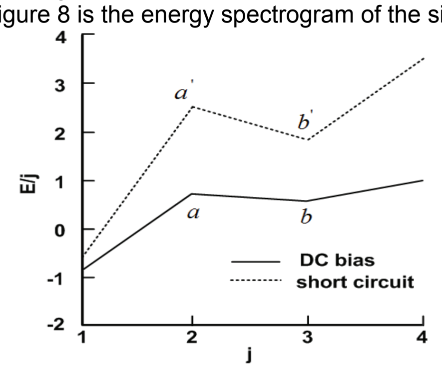

Fig.8. Energy spectrogram of current signals under different performance

Table 2. Calculation results under different performance

Type	k_1	k_2	k
Under DC bias magnetic	-0.15	0.41	0.366
Under short circuit fault	-1.25	2.39	0.401

We can see the calculation result from the table 2, after the DC magnetic biasing happens inside the transformer and the exciting current signal distortion emerges, the gradient of the ab segment is k_1=-0.15＜0, k_2=0.41＞0. Although it is more different from that of short fault, the symbolic change conditions are same, and $k=k_1/k_2$= (E (3)-E (2))/ (E (4)-E (3)) =0.366, which is very near to the 0.401, and reflects that the exciting current under the DC magnetic biasing and the internal short current are consistent under the condition of the energy change in the high-frequency band among the different scale. Therefore the consequence of transformer DC magnetic biasing is similar to that of the internal short fault. In the practical performance, the DC magnetic biasing probably causes the relay protection device movement of the transformer.

Conclusion

The thesis analyzes the exciting current in the DC biased power transformer with wavelet transform principle, and through deducing the mathematical expression of the distortion exciting current and analyzing the results of the algorithm examples, draws the conclusions:

(1) The mathematical expression of the distortion exciting current is deduced and the time slice of the exciting current distorting in a cycle is confirmed too. Theoretical derivation and the examples' results are anastomotic.

(2) By means of analyzing the LF approximation signal resolved of the exciting current, we obtain DC component value of the distortion exciting current and find the value increases based on the DC value inflowing the windings. HF detail signal accurately indicates the moment of the exciting current wave form distorting, and embodies the superiority of the wavelet transform, comparing with the Fourier Transform.

(3) From analyzing the energy spectrogram in the signal high-frequency band of distortion excitation current, it shows its consistency with the energy changes in the high-frequency band among the different scale, which can lead to the action of protection device and have the potential hazards to the power system.

The application of the principle provides a new path for analyzing the exciting current in the DC biasing transformer, and supports theoretical analysis to the follow-up practical application, however, in the process of studying, only the existing mother wavelet is selected to decompose the excitation current signal. Therefore, if we construct special one according to the distortion current signal, whether we can get more accurate analysis results remains to be studied in depth.

Acknowledgment

This work is supported by National Natural Science Fund Project（50877053）and Tianjin Natural Science Fund Project（09JCYBJC07100）

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