Measurement of inrush current in transformer based on optical current transducer

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Abstract. The accurate measurement of inrush current is a key problem in transformer protection. Traditional electromagnetic current transformer (CT) has nonlinear characteristics of its core. When the transformer generates inrush current, it will be saturated and lead to current distortion, which will lead to transformer differential protection misoperation. Optical current transducer (OCT) is not affected by saturation and can be used to measure and identify inrush current well. This paper analyses the mechanism of inrush current, the reason of CT saturation and the principle of OCT measurement. The simulation and experimental results show that OCT has better measurement quality than traditional CT and superiority to differential protection.

1. Introduction
Transformer is the main equipment in power system and plays an important role in the safe operation of power system. Inrush current has always been a key factor affecting transformer protection. Because the transformer will produce large inrush current when it closes without load. If it is not identified, it will lead to misoperation of differential protection. Therefore, accurate measurement of inrush current is the primary task of transformer protection.

At present, there are two main factors restricting the improvement of transformer protection operation rate: one is how to distinguish the inrush current from the internal fault current. The other is how to avoid the transient unbalanced current caused by external fault leading to differential protection maloperation. Through the current transformer, the transformer protection can sense the current information of the primary side, and then make the differential protection operate correctly [1]. With the increase of power system voltage level and transmission capacity, the transient output current of traditional electromagnetic current transformer is seriously distorted due to the influence of core magnetic saturation. To overcome this distortion, the complexity of relay protection devices will be greatly increased [2]. In addition, the traditional CT also has a small dynamic range, narrow frequency band, susceptible to electromagnetic interference, complex insulation structure, high cost, secondary open circuit will produce high voltage, ferroresonance, flammable explosive, large area and other defects. When transformer fails or no-load switching on, the non-periodic component of transient current on the primary side will cause magnetic saturation of conventional electromagnetic CT and distort the waveform of current on the secondary side of CT. Therefore, it cannot ensure the rapidity, sensitivity, selectivity and reliability of relay protection [3]. Optical current transducer has many advantages, such
as no saturation, strong anti-interference ability, longer transmission distance and so on. It has a great
inhibition on the above problems.

This paper analyses the saturation characteristics of electromagnetic current transformer, the factors
affecting CT saturation and the influence on inrush current identification. Then the basic principle and
measurement method of OCT are mathematically modelled. The conclusion that OCT can measure the
full waveform of current is obtained. The waveform of inrush current and standard current of two kinds
of transformers are compared by simulation. Finally, the waveforms of the two transformers are further
analysed by the transient experiment of the inrush current, and the correctness of the theory is verified.

2. Generation mechanism of inrush current

Under the condition of steady operation of transformer, the winding terminal voltage is:

\[ u(t) = U_m \sin(\omega t + \alpha) \]  

Among them, \( U_m \) is voltage amplitude, \( \omega \) is angular frequency, and \( \alpha \) is the initial phase. In order
to simplify the reasoning, the inductance calculation formula is set as: \( L = \frac{\Phi}{i} \). Without considering
transformer leakage reactance and winding resistance \( R \), the relationship between voltage \( u \) and
magnetic flux density \( \Phi \) is:

\[ \frac{d\phi}{dt} + R \frac{\phi}{L} = U_m \sin(\omega t + \alpha) \]  

(2)

The size of the inductor is nonlinear, varying with the saturation of the core. But since \( \frac{d\phi}{dt} \) is much
larger than the size of the inductor \( L \) after the voltage is applied, the inductor \( L \) can be set as a very small
constant here. This simplification has no great effect on the solution of the equation. The formula for
calculating the flux linkage can be obtained as follow:

\[ \phi(t) = \phi_m \sin(\omega t + \alpha - \phi) + [\phi_r + \phi_m \sin(\alpha - \phi)]e^{-\frac{t}{\tau}} \]  

(3)

Among them, \( \phi_m = \frac{U_m L}{\sqrt{R^2 + (\omega L)^2}} \) is the amplitude of the steady-state component of the flux linkage.
\( \phi_r \) is the remanence of the core. \( \phi = \arctan \frac{\omega L}{R} \). And because of \( \omega L \gg R \), so the attenuation of inrush
current in this process is not considered. The formula (3) can be simplified to:

\[ \phi_m = -\phi_m \cos(\omega t + \alpha) + \phi_r \cos \alpha + \phi_l \]  

(4)

The first one is steady-state flux and the other two is transient flux. When considering transformer
loss, transient flux will decay with time. Assuming that \( \phi_m \cos \alpha \) and \( \phi_l \) are in phase, when the no-load
switching half cycle, the core flux reaches the maximum. As shown in Figure 1, the maximum flux will
be generated when the voltage zero-crossing point is closed without load, which is much larger than the
saturated flux of the transformer.
When the transformer is closed at the moment of \( u = 0 \), the magnetic flux \( \Phi_r \) can be obtained and the inrush current \( i_e \) can be obtained by drawing a simplified magnetization curve. As can be seen from Figure 2, before the core is unsaturated (\( \rho < \rho_s \)), the current \( i_e \) is less than \( i_s \) and its value can be ignored. But when the core is saturated (\( \rho > \rho_s \)), the current will increase rapidly and the maximum amplitude will reach \( i_p \). As shown in Figure 2 (c), this current is called the inrush current of the transformer and it can reach 6-8 times the rated current [5].

![Figure 1](image1.png)

**Figure 1.** The curve of the relation between voltage and magnetic flux.

The flux waveform of transformer is shown in Figure 2 (a) when no load is switched on. The simplified magnetization curve is shown in Figure 2 (b). The magnetic flux \( \Phi_k \) is obtained and the inrush current \( i_e \) can be obtained by drawing a simplified magnetization curve. As can be seen from Figure 2, before the core is unsaturated (\( \rho < \rho_s \)), the current \( i_e \) is less than \( i_s \) and its value can be ignored. But when the core is saturated (\( \rho > \rho_s \)), the current will increase rapidly and the maximum amplitude will reach \( i_p \).

![Figure 2](image2.png)

**Figure 2.** Inrush current in unload switching of transformer.

The inrush current is related to the closing angle. When the closing angle \( \alpha \) is 0 or \( \pi \), the inrush current is the largest. As shown in Figure 3, at the same time, the waveform deviates completely from the side of the time axis and is discontinuous. It contains a large number of non-periodic components and a large number of high-order harmonic components. In the high-order harmonic, the second-order harmonic is dominant. The inrush current and fault current can be identified by the harmonic content or the closing angle.
3. Factors affecting the saturation of traditional CT

The core of the current transformer is a nonlinear component and its magnetization curve is shown in Figure 4. There are many reasons for the magnetic saturation of the core, among which the followings are the main points.

1) The aperiodic component of short-circuit current transient components. Generally speaking, the larger the aperiodic component is, the more severe the saturation is.

2) Saturated time constant of current transformer. The bigger the saturated time constant is, the easier it is to saturate.

3) Secondary side load and its load characteristics. The greater the load is, the easier it is to saturate.

4) Remanence of iron core. If the residual magnetic direction of the core coincides with the flux direction of the fault current, the saturation is easier.

In the factors that cause the saturation of the current transformer, the non-periodic component is the most important. When fault occurs, the fundamental cause of secondary current distortion caused by current transformer saturation is the nonlinear characteristics of the transformer core, most of the aperiodic components cannot be transmitted to the secondary side, thus becoming the excitation current. The larger the aperiodic component and the slower the attenuation, the more serious the saturation of the current transformer. When the flux density of the core reaches saturation, the magnetic conductivity of the core decreases rapidly and the excitation current rises sharply. Most of the primary current becomes the excitation current. The secondary current is seriously distorted, the waveform is defective and the amplitude decreases. In serious cases, the amplitude of the secondary current becomes very small, sometimes even close to zero. For relay protection, the correct action depends firstly on the correct response of the measuring element to the primary system. Because of the iron core in traditional CT,
when the fault current exceeds its allowable value, it will produce saturation, which cannot guarantee the accuracy of measurement. Especially in the transient process, due to the influence of non-periodic component of primary current, the current transformer will be in serious transient saturation.

4. Transient characteristics of optical current transducer

Optical current transformers can be based on a variety of optical effects, such as Faraday magneto-optic effect, magnetostrictive effect, piezoelectric effect and so on. Among them, the optical current transformer (OCT) based on Faraday magneto-optic effect is the most fully researched and practical one.

OCT based on Faraday magneto-optic effect indirectly measures the current by measuring the magnetic field caused by the measured current. The principle of Faraday magneto-optic effect is shown in Figure 5. When linearly polarized light passes through a magneto-optic medium under the action of an external magnetic field parallel to its propagation direction, the polarization plane will deflect and the deflection angle can be expressed as:

$$\theta = \mu \cdot V \cdot \int_L H \cdot d\tilde{l}$$

(5)

Among them, \(\mu\) is the permeability of Faraday magneto-optic materials. \(V\) is the Verdet constant of magneto-optic materials, which is related to the characteristics of the medium, the wavelength of the light source, the external temperature. \(H\) is the magnetic field intensity acting on magneto-optic materials. \(L\) is the optical path length of polarized light passing through magneto-optic materials.

Since the deflection angle of polarized light cannot be measured directly, the unmeasurable deflection angle signal is converted into the measurable polarized light intensity signal in OCT’s implementation. According to Marius’s law, the output light intensity is expressed as:

$$J_o = J_i \cos^2 \beta$$

(6)

Where \(\beta\) is the polarization angle between the polarizer emitted polarized light and the polarizer emitted polarized light. \(J_i\) is the input light intensity.

In order to maximize the intensity of polarized light emitted from the polarizer, the angle \(\beta\) between the start and the detector is usually set to \(\pi/4\). Because the Faraday rotation angle is very small, the output intensity can be further expressed as:

$$J_o = J_i(1 - \sin2\theta) \approx J_i(1 - 2\theta)$$

(7)

Because \(J_i\) and \(\theta\) are unknown quantities, in order to solve two quantities from an equation, we can use the single optical path method.

![Figure 5. Schematic diagram of single optical path method.](image-url)
polarizer shaft is $\pi / 4$. The photoelectric vector generated by the light source is $E_i$, and the Jones vector can be expressed as $E_i = \begin{bmatrix} E_{ix} \\ E_{iy} \end{bmatrix}$. The Faraday rotation characteristics of magneto optical medium can be expressed by Jones matrix as:

$F = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}$ (8)

According to the Jones algorithm, the output vectors after the Faraday medium and the analyzer are:

$E_o = \begin{bmatrix} \cos \pi / 4 & -\sin \pi / 4 \\ \sin \pi / 4 & \cos \pi / 4 \end{bmatrix} E_i = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} E_i = E_{o} = \frac{1}{\sqrt{2}} \begin{bmatrix} \sin(\theta + \pi / 4) \\ \sin(\theta - \pi / 4) \end{bmatrix}$ (9)

The relationship between the output light intensity $J_o$ and the input intensity $J_i$ is:

$J_o = \frac{1}{2} J_i (1 + \sin 2\theta)$ (10)

Among them, the AC component is $J_{oAC} = \frac{1}{2} J_i \sin 2\theta$. The DC component is $J_{oDC} = \frac{1}{2} J_i$. Single optical path detection method uses filter circuit to detect AC component and DC component respectively. In order to eliminate the influence of input light intensity fluctuation, modulation quantity is

$m = J_{oAC} / J_{oDC} = \sin 2\theta$ (11)

When the modulation system is relatively small, $m \approx 2\theta$.

Suppose the primary input current is $i_1 = I_1 e^{-\frac{t}{\tau}} - I_1 \cos \omega t$. The secondary current can be expressed as:

$i_2 = K (I_1 e^{-\frac{t}{\tau}} - I_1 \cos \omega t)$ (12)

According to (12), the response time of OCT can be neglected, the DC component can be transferred correctly, the steady state of each harmonic can be transmitted correctly and the secondary current can be attenuated by one time during fault removal. However, in the actual implementation process, the measurement accuracy will be affected by temperature, magnetic field interference, vibration and other factors. But these factors are within the error range for OCT steady state and transient measurements. Therefore, OCT has a great advantage over traditional CT, especially when there are a lot of aperiodic components in transient faults.

5. Simulation analysis

![Image of system simulation model](image-url)
Using Simulink and power system component library in MATLAB software, transformer simulation model can be easily established. Considering the same physical characteristics of three-phase system, a single-phase system model is adopted here. The simulation model of MATLAB system is shown in Figure 6.

The transformer is connected to 500kV system with rated capacity of 450MVA (single phase is 150MVA) and rated ratio is 500kV/230kV. The primary and secondary windings consider the effects of resistance, leakage inductance and remanence. The transformer is designed by using the model with saturation characteristic and the hysteresis characteristic design tool of MATLAB. The saturated CT module is represented by piecewise linear representation of the magnetization curve and remanence is taken into account. The voltage level is 500kV, and the transformer ratio is 2000/5. The primary load (R, L) is used to control the time constant. The circuit breaker closing time is used to control the aperiodic component. When the circuit breaker closes at the zero-crossing point, the aperiodic component is the largest and CT’s saturation is the most serious. The secondary load is adjustable resistance. Output the waveform of OCT with proportional link and delay link. Figure 7 is the simulation waveform of the system. From top to bottom, there are the original waveform of inrush current, the waveform measured by OCT (secondary side) and the waveform measured by traditional CT (secondary side).

The transmission performance of CT plays an important role in the reliability, sensitivity and speed of protection. It can be seen that when the traditional CT saturates, the secondary current will be distorted and then cannot accurately reflect the inrush current waveform of the primary. When this distorted current flows into the protection device, it may lead to maloperation or rejection of the differential protection. The saturation of CT will result in larger transmission error for primary value and incorrect operation of transformer differential protection. In the transient process, the short-circuit current or inrush current has a high non-periodic component, it is very likely to cause serious saturation and current distortion.

OCT is not affected by transient faults and can completely retain the inrush current information, in which the harmonic components and the closing angle can be completely retained and then lay a foundation for identifying the inrush current. Therefore, OCT can accurately measure the full waveform of inrush current in principle, especially in transient state and its excellent accuracy is far superior to traditional CT.

6. Experimental verification
In order to verify the ability of optical current transducer (OCT) to reflect the inrush current, an on-site operation experiment of OCT was carried out at Hushitai test site of Northeast Electric Power Academy. Two optical current transducers are connected in series in 220kV side circuit of Hushi test-bed
transformer (40MVA/220kV). By means of transformer impulse closing test, the operating condition and transient characteristics of OCT under switching vibration and inrush current of transformer are detected. The waveforms of inrush current output from two OCTs are checked to be consistent with those of traditional CT, compared with recorded inrush current waveforms.

Figure 8. Fifth closing current waveform (expanded waveform).

A total of 5 operations were performed. The interval was 10 minutes and the experimental waveforms were shown in Figure 8. The first and second waveforms are 2 OCT test waveforms and third waveforms are traditional CT test waveforms.

The fifth impact found that the seventh cycle began, optical current transformer and traditional transformer waveforms are greatly different. The OCT’s waveforms are correct, the traditional CT waveforms are error due to aperiodic component transmission and saturation. It is proved by experiments that the OCT has the advantage of transient measurement compared with the traditional CT.

7. Conclusion
This paper firstly analyses the inrush current containing a large number of non-periodic components, which will saturate the traditional CT transient and result in the failure to accurately obtain the inrush current. The transformer protection will maloperate or reject. Because of its own basic principles and measurement methods, OCT completely free from the impact of saturation can be thoroughly solve a series of problems caused by CT saturation. The saturation of the two is simulated by simulation software and tested by experiment. It is proved that OCT has excellent transient measurement quality and can realize the measurement information of current “full waveform”, which is of great significance to the progress of power system measurement and protection.

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