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Effect of CT transient characteristics on transfer of inrush

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Abstract: During the inrush period, multiple misoperation accidents of differential protection of transformers happened, which seriously threatened the safe and stable operation of power grid. In the traditional malfunction analysis, only the inrush current process is considered, and the electromagnetic transient interaction between the transformer and other non-linear ferromagnetic components such as CT is hardly considered. Here, the variation rule of inrush current waveform characteristic is analysed, and the influence rule of secondary load and type of CT on inrush current second harmonic proportion and dead angle is simulated by using the simulation Lucas model of industrial practical CT (P/PR). The results show that the second harmonic proportion of the inrush current and the dead angle of the waveform depend on the saturation angle of the transformer core. The larger the saturation angle is, the smaller the second harmonic proportion is, and the larger the dead angle of the waveform is. The second harmonic proportion of the inrush current becomes larger, and the dead angle of sympathetic inrush becomes smaller after CT transfer. The dead angle of magnetising inrush waveform depends on the secondary load resistance. It may increase or decrease..

1 Introduction

With the progress of power industry, China is gradually forming a complex large power grid with high-density AC/DC hybrids. A large number of non-linear ferromagnetic components such as transformers and current transformers (CT) are deployed. The transformer is the main equipment in power system, which plays an important role in the safe operation of power system. During transformer no-load closing or fault recovery, the transformer core is saturated to produce magnetising inrush, which often occurs and sympathetic inrush in adjacent transformers [1–4]. Owing to the characteristics of large differential current and small braking current, the inrush current is easily identified by differential protection as internal fault causing protection malfunction. There have been many accidents during the transformer inrush current in site. How to distinguish the inrush current and the fault current is the core problem of the differential protection of the transformer [5].

At present, a large number of studies have been conducted on the characteristics of magnetising inrush. Relevant scholars have proposed to identify the inrush current by using the characteristics of second harmonic proportion and the waveform dead angle of inrush current.

However, it is regreTable that there is no specific criterion for the identification of sympathetic inrush, but to be judged generally in conjunction with sympathetic inrush and magnetising inrush [6]. Some studies show that the waveform of sympathetic inrush is similar to magnetising inrush, but decays more slowly, which makes the CT to saturate easily. As a result, the criterion based on the waveform characteristics causes the differential protection malfunction.

In the study of the influence of transient characteristic of CT on the inrush current characteristics, it is extremely difficult to analytically analyse the transmission characteristics of CT due to the non-linear characteristics of the core and many influencing factors [7], including CT secondary load and CT types etc. In [8], the effect of CT saturation on the inrush characteristics is examined qualitatively by the double-break line method.

In this paper, the change rule of second harmonic proportion and waveform dead angle of inrush current is analysed theoretically at first. Secondly, the influence of CT saturation on the second harmonic proportion of inrush current is analysed. Finally, by using the Lucas model of industrial protection CT (P/PR), the effects of secondary load and type of CT on the second harmonic proportion and dead angle of inrush current are obtained through simulation.

2 Waveform characteristics of inrush current

In the criterion of inrush current closure of transformer differential protection, it is often locked with the waveform characteristic of inrush current. In this section, the characteristics of the second harmonic proportion and wave dead angle of the inrush current are analysed.

2.1 Waveform characteristics analysis of inrush current

2.1.1 Second harmonic proportion: The T-type equivalent circuit of the inrush current produced by the no-load closing of the single-phase transformer is shown in Fig. 1. Among them, u_s is the system power, r_s and L_s are system resistance and reactance, $L_{11\sigma}$ and $r_{11\sigma}$ mean the inductance and resistance of the transformer primary side, respectively, $L_{12\sigma}$ and $r_{12\sigma}$ mean the inductance and resistance of the transformer secondary side, respectively. L_{1m} and r_{1m} mean the excitation inductance and excitation resistance of the transformer, respectively.

When the transformer is not saturated, L_{1m} will be very large, much larger than the resistors and inductors above. In extreme saturation, it will drop to leakage resistance level. The study found that when the remanence of the transformer is 0 and the closing angle changes from 90° to 0°, the saturation degree of the transformer will gradually deepen and the amplitude of the inrush current will gradually increase.

During the closing process, the secondary side is unloaded, $r_{12\sigma}$ and $L_{12\sigma}$ will not participate in the process of inrush current. In fact,

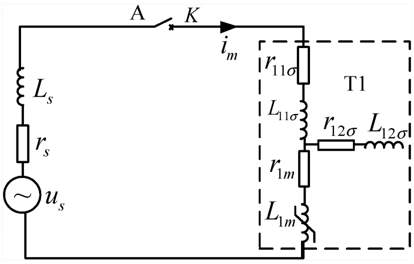

Fig. 1 *Equivalent circuit of a single-phase transformer no-load closing*

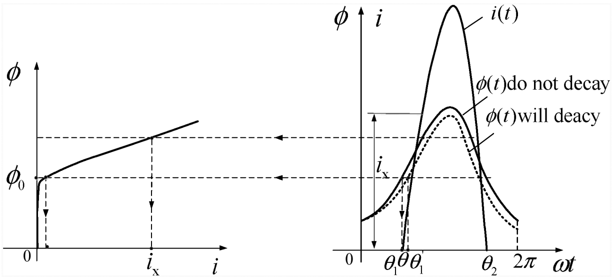

Fig. 2 *Diagramming of magnetising inrush of a single-phase transformer*

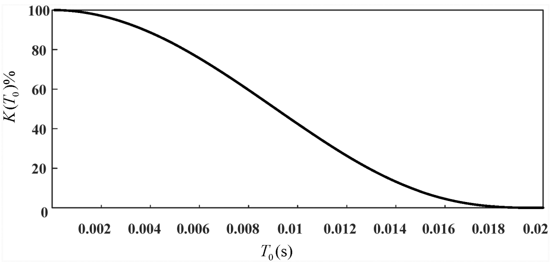

Fig. 3 *Second harmonic proportion of magnetising inrush*

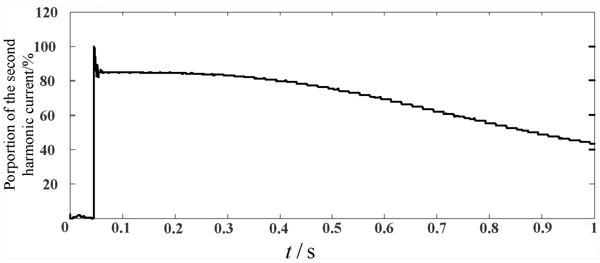

Fig. 4 *Magnetising inrush second harmonic proportion simulation diagram*

r_s and $r_{11\sigma}$ are obviously far smaller than L_s and $L_{11\sigma}$, and can be ignored. That is, there is only an inductor in the closing circuit, and inrush current will not decay at this time, and the transformer flux can be expressed as formula (1) [9]

$$\phi = -\phi_m \cos(\omega t + \alpha) + \phi_m \cos \alpha + \phi_r \quad (1)$$

where α is the closing angle and ϕ_r the remanence of the core of the transformer.

When the transformer is unsaturated, the value of L_{1m} will be very large and the inrush current is almost zero. After the core is saturated, L_{1m} will be greatly reduced and the inrush current will be greatly increased. It is assumed that at the time of $\omega t = \theta$, the core of the transformer is saturated, it is easy to deduce, that at the time of $\omega t = 2\pi - 2\alpha - \theta$, it will exit saturation, as shown in Fig. 2. Therefore, in a power frequency cycle, the transformer magnetising inrush can be expressed as follows:

$$i_m = \frac{1}{L}\int_{\theta/\omega}^{t} U_m \sin(\omega t + \alpha)\,dt \quad (2)$$

where L is the total inductance of the closing circuit, $L = L_s + L_{11\sigma} + L_{1m}$, and θ the corresponding electrical angle of the core saturation moment, abbreviated as saturation angle.

The formula (2) can be integrated into the below equation

$$i_m = \frac{U_m}{\omega L}(\cos\theta - \cos\omega t), \quad \theta < \omega t < 2\pi - 2\alpha - \theta \quad (3)$$

The effective value of the components of each harmonic current $I_m(n)$ can be extracted by Fourier decomposition of the inrush current, and the below formula can be obtained

$$\begin{aligned} I_m(n) = \frac{U_m T_0}{2\omega_0 L T}\Big[& S_a \frac{(n-1)\omega_0 T_0}{2} - 2\cos\frac{\omega_0 T_0}{2} \\ & \times S_a \frac{n\omega_0 T_0}{2} + S_a \times \frac{(n+1)\omega_0 T_0}{2}\Big] \end{aligned} \quad (4)$$

Among them, $T = 2\pi/\omega_0$ is the power frequency period, $T_0 = 2\theta/\omega_0$ is the time from the closing of the circuit breaker to the core saturation, and the $S_a(x) = \sin x/x$ is the sampling function.

Therefore, the fundamental and second harmonic effective values of the inrush current are (5) and (6), respectively

$$I_m(1) = \frac{U_m}{2\omega_0^2 L T}(\omega_0 T_0 - \sin\omega_0 T_0) \quad (5)$$

$$I_m(2) = \frac{U_m}{2\omega_0^2 L T}\left(\sin\frac{\omega_0 T_0}{2} - \frac{1}{3}\sin\frac{3\omega_0 T_0}{2}\right) \quad (6)$$

Finally, the second harmonic proportion of magnetising inrush is given in the below equation

$$K_2(T_0) = \frac{\sin(\omega_0 T_0/2) - (1/3)\sin(3\omega_0 T_0/2)}{\omega_0 T_0 - \sin\omega_0 T_0} \quad (7)$$

It can be seen, magnetising inrush second harmonic proportion depends on T_0, essentially depends on the saturation angle θ. As shown in Fig. 3, the larger θ is, the smaller the second harmonic proportion of magnetising inrush is.

Suppose the saturation magnetic flux of the transformer core is ϕ_0. In a power frequency cycle, the below equation is established

$$\phi_0 = -\phi_m \cos(\theta + \alpha) + \phi_m \cos\alpha + \phi_r \quad (8)$$

In fact, the non-periodic component $\phi_m \cos\alpha + \phi_r$ of the transformer flux will decay due to the resistance of the closing circuit, causing the inrush current to decay and the equivalent saturation angle θ to increase, as shown by the dashed line in Fig. 2. Therefore, with the inrush current attenuation, the inrush current second harmonic proportion will reduce, as shown in simulation Fig. 4.

2.1.2 Dead angle: From the graphical analysis of the inrush current in Fig. 2, it is known that there will be inrush current only within $\theta < \omega_0 t < 2\pi - 2\alpha - \theta$ in a power frequency period. At other times, magnetising inrush is almost zero, resulting in waveform discontinuity which is also one of the common features used to identify inrush current. If the dead angle of the inrush current is β then there is a formula (9) holding

$$\beta = 2\alpha + 2\theta \quad (9)$$

According to the above analysis, when the closing angle α is determined, as the inrush current decays, the breaking angle of the waveform will become larger and larger, as shown in Fig. 5 and Table 1 of the simulation.

2.2 Waveform characteristics analysis of sympathetic inrush

2.2.1 Second harmonic proportion: In the no-load closing operation of single-phase transformer $T1$, select and analyse the

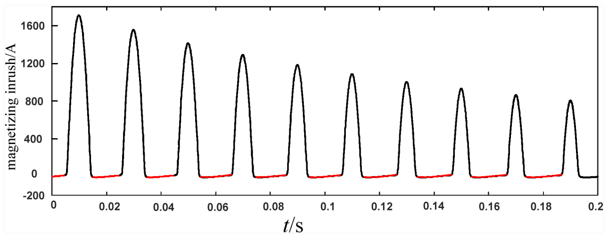

Fig. 5 *Dead angle of magnetising inrush waveform*

Table 1 Dead angle of magnetising inrush in different period

*n*th cycle	1	2	3	4	5	6
dead angle, °	157	175	188	205	224	227

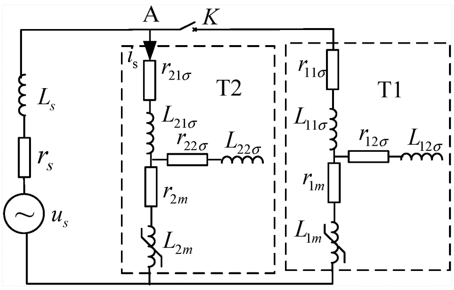

Fig. 6 *Equivalent circuit of sympathetic inrush in parallel*

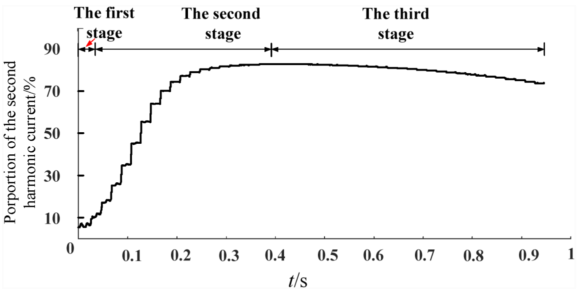

Fig. 7 *Simulation of the second harmonic proportion of magnetising inrush*

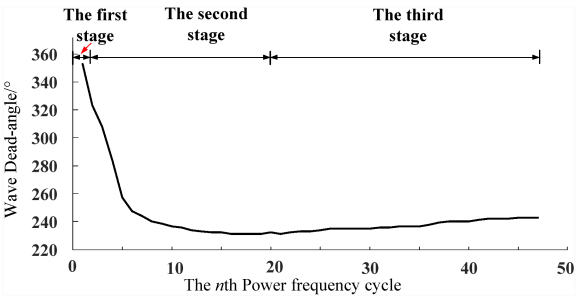

Fig. 8 *Simulation of the dead angle of sympathetic inrush*

case of operating with transformer $T2$ which produces sympathetic inrush in parallel. The equivalent circuit as shown in Fig. 6 can express the generation of sympathetic inrush. Since the system resistance is very small, it can be considered that the voltage at the primary side of the two parallel transformers is the power voltage after closing. In this case, the formula of the second harmonic proportion of the inrush current will be the same as that of the inrush current, and can be calculated by (7).

However, it should be understood that the process of inrush current generation differs from the process of magnetising inrush. In short [10–12], magnetising inrush contains a DC component, and when the DC component current flows through the system impedance, a voltage drop is generated, so that the primary side voltage of the transformer includes a DC component. Thus, the transformer core flux gradually accumulated to saturation, and sympathetic inrush will be generated finally.

Therefore, the second harmonic proportion of sympathetic inrush is changed and it can be divided into three phases:

The first stage: Within the time that the transformer is switched in no-load to the transformer core enters the saturation. During this time, sympathetic inrush should be almost zero, the core saturation angle θ is about 2π According to the formula (7), the second harmonic proportion of sympathetic inrush is ∼0.

The second stage: The core of transformer $T2$ go into saturation, and then the saturation angle θ of transformer $T2$ will be gradually reduced, so that the second harmonic proportion will increase.

The third stage: Owing to the resistance loss in sympathetic inrush loop, the magnetic flux of core will gradually decrease until it exits saturation. At this stage, the saturation angle θ will gradually increase, and the second harmonic proportion will decrease accordingly.

Under the switching angles of 0°, the simulation diagram of the change of second harmonic proportion is shown in Fig. 7.

2.2.2 Dead angle: It is the same as the analysis of the second harmonic proportion, the analysis of the dead angle is divided into three stages, according to (9).

The first stage: Transformer $T2$ core is not saturated, sympathetic inrush is almost zero, and waveform dead angle is about 2π.

The second stage: Transformer $T2$ core saturation, as the saturation gradually deepens, the saturation angle θ becomes smaller and the dead angle of wave decreases gradually.

The third stage: The resistance dissipation plays a leading role, the core of the transformer gradually withdrawal from saturation and the saturation angle θ becomes large, and the dead angle of the waveform is gradually increasing.

The simulation is done when the closing angle is 0°; the result is shown in Fig. 8.

3 Influence of transient characteristic of CT on second harmonic proportion of inrush current

The acquisition current of protection is the secondary current transferred by the CT. Therefore, the CT transient transmission to the characteristics of inrush current will have a direct impact on the transformer differential protection brake, which construct braking criterion by the second harmonic proportion and the waveform dead angle and other waveform characteristics.

The equivalent circuit of CT is shown in Fig. 9*a*, L_m and R_m are the excitation inductance and resistance of CT, L_2 and R_2 are the secondary winding leakage inductance and resistance after conversion. L_L and R_L are the secondary load inductance and resistance after conversion. The primary side current of CT is equivalent to an external equivalent current source, and the equivalent circuit is shown in Fig. 9, where $L'_L = L_L + L_2$, $R'_L = R_L + R_2$.

In a power frequency cycle, CT core may be in an alternating saturation state. Assuming that the average magnetising inductance of the CT is L_{ma}, the effective value of the nth harmonic component current of the primary side of CT is I_{1n}, and the effective value of the nth harmonic component current of the secondary side of CT is I_{2n}. According to the principle of circuit, the below equation can be obtained

$$I_{2n} = \frac{n\omega_0 L_{ma}}{\sqrt{n\omega_0 (L_{ma} + L'_L)^2 + R'^2_L}} I_{1n} \tag{10}$$

$K(n)$ is defined as follows:

$$K(n) = \frac{I_{2n}}{I_{1n}} \tag{11}$$

Then

$$K(n) = \frac{n\omega_0 L_{ma}}{\sqrt{n\omega_0 (L_{ma} + L'_L)^2 + R'^2_L}} \tag{12}$$

The derivative of $K(n)$ is defined as follows:

$$\frac{dK(n)}{dn} = \frac{\omega_0 L_{ma} R'^2_L}{\{[n\omega_0 (L_{ma} + L'_L)]^2 + R'^2_L\}^{3/2}} \tag{13}$$

Obviously, $(dK(n)/dn) > 0$, there is $K(2) > K(1)$, so

$$\frac{I_{22}}{I_{12}} > \frac{I_{21}}{I_{11}} \tag{14}$$

Further deduction can get the below inequalities

$$\frac{I_{22}}{I_{21}} > \frac{I_{12}}{I_{11}} \tag{15}$$

As can be seen, the second harmonic proportion of the inrush current will increase after the CT transfer. According to this reasoning, the high harmonic ratio of the inrush current after CT transfer will increase.

4 Influence of transient characteristic of CT on dead angle of inrush current

This section will take advantage of the CT (P/PR) Lucas simulation model [13, 14] that the author has constructed to consider the influence of two influencing factors that are secondary load and CT type on the dead angle of the inrush current waveform from the perspective of theory and simulation.

4.1 Secondary load of CT

First, the effect of secondary load on inrush current and PR type CT of protection with low leakage magnetic inductor is analysed, that L_2 is ∼0. Assuming that the core saturation flux of CT is ϕ_{ct0}, when the core is not saturated, the primary current almost all flows into the secondary load branch. Therefore, ϕ_{ct0} is expressed as follows:

$$\phi_{ct} = \int_0^t i_1 R'_L \, dt \tag{16}$$

In a power frequency period, the inrush current is >0 in $\theta_1 < \omega t < \theta_2$, and the inrush current is ∼0 in $0 < \omega t < \theta_1$ and $\theta_2 < \omega t < 2\pi$. The secondary current of the CT can be graphically represented as Fig. 10.

As shown in Fig. 10*a*, when the equivalent secondary load resistance of the CT is very small, the magnetic flux of the CT core will not be saturated, which is called the first case. At $\omega t = \theta_2$, ϕ_{ct} reaches the maximum. After that, magnetising inrush changes to 0. The flux of core attenuates with time constant $\tau = L_m/R'_L$ under the joint action of the excitation branch inductance and the equivalent secondary load resistance of the secondary circuit. When the R'_L is very small, τ is very big and the flux attenuation is slow. According to $i_2 = (d\phi/dtR'_L)$, we know that secondary current is >0 when $\theta_1 < \omega t < \theta_2$, and it is <0 when $\theta_2 < \omega t < \theta_3$. Obviously, in this case, the dead angle of magnetising inrush decreases after the CT transfer. It is possible that the magnetic flux cannot decay to 0 in a power frequency period, and the dead angle of the waveform is 0.

The equivalent secondary load resistance R'_L continues to be increased, and it is assumed that the CT core is saturated at $\omega t = \theta_4$. It is called second case, as shown in Fig. 10*b*. After that, the magnetic flux of CT core will remain unchanged in the period of $\theta_4 < \omega t < \theta_2$. So, magnetising inrush will be 0. Also, the core flux will be attenuated in the period of $\theta_2 < \omega t < 2\pi$. Compared with the first case, the attenuation time constant will increase. From the above analysis, it is known that the secondary current of the CT produces a dead angle in $\theta_4 < \omega t < \theta_2$, and whether there is a dead angle in $\theta_2 < \omega t < 2\pi$ depends on the decay rate of magnetic flux.

Third, R'_L continued to increase greatly, we know that CT saturation angle θ_4 will be further reduced, as shown in Fig. 10*c*. As the core is seriously saturated, L_m will become very small, and the decay time constant τ will become very small during the withdrawal of the core from saturation. After the inrush current is disappearing, the secondary current of the CT can only be maintained for a very short time. Therefore, in a power frequency cycle, CT secondary current will be 0 for most of the time. In this case, the waveform dead angle of the CT secondary current will be greater than magnetising inrush.

From the above analysis, it is known that under the inrush current, with the increase in the CT secondary load resistance, the secondary current dead angle of CT will increase. However, compared to the inrush current, transferred dead angle may become bigger or smaller. The influences of secondary load on the dead angle of sympathetic inrush waveform were compared and analysed. As sympathetic inrush is far less than the inrush current, according to the analysis of formula (16), the inrush current is not easy to cause CT saturation. Thus, it can be analysed according to the first situation of magnetising inrush above. It can be analysed that the dead angle of sympathetic will decrease after transferred by CT under different secondary loads.

Through simulation, the influence of CT secondary loads on the dead angle of the inrush current is studied by using PR Lucas model. The result is shown in Fig. 11.

4.2 Type of CT

The transient transmission characteristics of different types of CT are also different. Under the rated load, the excitation inductance of the P-type CT is large, the excitation current is small, but it is easy to saturate. The PR type CT has gas gap and is not easy to saturate. However, under the rated load, the excitation inductance is small and the excitation current is large. Fig. 12 compares the effects of the P and PR types of CT on dead angle of inrush current under the same operating conditions.

As can be seen from the figure, under various operating conditions, the dead angle of the inrush current after the PR type of CT transfer is smaller than that of the P-type CT. Therefore, it can be inferred that the more difficult the CT is to be saturated, the smaller the dead angle of the inrush current waveform after the transformation is, and the larger the converse.

5 Summary

During the period of transformer sympathetic inrush, the characteristic of inrush current and its characteristic after CT transformation are the core problems in the research of braking criterion for differential protection of transformers. In this paper, the variation regularity of transformer inrush current characteristics is analysed, and the CT Lucas simulation model is used to analyse

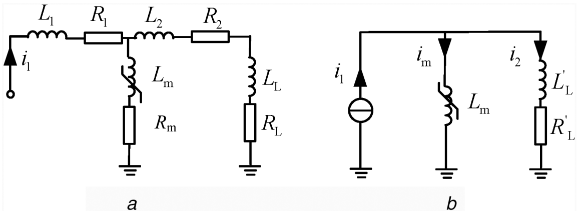

Fig. 9 *Equivalent circuit of CT*
(a) Equivalent circuit of CT, ***(b)*** The simplified equivalent circuit of CT

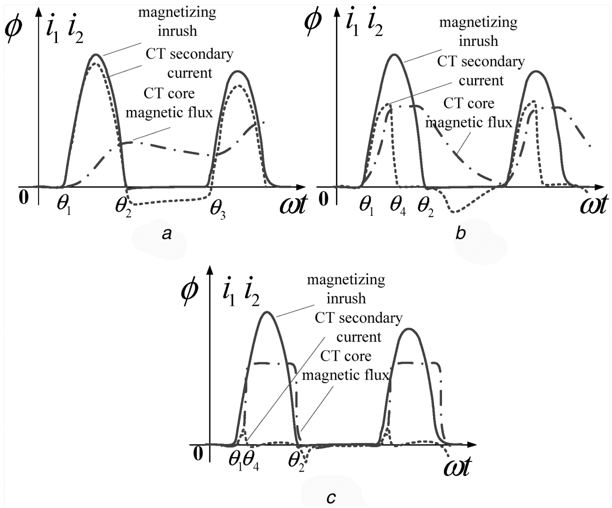

Fig. 10 *Influence of secondary load on dead angle of inrush current waveform*
(a) With very small resistance, ***(b)*** With bigger resistance, ***(c)*** With large resistance

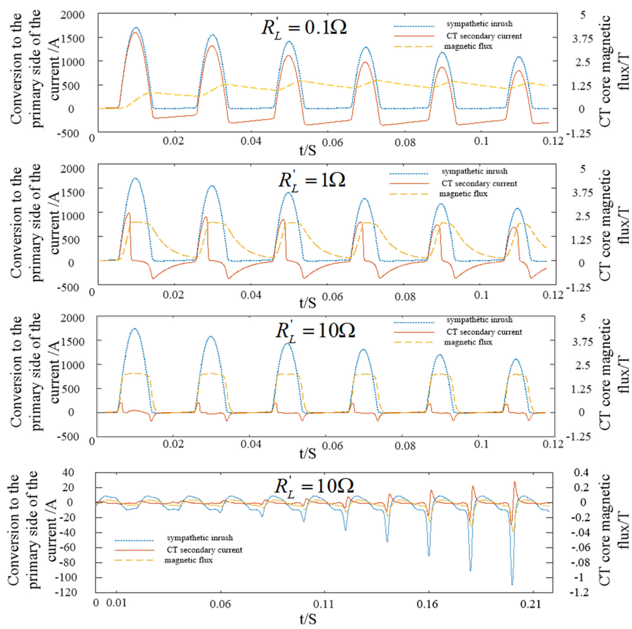

Fig. 11 *Effect of load on inrush current dead angle*

the influence law of CT transient transfer characteristics on the inrush current characteristics. The main conclusions are as follows:

i. The second harmonic proportion of the inrush current and the dead angle of the waveform depend on the saturation angle of the transformer core. The larger the saturation angle is, the smaller the second harmonic proportion is, and the larger the dead angle of the waveform is.

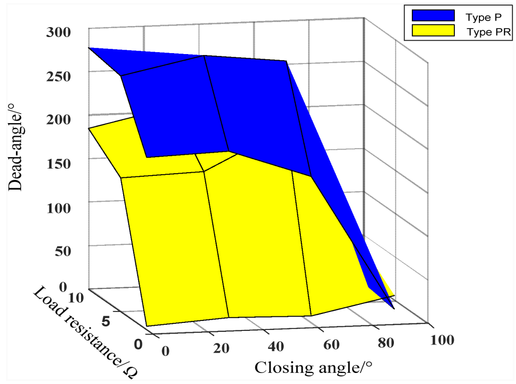

Fig. 12 *Effect of different types of CT on the dead angle*

ii. The second harmonic proportion of the inrush current will increase after the CT transformation, more conducive to the inrush current braking with the second harmonic proportion as the braking criterion.

iii. The larger the equivalent secondary load resistance of CT, the easier the CT type is to saturate, and the larger the dead angle of the inrush current waveform after CT transfer is. It is more conducive to the dead angle criterion braking.

iv. After CT transfer, the dead angle of sympathetic inrush will decrease. When compared with the inrush current, the braking criterion of the dead angle of the waveform is more likely to fail.

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