Calculation and Testing of K-Factor and RMS Values for Single-Phase Transformer Short-Circuit Tests

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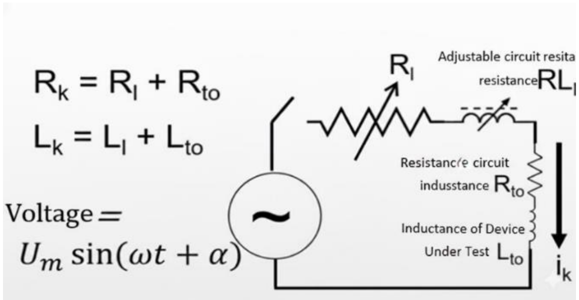
1. Background

In a power system, the short-circuit withstand capability of a transformer is a core indicator for ensuring power supply reliability. When a short-circuit fault occurs, the relationship between the force exerted on the transformer's metallic conductors and the short-circuit current is $F = B \times I \times L \times \sin\theta$, and the relationship between the magnetic field and the current is $B = (\mu_0 \times I) \div (2\pi r)$. Therefore, the force exerted on the metallic conductors during a short circuit is approximately proportional to the square of the short-circuit current. To verify the robustness of the equipment, a “Short-Circuit Withstand Test” must be conducted.

Currently, for the acceptance testing of Taipower’s single-phase transformers, including “Taipower Material Specification C001 $_{(104\text{-}07)}$” and “Taipower Material Specification Y065 $_{(101\text{-}06)}$”, short-circuit tests are performed at the Taiwan Power Research Institute (TPRI). According to IEEE standards, the test is considered successful only if the peak current and the RMS (root mean square) value generated during the test reach at least 95% of the calculated values.

During the short-circuit test, the high-voltage side of the transformer is connected to the test circuit, while the low-voltage side is short-circuited using copper bars. The complete test circuit diagram is shown in Figure 1, where R_{to} and X_{to} correspond to the r and x mentioned below.



Source: This study

Figure 1. Test Circuit Diagram

2. Calculation Methods for K-factor and RMS in Short-Circuit Tests

Using the C001$_{(104\text{-}07)}$ 50kVA pad-mounted transformer as an example, its basic characteristics must be measured as shown in Table 1 prior to the application of the short-circuit current. The K-value can then be calculated according to the IEEE C57.12.00 (2015) formula.

Table1. Comparison of RMS Current Multiples and Duration for Short-Circuit Tests (Example: Single-phase 50kVA Transformer)

50kVA	IEC 60076-5 (2006)	IEEE C57.12.90 (2021)	CNS 598 (2017)
Peak Current	95%~105% of the specified value	> 95% of the specified value	95%~105% of the specified value
RMS Current	Specified value = Rated Current ÷ (Impedance Voltage%) 90%~110% of specified value	Min of (35 x Rated Current) or (Rated Current÷Impedance Voltage %) > 95% of specified value	Rated Current ÷ Impedance Voltage% 90%~110% of specified value

50kVA	IEC 60076-5 (2006)	IEEE C57.12.90 (2021)	CNS 598 (2017)
Duration & Frequency	0.5s ± 10%; 3 times each for Maximum Voltage, Rated Voltage, and Minimum Voltage, for a total of 9 times.	Rated Voltage: 0.25s for 5 times(5 tests at Rated Voltage, 0.25s each) Test Duration = (1250 ÷ 352)s for 1 time(Test Duration = $(1250 \div 35^2)$ seconds, 1 iteration) Out of 6 tests, 2 must reach 95% of the specified Peak Current value. (2 out of 6 tests must achieve 95% of the required Peak Current.)	0.5s ± 10%; 3 times each for Maximum Voltage, Rated Voltage, and Minimum Voltage, for a total of 9 times.

Source: This study

The measurement method for load loss is as follows: apply the rated current to the high-voltage (HV) side with the low-voltage (LV) side short-circuited. The voltage measured on the HV side at this stage is the impedance voltage (expressed as a percentage: 161.9V ÷ 6930V = 2.336%).

According to IEEE C57.12.00 (2015) section 7.1.5.2, the calculation for K is as follows:

$$K=\left\{1+\left[e^{-\left(\phi+\frac{\pi}{2}\right)\frac{r}{x}}\right]\sin\ \phi\right\}\sqrt{2}$$

- Impedance Z = 169.1÷7.21 = 22.44Ω
- Resistance r = √(345W÷7.21A) = 6.63Ω
- Reactance x = $\sqrt{(Z^2 - R^2)}$ = 21.44Ω
- Φ: $\tan^{-1}(X \div R)$ = 1.27
- Calculated K: 1.997

Transformer manufacturers typically reference impedance voltage to 75°C or 85°C. However, as resistance increases with temperature, the K-value decreases. A smaller K-value fails to reflect the peak current during low-temperature or low-load short-circuit faults; therefore, the aforementioned calculations use parameters measured at room temperature.

(1) The RMS value is determined by the capacity and multiplier specified in the Taipower Material Specification C001 (104-07), as summarized in Table 2. The calculation is as follows: RMS = 35 times the Rated Current = 35 × 7.21A = 252.35A.

(2) To comply with test regulations, the peak current must reach 478.75 A (at least 95% of 1.997 × 252.35 A) and the RMS value must reach 239.73 A (at least 95% of 252.35 A).

(3) If the short-circuit test for the transformer is conducted according to IEC/CNS standards, the K-value derived remains identical to the one calculated from the IEEE standard. However, based on the formulas in Table 3, the short-circuit current and peak current under IEC/CNS standards are 308.6 A and 616.3 A, respectively. Under these conditions, the force exerted on the transformer conductors is approximately 1.5 times that under the IEEE standard, which may lead to transformer failure during the test. The calculations for short-circuit current, peak current, and the force multiplier according to IEC/CNS standards are as follows:

A. Short-circuit Current = 7.21 ÷ 2.336% = 308.6 A

B. Peak Current = 308.6 × 1.997 = 616.3 A

C. Force Multiplier = $(308.6 \div 252.35)^2$ = 1.5 times.

Table 2. Measured Parameters

Oil Temp.	Rated HV Current	Impedance Voltage (V)	Impedance Voltage (%)	Load Loss
13.6°C	7.21A	161.9V	2.336%	345W

Source: This study

Table 3.

Transformer Capacity (kVA)		Short-Circuit Current Magnitude (A)
Single-Phase	Three-Phase	
25	75	40 × Rated Current
50.100	150.300	35 × Rated Current
167	500	25 × Rated Current

Source: Taipower Material Specification C001(104-07)

3. Test Results and Operational Procedures

(1) According to the rule of thumb, multiple “pre-tests” (trial shots) are first conducted at currents less than 70% of the rated short-circuit value to minimize damage to the transformer, followed by the 100% rated short-circuit current test.

(2) Adjustment of the closing angle is performed using the waveforms generated during these pre-tests. By observing the K-value of the current waveform, the controller’s closing angle is repeatedly adjusted, typically in increments of ±5 degrees, until the K-value meets the requirement of 1.997 ± 5%, at which point the pre-testing is complete.

(3) Execution of the 100% rated short-circuit current test: After accounting for the voltage drop, the final generated waveform must satisfy Taipower specifications; specifically, both the RMS value and the peak current must be at least 95% of the calculated values. Furthermore, the short-circuit test is deemed qualified if the transformer characteristics after the test meet the following criteria: excitation current change rate is < 25%, and the impedance voltage change rate is < (22.5 - 500 × impedance voltage%)% = (22.5 - 500 × 2.336%)% = 10.82%.