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Radial-Strength Research of Transformer Windings Considering Temperature Effect Under Reclosing Short-Circuit Conditions

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Abstract: With the fast capacity growth in power systems, transformer failures caused by short circuits have become the primary problems in maintaining their operation reliabilities. In addition, automatic reclosing will make the transformers suffer multiple short-circuit impacts in a short time interval, therefore challenging the transformers' short-circuit stability. In this study, a comprehensive analysis of radial strength under reclosing short-circuit conditions is carried out on a 50 MVA transformer taking the temperature influences into consideration. First, the power transformer's fault model is established to calculate the short circuit currents under initial short circuit and reclosing conditions. Then, three-dimensional (3D) finite element analyses of the transformers' winding short-circuit forces with initial short circuits and reclosing are conducted. Finally, the temperature influences on the windings after the reclosing are calculated. By taking into account the qualities of the self-adhesive transposition wire with temperature effect, the stress characteristics of the windings are calculated.

Keywords: Short-circuit, reclosing, radial strength, finite element analysis (FEA), temperature.

1 Introduction

Transformers are the key components in power systems, deciding directly the power supply safety by their long-term operation reliability [1-2]. With the capacity growth in power systems, transformers' winding failure caused by short circuits has become one of the main causes of transformer accidents [3]. Furthermore, when experiencing reclosing, the transformers will also be subjected to multiple more severe impacts [4], so endangering the stability of their short circuit.

Study has been done recently to examine transformers' short-circuit performances [5-7]. In most short-circuit settings, a nonlinear buckling analysis approach is described to analyze the deformation of the windings for a model transformer under short-circuit tests [8]. The residual deformation is used as the initial condition, and the built-up effect is taken into account. In [9], plastic deformation and thermal effect are considered in the calculation method of transformer winding buckling strength, and the relationship model between temperature and yield strength is established. The temperature rise and ultimate buckling load of transformer winding are analyzed by finite element method and experimental method. In [10], a three-phase, five-limb power transformer's mechanical strength, windings' short-circuit electrodynamics force, and transient electromagnetic field are simulated and examined. In [11], the electromagnetic force of transformer windings is tested when short-circuit current is applied to the model. In [12], the mechanical flaws in oil-immersed power transformers with disc-type windings are investigated, and the short-circuit tests are conducted on eight aged transformers. In [13], puts forward and describes various equivalent diagrams for multi-winding transformer modeling. On the basis of the example data, taking four-winding and five-winding transformers as examples, the parameters of each scheme are determined, and the example short-circuit analysis is carried out, pointing out the similarities and differences of modeling methods and their influence on the calculation results. A new method for simulating cumulative deformation of

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transformer windings considering short-circuit impedance is studied. In [14], the influence of MFL on the short-circuit resistance of the transformer was studied and the radial and axial MFL distributions of each winding under different working conditions were analyzed. The radial stability of transformer winding under short circuit is studied. In [15], the dozens of short circuit and accumulation tests are carried out under high voltage to medium voltage (HV-MV) short circuit. In [16], the circular radial stability of the inner winding is investigated using an enhanced radial buckling analysis method by defining equivalent flexibility and MD. A total of 73 cumulative short-circuit tests are conducted until the impedance surpasses the allowable value based on the assessment. In [17], the effects of core and pre-stress on short circuit features as well as the cumulative impact of single-phase transformers are investigated. The temporal response and spatial distribution of the mechanical and electromagnetic properties under short-circuit impacts are also analyzed.

Throughout the transformers' reclosing processes, the winding employs self-adhesive transposed wires, and the initial short circuit will raise the winding temperature. By these means, the temperature influences the properties of the wires and self-adhesive paint, which in turn affects the mechanical properties of the winding during the second short circuit in the reclosing process. However, little research has been done on how temperature affects the self-adhesive transposed wires when reclosing occurs.

For this reason, this study provides the reliability investigation of an SSZ11-50000/110 transformer under reclosing short-circuit situations, taking into account the impact of temperature. First, to compute the short-circuit current transient process following the initial short-circuit and reclosing, the power transformer's short-circuit fault model is constructed. Secondly, by creating a 3D finite element model of the transformer, the leakage magnetic field and the magnetic density distribution in the winding area are computed, and the radial electromagnetic force of the winding is simulated following the initial short-circuit and reclosing. The third step involves calculating the temperature change of the winding following the primary short-circuit during reclosing. This is done to examine the impact of temperature on the self-adhesive conductor's performance that account for the temperature effect. The distribution characteristics of the wire cake displacement following the initial short-circuit and reclosing are then investigated.

2 Prototype structure and parameters

In this paper, an SSZ11-50MVA/110kV transformer is taken as the prototype, as shown in Fig. 1. The high voltage, medium voltage, and low voltage windings have 70, 88, and 78 cakes, respectively. During simulations, the high and medium operating condition is considered. Table I lists the prototype's key parameters.

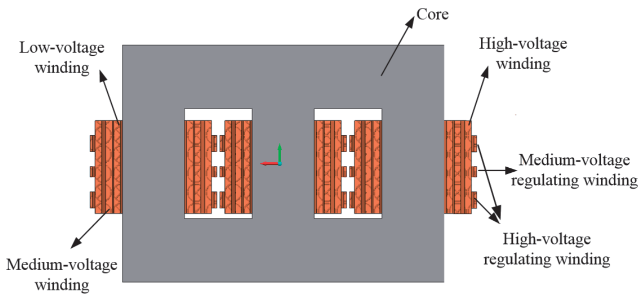


Fig. 1 The transformer prototype.

Tab. 1 Key parameters of the transformer

Parameter	Value
Rated capacity	50000 kVA
Impedance percentage	10.49 %
Rated voltage of high voltage winding	110 kV
Rated current of high voltage winding	262.4 A
Turns number of high voltage winding	472
Rated voltage of medium voltage winding	38.5 kV
Rated current of medium voltage winding	749.8 A
Rated current of medium voltage winding	165

3 Radial strength analysis of reclosing short-circuit impact

3.1 Transformer short-circuit current calculation

To simulate the power transformer short circuit failure, a power system short circuit fault circuit model is established, as depicted in Fig. 2. Changing the short-circuit conditions of the system will result in different short-circuit conditions (single-phase short circuit, two-phase short circuit, and three-phase short-circuit) under the winding current waveform. The short-circuit conditions are realized as follows: the circuit breaker is closed at 0s, then the short-circuit occurs at 0.1s, and the circuit breaker tripped to cut off the power supply at 0.5s.

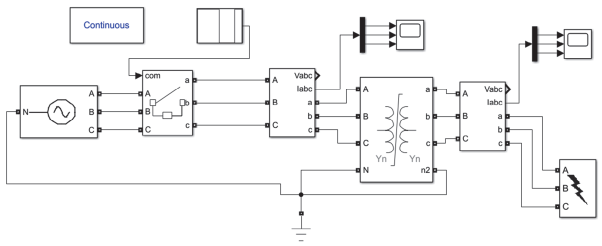


Fig. 2 Power system short circuit fault circuit model.

The current waveform in response to a short-circuit impulse is simulated. Taking the medium voltage winding as an example, the short-circuit current curves under various short-circuit conditions are calculated and illustrated in Fig. 3. Under high and medium voltage operating conditions, the closing phase angle of phase A is set to 0.

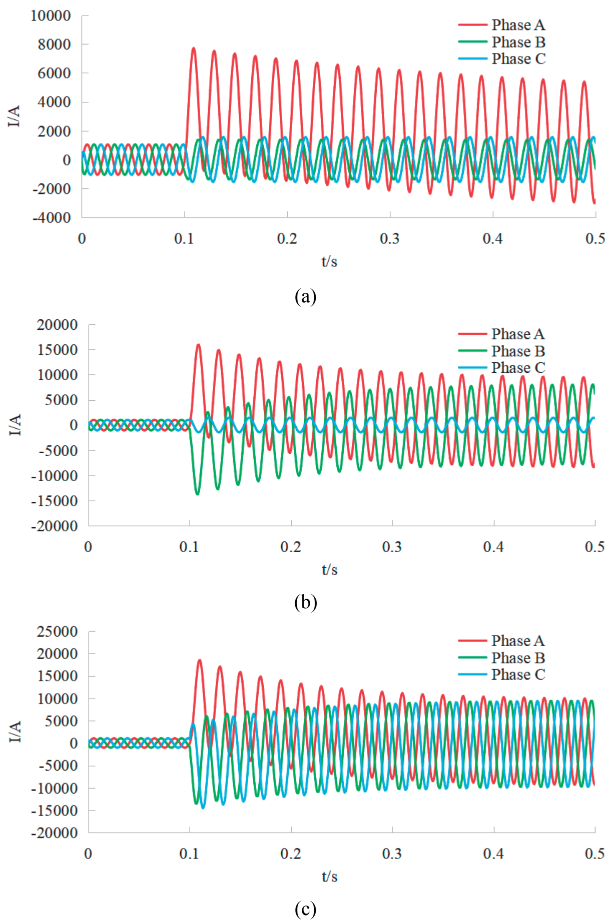


Fig. 3 Short-circuit current waveform under different short-circuit conditions of medium voltage winding: (a) single-phase short-circuit; (b) two-phase short-circuit; (c) three-phase short-circuit.

It is evident from Fig. 3 that the system encounters a short circuit accident at 0.1s. The current will increase quickly in the following scenarios: single-phase short circuit (A phase short circuit), two-phase short circuit (A/B phase short circuit), and three-phase short circuit. The three-phase short circuit exhibits the most significant rise of the three short circuit circumstances, with a maximum value of 17960A. In addition, when a transformer experiences a short circuit, there is no residual magnetism inside the iron core. However, when the transformer undergoes automatic reclosing, there may be high residual magnetic flux inside the iron core, which will have an impact on the short-circuit current after reclosing.

Consequently, the remaining magnetic values per unit of the iron core are set to 0.8, -0.4, and -0.4, respectively, when calculating the reclosing short circuit of a transformer. As seen in Fig. 4, the short-circuit current of the medium voltage winding

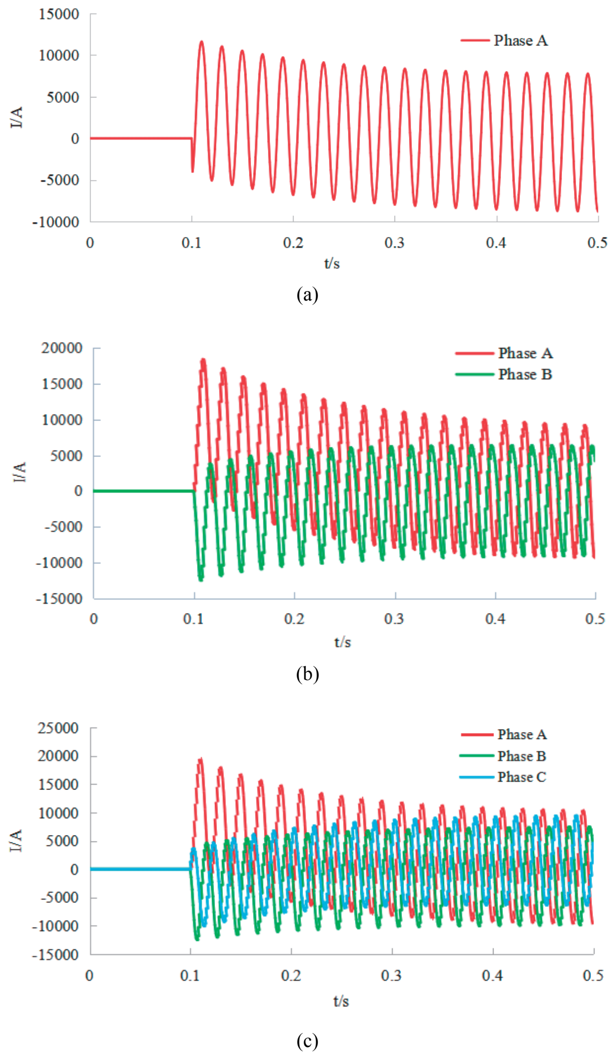


Fig. 4 Short-circuit current waveform of medium voltage winding under different reclosing short-circuit conditions: (a) single-phase short-circuit; (b) two-phase short-circuit; (c) three-phase short-circuit.

under three distinct short-circuit situations following reclosing is computed. It is evident from the figure that, in comparison to a single short-circuit, the short-circuit current has increased under various short-circuit situations following reclosing. Using the medium voltage winding as an example, the short-circuit impulse current will reach 19220A in a three-phase short-circuit condition.

Table II shows that the short-circuit impulse current of reclosing during a single-phase ground fault, the value is 1.61 times greater than that of the initial short-circuit, and the increase in a three-phase short-circuit is the least.

Nevertheless, taking into account the particular short-circuit current amount, the amplitude is still at its highest following a three-phase short-circuit fault, even if the rise in reclosing short-circuit current is largest following a single-phase short-circuit. The amplitude of the reclosing short-circuit current is at its maximum following a three-phase short-circuit fault, despite the fact that the rise is greatest following a single-phase short-circuit. This is because of the particular short-circuit current value.

However, in practice, the reclosing short circuit problems often occur after single-phase short circuits. Consequently, the investigation of the influence of reclosing short circuits following single-phase short circuit failures in transformers remains the primary focus of the verification process of the winding's strength characteristics after reclosing.

Tab. 2 The gain of the reclosing short-circuit current under different short-circuit conditions

Condition	Multiple
Single-phase short-circuit	1.61
Two-phase short-circuit	1.25
Three-phase short-circuit	1.07

Table 3 shows the impact current of the winding after reclosing under different remanence. It can be seen that when the remanence direction is consistent with the excitation direction of the power supply voltage, the short-circuit current increases with the increase of remanence. When the remanence direction is opposite, the value of the short-circuit current is smaller than that of the initial short-circuit current. Therefore, when only positive remanence is left in the core, the short-circuit strength of the transformer winding after reclosing needs to be checked.

Tab. 3 Current amplitude under different remanence

residual magnetic flux	0.4	0.6	0.8
current/A	18 877	18 939	18 220

Table 4 shows the calculation results of the maximum short-circuit current at different reclosing initial phase angles under the condition of certain core remanence (0.8). As can be seen from the table, with the increasing of the closing phase Angle, the short-circuit impulse current of the transformer will gradually decrease.

Tab. 4 Short-circuit inrush current at different closing phase angles

Initial phase Angle(deg)	0	45	90
Single-phase short-circuit/A	15 760	13 290	7 144
Two-phase short-circuit/A	16 870	13 890	9 253
Three-phase short-circuit/A	19 220	15 780	9 610

3.2 Short-circuit electromagnetic force calculation

The radial short-circuit electromagnetic forces of the transformer windings are calculated based on the axial flux densities as [18]:

$$F_x = B_y i_k \tag{1}$$

where B_y is the axial magnetic density of the windings. The electromagnetic field of the transformer is simulated by FEM, as shown in Fig. 5, while the axial magnetic densities of the high-voltage (HV) and medium-voltage (MV) windings are then retrieved, as seen in Fig. 6.

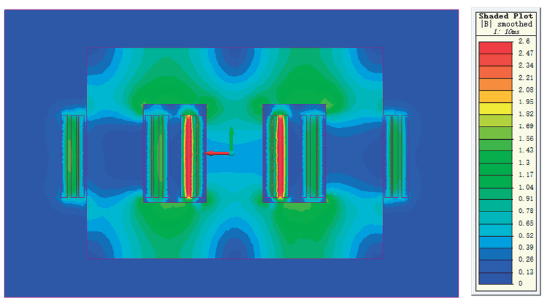


Fig. 5 Flux density distribution of the transformer.

Then, the radial forces of transformer's HV and MV windings under initial and reclosing short circuits are compared in Fig. 7. The figures show that when a reclosing short-circuit occurs, the radial electromagnetic force acting on the windings increases. The winding cake near the middle region will experience a higher short-circuit force.

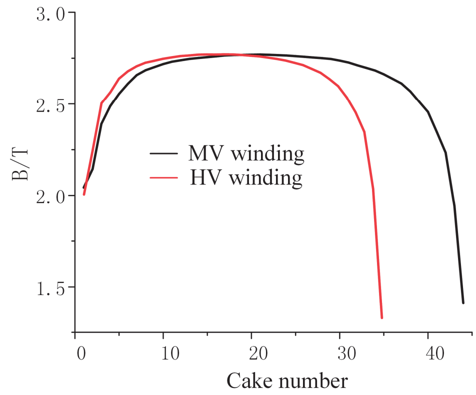


Fig. 6 Axial magnetic density curve of transformer winding

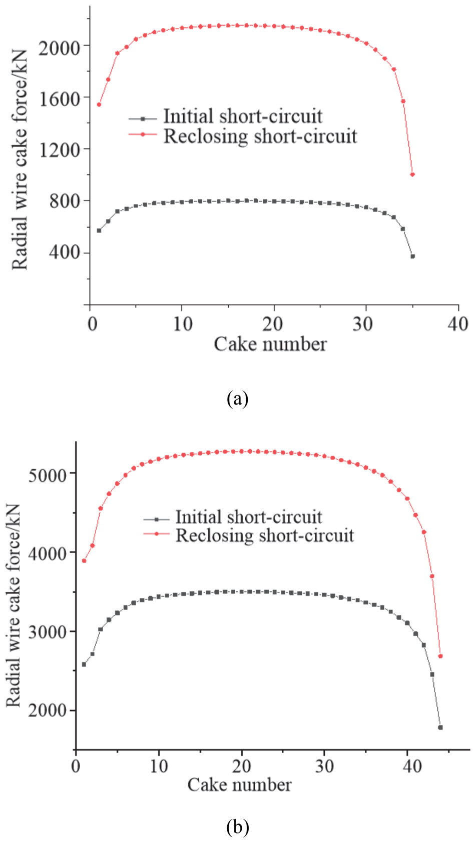


Fig. 7 Radial electromagnetic force comparison under initial short-circuit and reclosing short-circuit of transformer winding: (a) HV winding; (b) MV winding.

3.3 Radial strength analysis under reclosing

During reclosing, transformers will suffer very different impacts from conventional short circuits, as heat can accumulate and affect the mechanical characteristics by the temperature rise generated.

To examine the transformers' ability in withstanding short circuits, the related bending forces should be calculated. For non-self-adhesive transposition wires, the bending forces can be formulated as [19]:

$$\sigma_{br} = \frac{f_r l^2}{2hb^2} \tag{2}$$

where f_r is the amplitude force per unit length of the conductor, h is the axial dimension of the wire, b is the amplitude dimension of the wire, and l is the distance between the two braces of the winding cake. However, for self-adhesive transposition conductors, the effect of the curing factor of the self-adhesive transposition conductor will influence the bending forces. The amplitude-direction bending stress of the coil conductor is calculated as:

$$\sigma = \frac{\sigma_{br}}{f_s} \tag{3}$$

where f_s is the curing factor of the self-adhesive transposition conductor.

As to tested values of the curing factors [15], the overall flexural strength of self-adhesive transposition wires is related to temperature. During reclosing, winding temperature after the primary short-circuit will increase, since the heat is not dissipated in time. The temperature rise of the windings is calculated as:

$$\theta_1 - \theta_0 = \frac{2(235+\theta_0)}{\frac{106000}{\delta^2 t} - 1} \tag{4}$$

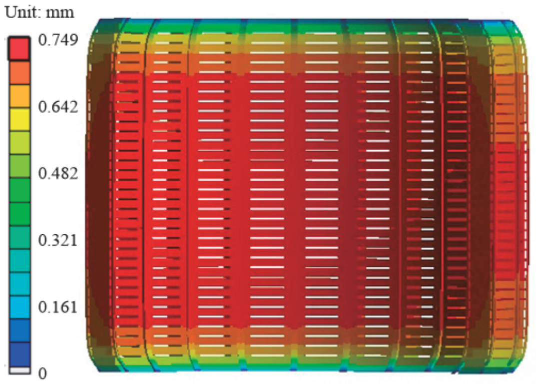
where θ_1 is the average winding temperature of the transformer after the short-circuit, θ_0 is the starting temperature of the transformer windings, δ is the short-circuit current density. As the temperature increase from 105 ℃ to 111.7 ℃ after primary short circuit, the self-adhesive transposition wire's cure factor will decrease from 4.5 to 2.8, based on the tested results in [20], causing the radial compressive stresses of the MV winding to increase. The values before and after short circuit are illustrated in Table 5.

Tab. 5 The bending stresses calculated under different conditions (MPa)

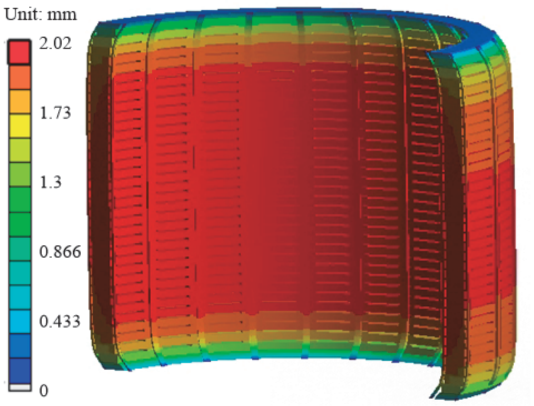
Winding	Primary short circuit	Reclosing short circuit	
		Without temperature influences	With temperature influences
HV	20	52	84
MV	53	79	127

3.4 Radial deformation analysis under reclosing

Based on FEM simulations, the radial deformations of the windings are obtained. Figs. 8 and 9 depict the radial displacements of the MV windings and the HV windings following the initial and reclosing short-circuit, respectively. The displacement of the winding cake is comparatively considerable in the middle and progressively diminishes towards both ends, as can be observed in the image.



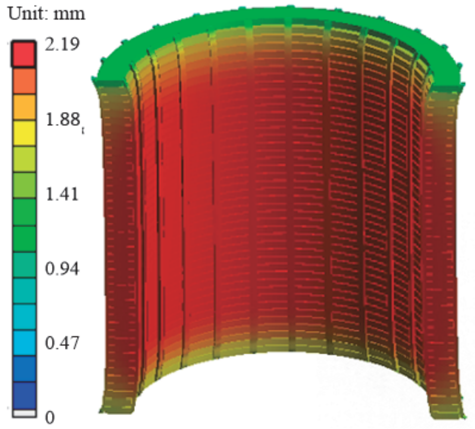
(a)



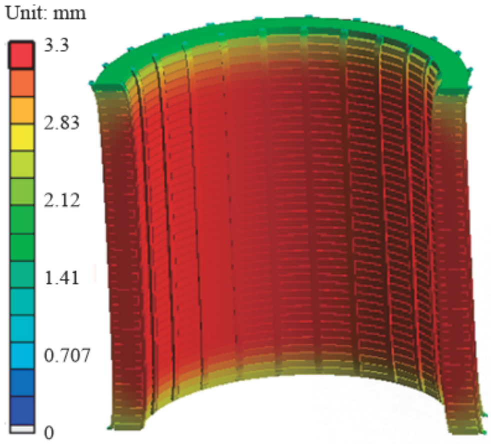
(b)

Fig. 8 Radial displacement distribution of HV winding: (a) initial short-circuit; (b) reclosing short-circuit.

The HV winding's radial displacement increases by 1.27 mm to 0.749 mm under the initial short circuit and 2.02 mm under reclosing conditions. The medium voltage winding's radial displacement is 2.19 mm and 3.3 mm, respectively, with a 1.11 mm increase. The simulation results show that while examining the short-circuit performances of transformers, it is critical to take temperature-relevant parameters into account.



(a)



(b)

Fig. 9 Radial displacement distribution of MV winding: (a) initial short-circuit; (b) reclosing short-circuit.

4 Conclusion

This paper presents a comprehensive analysis of a 50 MVA transformer's winding strength under reclosing short-circuit conditions. The circuit model of power transformer short-circuit fault is built, the real short-circuit condition of power transformer is simulated, and the short-circuit current of transformer reclosing is calculated. The magnitude of the short-circuit current after the reclosing process increased compared to that under the initial short-circuit, and the most significant increase occurred in the single-phase (1.61 times that under the initial short-circuit current). By creating a 3D finite element model of the transformer, the leakage magnetic field and the magnetic density distribution in the winding area are computed, and the radial electromagnetic force of the winding is simulated following the initial short-circuit and reclosing. In reclosing short circuit, the axial magnetic density of the winding reaches 2.7T, and the radial force of the wire cake in the middle of the winding is obviously greater. The bending stresses of the self-adhesive wires with and without considering the temperature influences during reclosing are calculated and compared. The radial displacement of the HV windings increased by 1.27 mm, and that of the MV windings increased by 1.11 mm under the reclosing short circuit.

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