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Features of Testing Distribution Transformers for Short Circuit Withstand Strength

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Abstract—Short circuit (SC) withstand strength is one of the key characteristics that define the reliability of power transformers. The SC withstand strength test methods are stated in State Standards *GOST* (State Standard) 20243 and 55188 (IEC 60076-5). This work considers problems related to the SC withstand strength test of distribution transformers that are not indicated in these standards. The dependence of SC peak current on average temperature of windings is considered. The possibility of heating of the windings of distribution transformers during the SC withstand strength test and related to it change of peak factor are revealed. The requirements of standards related to the winding temperature when the SC withstand strength test are considered. It is revealed that during the test of distribution transformers, one can expect the deviation of actual peak factor from its designed value by about 5% that should be taken into account when testing and analyzing the test results. The specific of test of the transformers with δ-connected winding is that, as a rule, merely the line currents of this winding can be recorded during SC experiments, at that, there are differences in peak currents for line currents and phase currents of windings. The requirements presented in *GOST* (State Standard) 20243 and R 55188 (IEC 60076-5) for SC peak current were stated as applied to the phase currents of windings, as well as to the line currents of star-connected windings. The difference of the peak factor for the line currents when testing the transformers with star- and δ-connected windings was revealed in the work, and it was concluded that the abovementioned standards for the requirements and test methods to SC withstand strength of the transformers need to be refines.

Keywords: distribution transformers, short circuit withstand strength, test, peak factor, tests schemes

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The short circuit (SC) withstand strength is one of the key characteristics that define the reliability of power transformers. According to [1], the adoption of power transformers with a capacity of up to 40 MVA inclusive with respect to the SC withstand strength should be carried out by means of a test or calculation comparison with a prototype transformer that was earlier successfully tested for SC withstand strength.

The requirements for SC withstand strength of power transformers, namely, normalized values of steady-state and peak SC currents that the power transformers need to withstand. are stated in [1, 2]. The test methods for SC withstand strength of power transformers are stated in [2, 3], in a guide to procedure and testing schemes, evaluation of test results, etc., are stated in sufficient detail.

Problems related to the test of distribution transformers on SC withstand strength that are not indicated in these standards are considered in this work.

According to [1, 2], steady-state SC current $I_{\text{sc.st.}}$ for which the transformer should be designed is

$$I_{\text{sc.st.}} = \frac{U_{\text{nom.br.}}}{\sqrt{3}(Z_{\text{t.br.}} + Z_{\text{n}})}, \quad (1)$$

where $U_{\text{nom. br.}}$ is the nominal line voltage of the branch, kV; $Z_{\text{t.br.}}$ is SC resistance of the transformer, Ω; and Z_{n} is the SC resistance of the network.

The peak SC current is determined by the steady-state SC current by the formula

$$i_{\text{p}} = I_{\text{sc.st.}} K_{\text{p}} \sqrt{2}, \quad (2)$$

where K_{p} is the peak factor, which, in accordance with [3], is

$$K_{\text{p}} = 1 + \left(e^{\frac{(\varphi+\pi/2)R}{X}}\right) \sin\varphi, \quad (3)$$

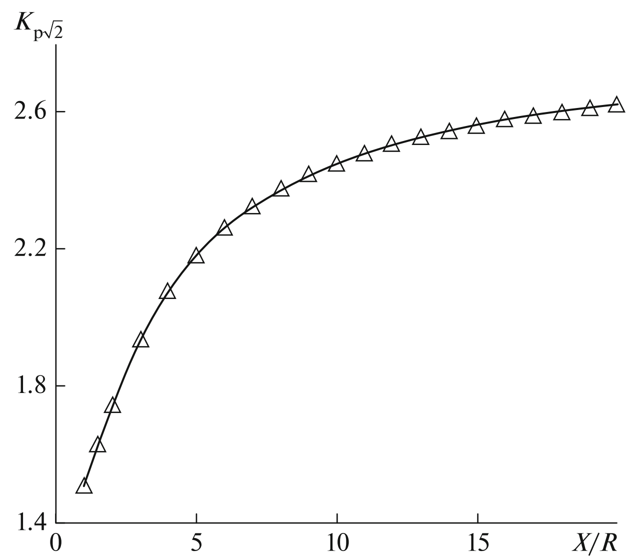

Fig. 1. Dependence of $K_{p\sqrt{2}}$ on X/R ratio.

where $\varphi = \arctan\frac{X}{R}$ is the phase angle, R is the sum of resistances of the transformer and the network, and X is the sum of reactances of the transformer and the network.

The steady state SC current is usually expressed in root-mean-square values, and the peak SC current is expressed in maximum values; therefore, in practice, it is easier to use factor K_p instead of $K_{p\sqrt{2}}$. The dependence of this factor on ratio X/R has a sharply nonlinear behavior, and, given low values of ratio X/R, small changes in it lead to large changes of $K_{p\sqrt{2}}$ (Fig. 1).

If the SC resistance of the network is taken into account in the calculations of SC current, then ratio X/R for the network is usually taken equal to ratio X/R for transformer. Taking this into account, in formula (3), ratio U_r/U_a, where U_r and U_a are the reactive and active components of the SC voltage of the transformer, can be used instead of ratio X/R.

In addition, according to [1, 2], for transformers with a capacity less than 3150 kVA, when calculating SC currents, it is permitted to neglect the resistance of the SC network if it does not exceed 5% of the SC resistance of the transformer. As a rule, for distribution transformers with a capacity up to 1600 kVA, this condition is fulfilled, since their SC resistance is one to two orders greater than the SC resistance of the network.

Ratio U_r/U_a for distribution transformers with a capacity up to 2500 kVA, as a rule, is within 1.5–7.0 (larger value corresponds to larger capacity), the peak factor usually is 1.15–1.65 and factor $K_{p\sqrt{2}}$ is 1.63–2.33 (Fig. 1).

When SC withstand strength test according to [2] the permissible deviations of actual values of peak and steady state SC currents should not exceed 5 and 10% respectively.

As it is known, the active component of SC resistance of the transformers is determined by the loss in their windings, which significantly depend on temperature. SC voltage U_{sc} and its active component of U_a usually are reduced to a design temperature, which is determined by the corresponding normative instruments. For example, for oil-immersed transformers, according to [1], the SC voltage is reduced to design temperature 75°C. For distribution transformers with capacity up to 2500 kVA at the temperature of windings of 20°C, active component U_a may be around 20% less than its design values. For dry-type transformers of class F of thermal resistance, in accordance with [4], the SC voltage according to [5], is reduced to the design temperature of 120°C, and the decrease in U_a can reach 30%.

According to [1, 2], the design values of SC current are determined based on the design values of SC resistance of the transformer. It is equivalent to the fact that, at the time of SC occurrence, the winding temperature is close to design value, for example, 75°C for oil-immersed transformers. At the same time, when operation and the test of SC withstand strength, the winding temperature can be less than the design temperature, which leads to a decrease in voltage U_a, an in increase in ratio U_r/U_a, and, as a consequence, an increase in the peak SC currents. This is illustrated in Fig. 2, in which the ratio of design values of peak factors defined by ratio U_r/U_a, at the actual and designed winding temperature (75°C) for oil-immersed transformers with capacity of 63 and 1000 kVA is shown. When testing the distribution transformers, the SC resistances of which in absolute values are much larger than the resistance of the testing scheme, the peak factor is determined by ratio U_r/U_a. In addition, it follows from Fig. 2 that reducing the actual temperature of windings from 75 to 10°C can lead to an increase in the peak currents of distribution transformers of around 4–6%.

This means that, when testing transformers with a capacity of up to 2500 kVA under conditions in which the average temperature of the windings is 10–20°C, one can expect that the deviation of actual value of peak current from design value will be around 5%, which should be taken into account when testing and processing the results. One way to eliminate the discrepancy between the design value of the SC current and actual peak SC current is calculation of SC currents when testing taking into account the actual temperature of windings.

In addition, another possible cause should be noted of deviation of the peak current during the test related to heating the windings by flowing the SC current during debugging and test SC experiments. Such a deviation appears in a greater degree when testing low-capacity transformers with a small value of U_r/U_a and can be illustrated by Fig. 3, which shows the change in the peak factor in test SC experiments with a duration of 0.5 s each when testing transformers with a capacity of 1000 kVA. It follows from Fig. 3 that, in the example under consideration, when testing by 1.5-phase scheme (curve *1* in Fig. 3) there is no evident trend towards reducing the peak factor. Taking into account Fig. 2, this points to the absence of a significant change in the temperature of windings in test SC experiments; the increasing K_p may be related to cooling of the winding after heating in debugging and in the first two test SC experiments due to the different durations of pauses between SC experiments. When testing transformers with the same capacity using the three-phase scheme, an around 4% decrease in K_p (curve *2* in Fig. 3) was observed in the fifth test experiment as compared with the first experiment, which can be explained by the fact that, given a three-phase supply, the normalized steady state SC current flows over all the windings and the loss power in the transformer is twice than in the 1.5-phase scheme, which leads to greater heating of the transformer as a whole from experiment to experiment.

The latter circumstance results in a greater stability of peak factor values when testing by the 1.5-phase scheme, which makes this scheme preferable to the three-phase test scheme.

In the light of the abovementioned influence of winding temperature on peak SC current for transformers with a capacity up to 2500 kVA, the question arises of what the winding temperature should be at the beginning of an SC withstand strength test.

In [2, 3], the instructions regarding winding temperature are slightly different. According to [3], the transformers should be tested after preheating (by one of the methods of *GOST* (State Standard) 3484.2 methods), so that at the end of the fifth test of the SC experiment the winding temperature reaches the maximum permissible value. This recommendation in fact is unfulfilled in practice, since in testing there is a transient process of heating of the transformer during flowing of the SC current and its cooling during the pauses between SC experiments. Since the durations of the pause between individual SC experiments are not normalized from experiment to experiment—they can be longer or shorter and with different duration of pauses—one can obtain both a progressive increase in the winding temperature and some decrease. This indirectly is illustrated in Fig. 3: given a 1.5-phase supply (curve *1*) of a transformer with a capacity of 1000 kVA, there is no significant change of the peak factor in the fifth test experiment and, hence, the winding temperature to this experiment does not change significantly, while, given a three-phase supply, the change in the peak factor turned out to be greater (approximately by 4%), but, according to Fig. 2, a relatively

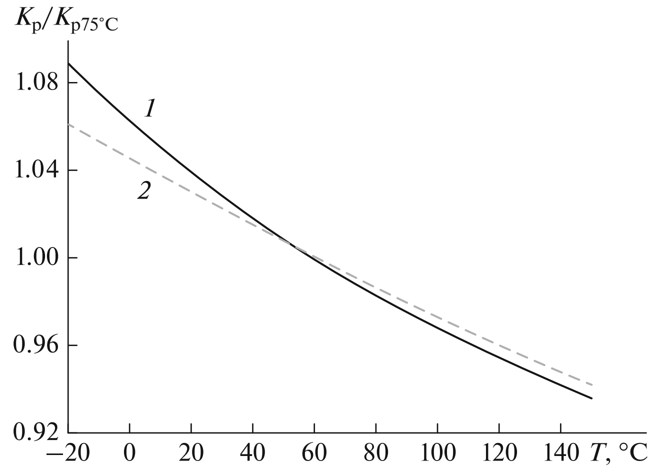

Fig. 2. Temperature dependence of $K_p/K_{p.75°C}$ ratio for oil-immersed transformers with a capacity of (*1*) 63 and (*2*) and 1000 kVA.

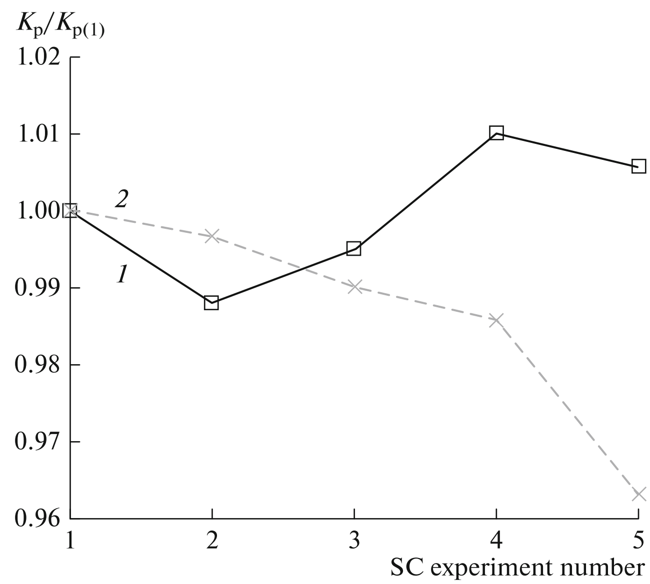

Fig. 3. Change in the peak factor in test SC experiments of two oil-immersed transformers with a capacity of 1000 kVA: (*1*) transformer no. 1, test under 1.5-phase supply; (*2*) transformer no. 2, test under three-phase supply.

small change in the winding temperature corresponds to this change.

According to [2] and IEC 60076-5, before beginning a test of SC withstand strength, the average winding temperature should be within 10–40°C. Using this is a standard makes things clearer, but it does not fully take into account the peculiarities of Russian climatic conditions, because in winter the temperature can be much lower than +10°C. Ensuring the lowest value of temperature according to [2] (IEC 60076-5) involves either necessary preheating of the transformer or abandonment of the test in the autumn–winter period. Both appear to be unnecessary for the following reasons. On the one hand, distribution transformers often operate with a loading less than 40–50%; thus, the winding temperature is significantly less than the designed values corresponding to operation with nominal capacity and an ambient temperature of +20°C. When operating the transformer in winter, the winding temperature will hardly be +10°C or greater. The test of distribution transformers under winding temperatures less than +10°C is a test of their reliable operation under conditions close to real service conditions, in which, upon the appearance of an external SC, the peak current will be somewhat larger than the peak current of the transformers with a winding temperature exceeding +10°C. The latter circumstance to some extent is compensated by the fact that, with decreasing temperature, the permissible mechanical loads on the main active materials, such as winding conductor materials and structural steel, increase. It should be noted that this is true first of all for distribution transformers, in which, as a rule, a transposed wire with glued elementary conductors is not used, as well as for power transformers with windings made of transposed wires with gluing, in which an epoxy adhesive tends to reduce the permissible shear force with temperatures increasing over 100°C. It is important to test such transformers in a heated state. On the other hand, using preheating when carrying out a test of SC withstand strength at ambient temperatures lower than +10°C is connected to a significant increase in price and test duration.

Taking all this into account, it is appropriate to clarify point 4.2.2.3 of *GOST* (State Standard) R 55188 as applied to distribution transformers regarding the possibility of conducting a test with a winding temperature less than +10°C if the technical capabilities of the test bench do not make it possible to provide a winding temperature within a standardized range from the start of the test.

According to [2, 3], a test of the SC withstand strength of three-phase double-wound power transformers can be performed under three- or single-phase supply of the primary winding; moreover, the secondary winding has been previously short-circuited. The time of energizing is chosen in such a way as to ensure the greatest peak SC current in the desired phase of the transformer. Given a three-phase supply, the greatest peak SC current is provided in the middle phase of the transformer (for transformers with a planar magnetic system).

It is a specific characteristic of the test of transformers given a three-phase supply of the δ-connected winding that, as a rule, during SC experiments, only the line currents of the winding to be supplied can be recorded that are a combination of the phase currents of this winding.

To obtain the greatest SC peak current in the middle phase of the transformer, energizing should be carried out when the corresponding line voltage is zero. For the other two phases, this time gives a smaller aperiodic component of SC current. Thus, in general, the value of peak factor K_p that is equal to the ratio of the peak SC current to the amplitude value of the periodic component of SC current for line currents of a δ-connected winding are not equal to the value of K_p of the phase current of the middle phase for this winding, nor are they equal to the value of K_p of the line currents of a star-connected winding.

As was indicated above, the desired value of the peak SC current is the product of amplitude value of the design steady state SC current and K_p, which is determined according to [1, 2], where it is stated without any instructions as to its application to line currents of δ-connected windings. Using the value of K_p that holds for a star-connected winding to calculate the line currents of a δ-connected winding in practice is one reason for the deviation of designed and actual SC currents under a three-phase supply.

This deviation can be illustrated by the results of calculations by analytical expressions [6] for transient current assuming the connection of an *RL* circuit to an alternating voltage. As applied to the transformer with the scheme and group of winding connections Δ/Y_1-11 under a three-phase supply of highest voltage (HV) winding, the following expressions for phase currents of this windings can be written as

$$\begin{cases} i_{AB}(t) = I_m\left[\sin\left(\omega t + \psi + \frac{2\pi}{3} - \varphi_k\right)\right. \\ \left. - e^{-\frac{t}{\tau}}\sin\left(\psi + \frac{2\pi}{3} - \varphi_k\right)\right]; \\ i_{BC}(t) = I_m\left[\sin\left(\omega t + \psi + \frac{2\pi}{3} - \varphi_k\right)\right. \\ \left. - e^{-\frac{t}{\tau}}\sin(\psi - \varphi_k)\right]; \\ i_{CA}(t) = I_m\left[\sin\left(\omega t + \psi - \frac{2\pi}{3} - \varphi_k\right)\right. \\ \left. - e^{-\frac{t}{\tau}}\sin\left(\psi - \frac{2\pi}{3} - \varphi_k\right)\right]. \end{cases} \quad (4)$$

where I_m is the amplitude of the steady state three-phase SC current, $\omega = 2\pi(f)$ is the circular frequency, $f = 50$ Hz, ψ is the phase of turned-on voltage, $\varphi_k = \arctan(X/R)$, $\tau = X/(\omega R)$ is the time constant of attenuation of aperiodic current, and R and X are the sums of resistances and reactances of the transformer and source.

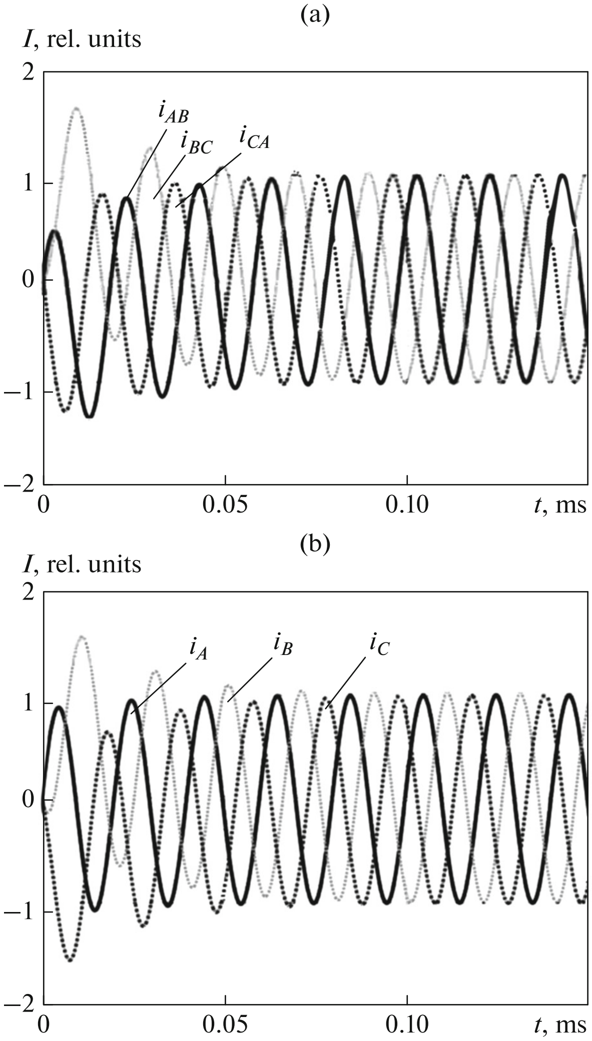

Fig. 4. (a) Phase and (b) line SC currents of δ-connected HV winding of the transformer given three-phase supply and $X/R = 7$.

The line currents of the HV winding can be defined as the difference between the corresponding phase winding currents:

$$\begin{cases} i_A = i_{AB} - i_{CA}; \\ i_B = i_{BC} - i_{AB}; \\ i_C = i_{CA} - i_{BC}. \end{cases} \quad (5)$$

The maximum current in the middle phase of an HV winding is achieved when turning the line voltage to zero between terminals *A* and *B*. Equality $\psi = 0$ in expression (4) corresponds to this condition.

Figure 4 presents the design oscillograms of phase and line currents determined by expressions (4) and (5) at $X/R = 7$.

The peak factors of phase and line currents can be determined by expressions (4) and (5) as the ratios of the largest values of these currents to the amplitude of steady-state SC current. In addition, the design values of K_p for the phase current of phase *B* and for the line winding currents (Fig. 5), as well as the ratio of K_p of line currents to the phase current of phase *B* (Fig. 6), in the range of values of X/R from 1 to 20 are presented.

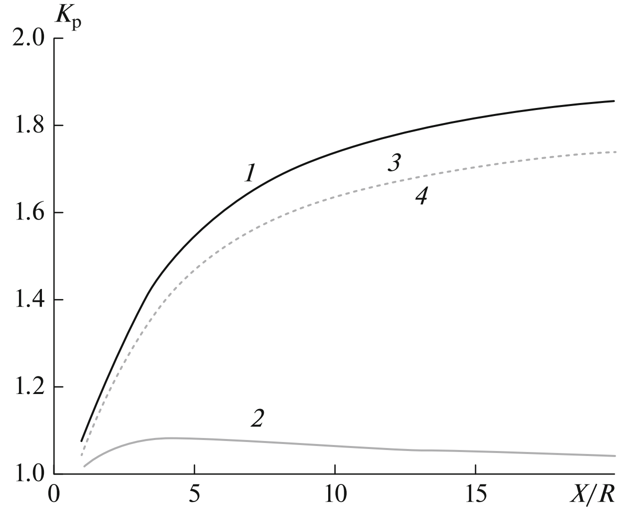

Fig. 5. Peak factors of (*1*) phase current of phase *B* and line currents of phases (*2*) *A*, (*3*) *B*, and (*4*) *C* of hexagon-connected winding.

It is seen from Figs. 5 and 6 that K_p of line currents of phases *B* and *C* in a wide range of values of X/R is less than K_p of the phase current of phase *B*, which corresponds to the values presented in [1, 2]. With increasing X/R, the difference between K_p of line and phase currents increases.

In the range of values of X/R from 2 to 6 that corresponds to distribution transformers with a capacity up to 1600 kVA, for a δ-connected winding, K_p of line current is less K_p of phase current by 3–5%.

This difference in the peak factor should be taken into account when testing and processing their results. In practice, this may hold when the value computed from line currents that are measured in the course of debugging SC experiments line is used as a basis to provide a design value of peak current in test SC experiments with a rated 5% tolerance, and some increase in the root-mean-square value of SC current in windings over the design value may be required, which is also related to the increasing peak current in the phase under test over design value. Thus, the absence in [1, 2] of instructions as to the applicability of the presented values of K_p to line currents of δ-connected windings may lead to repeated test of windings or to noncompliance with the requirements of 5% tolerance of peak current.

It should be noted that, when using a single-phase supply and so-called “equivalent (1.5-phase) test scheme,” the above-considered differences in the peak

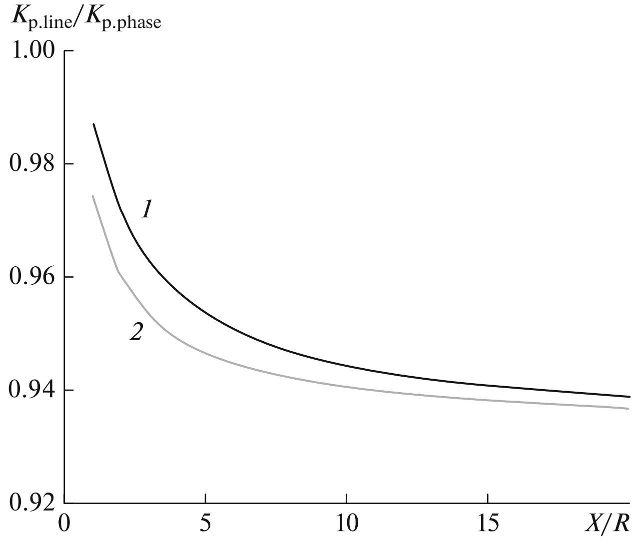

Fig. 6. Ratio of peak factors of line currents of phases (*1*) *B* and (*2*) *C* and the peak factor of phase current.

factors of the phase and line currents are absent, which makes this scheme preferable to allowing for the design values of SC currents.

It follows from this that the three- and 1.5-phase schemes, as applied to the test of distribution transformers, have their own characteristics, the main ones of which are summarizes in Table 1.

Thus, the three- and 1.5-phase test schemes have advantages and disadvantages. It is difficult to say that one or the other scheme is better. The choice of scheme can be made in each specific case based on the technical possibilities and limitations of the test scheme, as well as the design features of the object under test.

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