Study on practical voltage secondary loop testing tool

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Abstract. A practical test tool for voltage secondary circuit is used for field test of Secondary Screen Cabinet in transformer substation, such as power quality and microcomputer protection. Because of the influence of the structure of the voltage connection terminal and the site environmental conditions, there are unreliable contacts between the test terminals in the voltage test, which not only affects the test efficiency, but also has the risk of Electric leakage which effects personal safety. The whole structure of the voltage testing tool of this project adopts self-locking fixture structure. In the design, first of all, considering the stability of the structure, the main body of the voltage testing tool adopts the hook structure which is fully fitted with the voltage terminal. In practical use, it can quickly realize the tight combination with the voltage terminal and the requirements of the voltage testing tool which includes the stability and ease of use.

1. Introduction
With the rapid development of China’s economy, electricity, as a necessary factor for people's lives, has penetrated into all aspects of society, so the security and stability of power system is very important. Electrical test is an important means to ensure the sustainable supply of power resources in power system. Electrical test is not only an indispensable link to ensure the efficient operation of power system, but also the basis of power system stability [1]. The high risk factor of electrical test can easily lead to personal hazards and damage of electrical equipment, resulting in significant economic losses. Therefore, the safety is the most important in the electrical test. When the equipment is tested, the wiring should be dismantled frequently. Especially the test equipment with larger capacitance or electrostatic induction has higher operating voltage. Usually, the electrical test is more dangerous than the maintenance of the general electrical equipment.

Technological improvement and innovative thinking are important means to improve the safety and reliability of electrical test. In voltage testing, in order to facilitate testing, electrical personnel often use single-core copper wire and instrument test wire to hinge together, and then wrapped with insulation tape to make a simple joint, which is also an innovation. However, this simple joint has great potential safety hazards, first of all, the reliability is very poor; secondly, the insulation is not good. Therefore, it is difficult to ensure the safety of the user when the self-made joint is in use.

In order to develop a reliable, practical and stable test tool for voltage secondary circuit, we studied various environments used for voltage terminals, summarized the use scenarios of voltage terminals, and put forward a new design concept for voltage secondary circuit test tool:

- Adopt flat design to reduce equipment height and increase equipment reliability.
- The reliability of testing equipment is improved by using stress self-locking mechanism.
- Insulating material is used to design the whole equipment to improve the safety and service life.
of the equipment.

- The design of tandem terminals is adopted to increase the installing stability and generality of the equipment and improve the availability of the equipment.

2. **Key technologies in the design of testing tool**

In order to obtain higher reliability and stability, the designers have repeatedly demonstrated and experimented on the design scheme. Finally, they establish the scheme of the joint structure and flattening design. Adopting self-locking mechanism makes the testing tool have reliable usability. The establishment of this scheme greatly improves the reliability and stability of voltage testing tools. This kind of structure is similar to crank rocker mechanism. When using this kind of structure, pay attention to the strength of each part of the component should meet the using requirements. First of all, the stress of each corner of the testing tool shouldn’t destroy the whole structure of the tool; secondly, when locking the self-locking structure repeatedly, each component of the testing tool should have enough elastic deformation and strength to ensure the reliability and life of the testing tool. Therefore, the calculation of component mainly involves fatigue strength calculation and stress analysis calculation in different situations, including fatigue strength calculation of mechanical parts under unidirectional stable variable stress, fatigue strength calculation of mechanical parts under biaxial stable variable stress, and extended finite element method (XFEM).

2.1. **Fatigue strength calculation of mechanical parts under unidirectional stable variable stress**

- The position of parts’ stress in the Limit stress line graph coordinates: When calculating the fatigue strength of mechanical parts, the maximum stress ($\sigma_{\text{max}}$) and the minimum stress ($\sigma_{\text{min}}$) on the dangerous section of mechanical parts are required at first. According to the average stress ($\sigma_{\text{m}}$) and stress amplitude ($\sigma_{\text{a}}$) which are calculated. Then, a working stress point M or N corresponding to $\sigma_{\text{m}}$ and $\sigma_{\text{a}}$ can be marked in the Limit stress line graph coordinates. As shown in figure 1.

![Figure 1. Limit stress line diagram.](image)

- Typical stress variation law: the ultimate stress used in strength calculation should be the stress represented by a point on the limit stress curve (AGC). According to the possible variation law of stress due to structural constraints in parts determines which point representative the ultimate stress. According to the variation law of part load and the difference of mutual restraint between parts and adjacent parts, there are three typical stress variation laws.

  - When $r=C$, it is necessary to find a limiting strain value whose cyclic characteristics is equal to the working stress of the parts’ cyclic characteristics.

  When the working stress is unidirectional, the strength formula is

  $$S_{\text{ca}} = \frac{\sigma_{\text{lim}}}{\sigma} = \frac{\sigma}{\sigma_{\text{max}}} = \frac{\sigma}{\sigma_{\text{a}} + \sigma_{\text{m}}} \geq S$$
When σm=C, it is necessary to find a limiting strain value whose mean stress is equal to working stress of parts’ mean stress.

The calculated safety factor (Sca) and strength condition based on maximum stress are

\[
S_{ca} = \frac{\sigma_{lim}}{\sigma} = \frac{\sigma'_{max}}{\sigma_{max}} = \frac{\sigma^{-1} + (K_\sigma - \psi_\sigma) \sigma_m}{K_\sigma (\sigma_a + \sigma_m)} \geq S
\]

When σmin=C, it is necessary to find a limiting strain value whose minimum stress is equal to working stress of parts’ minimum stress.

\[
S_{ca} = \frac{\sigma_{lim}}{\sigma} = \frac{\sigma'_{max}}{\sigma_{max}} = \frac{\sigma^{-1}}{K_\sigma \sigma_a + \psi_\sigma \sigma_m} \geq S
\]

If only the mechanical parts are required not to occur fatigue damage in a short service life, specifically, when the number of parts stress cycles is within the range of \(10^4 < N < N_0\), then the limit stress elin used in the calculation of fatigue strength is the finite fatigue of the required life. In the previous relating formulas, σ should be replaced by σN which is calculated by the formula.

2.2. Fatigue strength calculation of mechanical parts under bidirectional stable variable stress

When the same phase of normal and tangential symmetry cycle is used to stabilize the variable stress \(\sigma_a\) and \(\tau_a\) at the same time on the parts, for steel, the ultimate stress relation obtained through tests is:

\[
\left(\frac{\tau}{\tau_{-1\varepsilon}}\right)^2 + \left(\frac{\sigma}{\sigma_{-1\varepsilon}}\right)^2 = 1
\]

![Figure 2. Relationship of ultimate stress.](image)

In the above formula, \((\frac{\sigma_a}{\sigma_{-1\varepsilon}}) - (\frac{\tau_a}{\tau_{-1\varepsilon}})\) in the coordinate system is a unit circle. In the above formula, \(\tau_a'\) and \(\sigma_a'\) are the limit of the stress amplitudes of tangential and normal. Since it is a symmetrical cyclic variable stress, the stress amplitude is the maximum stress. As shown in figure 2, any point on the arc AM 'B represents a pair of limit stresses \(\sigma_a''\) and \(\tau_a'\). If the stress amplitude \(\sigma_a\) and \(\tau_a\) on the parts are expressed by M on the coordinates, it is safe because the work stress point is within the limit circle and the limit condition is not reached.

\[
S_{ca} = \frac{S_\sigma S_\tau}{\sqrt{S_\sigma^2 + S_\tau^2}}
\]

2.3. Extended finite element method (XFEM)

The extended finite element method was proposed by professor Belytschko in 1999. The extended finite
element method overcomes the disadvantages of the finite element method in the simulation of fracture problem: There is no need to repartition the network during crack propagation. Tip does not require encryption. Because the same network is used, there is no problem with data transfer. The extended finite element method improves the displacement solution space of finite element by adding enrichment function. It can reconstruct some characteristics of continuous problems. The geometric characteristics of discontinuous problems can be determined by level set function, so it has obvious advantages in dealing with discontinuous problems [2]. For the extended finite element method, the displacement of any gaussian point x in the element can be expressed as follows:

\[ \mu_{x_{fem}}(x) = \sum_{j=1}^{n} N_j(x) \mu_j + \sum_{h=1}^{m} N_h(x)(H(x) - H(x_h))a_h \\
+ \sum_{k=1}^{m_t} N_k(x)\left[\sum_{l=1}^{4} (F_l(x) - F_l(x_k)) b_l^k\right] \]

In which, \( n \) is the number of conventional finite element nodes of the element, \( N_j \) is shape function, \( u_j \) is the degree of freedom vector of conventional finite element nodes, \( m_h \) is the number of enhancement nodes on both sides of the crack surface, \( H(x) \) is the Heaviside value of the gaussian point x, \( a_h \) is the degree of freedom vector of strengthened nodes on both sides of the crack surface, \( m_t \) is the number of crack tip enhancement nodes, \( F_l(x) \) is the value of the crack tip enhancement function at the gaussian point x, \( F_l(x_k) \) is the value of the crack tip enhancement function at the enhancement node k, \( b_l^k \) is the degree of freedom vector of the strengthened node at the crack tip.

The Heaviside enhancement function takes the value of 1 on one side of the crack surface and -1 on the other side. Fl is the split-tip enhancement function, it is a group of linearly independent bases extracted from the analytical expression of tip displacement field in linear elastic fracture mechanics. It is defined in the split-tip polar coordinate system, and its expression for isotropic materials as follows:

\[ \{F_l(r, \theta)\}_{l=1}^{4} = \{\sqrt{r} \sin \frac{\theta}{2}, \sqrt{r} \cos \frac{\theta}{2}, \sqrt{r} \sin \theta \sin \frac{\theta}{2}, \sqrt{r} \sin \theta \cos \frac{\theta}{2}\} \]

In which, \((r, \theta)\) is the coordinates of the gaussian point x in the sharply polar coordinate system.

- In the selection of Heaviside enhanced nodes, Gauss points should be included in the support region on both sides of a fracture.
- When Heaviside enhancement node is selected, Gauss points must be guaranteed in the support region on both sides of the crack, otherwise the enhancement cannot be performed.
- The calculation of fracture opening is only related to the enhanced degree of freedom, and has nothing to do with the FEM degree of freedom.

3. The design scheme of voltage testing tool
Voltage testing tool adopts innovative design scheme, flat design, lock lock structure, main insulation design, row structure and so on. The flatter design emphasizes the lower center of gravity, and the closer to the center of gravity of the terminal bank, the better the stability of the voltage testing tool. The voltage testing tool is designed with a flat structure which is partly surrounded by voltage terminals, so as to minimize the center of gravity. Self-locking mechanism makes voltage testing tool easy to operate and easy to promote. Product innovation can be divided into functional innovation, form innovation, material innovation and structural innovation. Among them, the function innovation is that the designer makes the function design of the product more humanized, thus producing market value; the construction innovation is that the designer adjusts the unreasonable structure and designs the product that meets the needs of use [3]. This project uses modern design methods to break the conventional design concept and create a new structure.
3.1. Integral structure plan
The integral structure of voltage testing tool is divided into three parts: main part, clamping part and testing part. As shown in figure 3. The main part adopts the hook structure of fitting voltage terminal, which can quickly realize the close combination with voltage terminal in practical use. The clamping part and the main part are connected by a rotating shaft, and there is a certain angle relative to the main part, so that it can cooperate with the main part to clamp the voltage testing tool on the voltage terminal. The test unit outputs the voltage of the voltage terminal to the interface of the test instrument, and the design of this part requires good contact with the live part of the voltage terminal to ensure the reliability of the test. The whole structure of voltage testing tool adopts three-dimensional drawing method, and realizes accurate drawing by computer aided design [4].

![Figure 3. Integral structure diagram of voltage testing tool.](image)

3.2. Main part design scheme
The main component is the main support structure of voltage testing tool. Other structures of the voltage testing tool are installed and operated on the basis of the main structure. The main structure must be strong enough to withstand various stresses in the voltage test. Therefore, the main part adopts wide-body cascade design, which can test three voltage terminals at the same time. The advantages of this method as follows: Firstly, the contact area between the voltage testing tool and the voltage terminal increases, which makes the voltage testing tool more stable and reliable. Secondly, multiple voltage terminals are tested at the same time, which simplifies the testing process and makes the testing tool easier to use. Finally, the widebody design of the joint debugging structure in the main structure design can bear more equipment structure, so that the test tool universality and scalability better. The side view of the main structure is shown in figure 4. The top view of the main structure is shown in figure 5.

![Figure 4. Side view of the main structure.](image)
3.3. Clamping part design
The clamping part is a fastening part of the voltage testing tool, it also includes a self-locking structure. The usability of voltage testing tool is mainly reflected in this part. The fastening part is connected with the main part by a rotating shaft. The fastening part and the main part clamp the voltage testing tool to the voltage terminal like a clamp. As shown in figure 6.

The material of fastening parts is the key of design. First of all, the material must have a certain strength, which can withstand the stress of clamping pressure and voltage test. Secondly, the material must have a certain degree of elasticity, which can support the long-term use of self-locking mechanism. And it should be the new material with both strength and toughness.

3.4. Test part design
The test unit is the conductive part of the entire voltage testing tool. The voltage of the voltage terminal is extracted through the test component, which can be used for various voltage tests. As we know, the test tools used in various test instruments are standard connectors with a diameter of 4 mm. Therefore, the test part of the voltage testing tool also adopts standard structure, which can match various voltage standard connectors commonly used nowadays. As shown in figure 7.

The test part is connected to the main structure through screws. The screw used here has two purpose: First, the screw connection can improve the overall reliability of the voltage test tool, so that the whole test tool can be closer and more stable; Second, the screw can make the voltage test components more closely connected with the voltage terminal, increasing the reliability of electrical conduction. At the same time, it is also a voltage testing tool with better stability in the experiment.

4. Technical features of voltage testing tools
On the basis of fully studying the domestic voltage testing tools and the voltage terminal row of the substation, the designer has done a lot of work to solve the problem of low safety in the electrical test of various substations with different construction years. In this project, a large number of advanced design ideas and new technologies have been adopted, and many innovations have been realized. Realize the design goal of easy to use, good safety and high reliability.

- The reliability of voltage testing tools is greatly improved by innovating the design idea of flattening.
After investigating, there is no one who has adopted the flat design idea to design the voltage testing tool. This technical innovation makes the center of gravity of voltage testing tool and voltage terminal very close to each other, so that the voltage testing tool and voltage terminal are close to integration. Therefore, the reliability and stability of use are greatly increased.

- The hasp type self-locking structure is adopted for innovation, and the usability of voltage testing tool is improved greatly.

There are many types of self-locking structures, but few that can be used in voltage testing tools. This is mainly reflected in the small size of the voltage testing tool itself, the relatively large stress in the process of using the experiment, and the general self-locking structure is either complicated or not stable enough to meet the requirements of using the voltage testing tool. In this project, the hasp type self-locking structure is created, which greatly simplifies the structure of voltage testing tool and increases its reliability and usability.

- By the insulation design, the voltage testing tool security has been greatly improved.

The main function of the voltage testing tool is to transfer the voltage of the voltage terminals to various experimental instruments and equipment. Therefore, it is necessary to contact the substation secondary voltage circuit to work properly for using. The voltage testing tool must be insulated to ensure the personal safety of the experimenter. Therefore, this project adopts new insulation materials to make voltage testing tools, which not only can meet the insulation requirements, but also can meet the voltage testing tool parts of the strength requirements, toughness requirements, so that the safety of voltage testing terminals to be reliable assurance.

- By the row structure design for innovation, the stability of voltage testing tool is improved greatly.

Voltage terminal volume is small, especially its thickness is only 6 mm, due to its small size, structural strength and the range of use, the conventional single terminal test tools are greatly affected. In addition, the single terminal testing tools are cumbersome to use without strange universality and high security. Therefore, this project innovatively adopts the cascade structure design, which greatly improves the stability and universality of voltage testing tools.

5. Conclusion

In this paper, a practical testing tool for voltage secondary circuit is introduced in detail. Flat design idea and self-locking structure are adopted to realize fast and reliable testing of voltage circuit. Successful development of practical voltage secondary circuit testing tool provides great convenience for voltage testing of substation, and makes voltage testing simple, safe and reliable. It can play a very good role in improving the voltage test environment of substation, improving the test efficiency and ensuring the safety of testers.

References

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