The on-line detection technology of oil level in main transformer conservator of an 110kV Substation

Jun Liu¹, Yujing Hu²*, Wen Yang¹, Xiongwen Pan¹, Yibin Li¹, Guomin Qu², Yi Xie² and Wei Qiu³

¹ State Grid Hunan Electric Power CorporationYueyang Power Supply Company, Yueyang, 414000, China
² State Grid Hunan Electric Power Company Limited Research Institute, Changsha 410007, China
³ Changsha University of Science & Technology, Changsha 410114, China
*Corresponding author’s e-mail: yjhu1@mail.buct.edu.cn

Abstract. The oil level of transformer conservator is related to the safe operation of transformer. There is no better way to detect the oil level of the conservator, when the indication of the oil level gauge is unclear or the jam fault. Through the selection of ultrasonic sensor, design of measurement and verification device and field practice, this paper studies and develops an on-line detection technology based on the ultrasonic principle, which can effectively and accurately detect the oil level of existing conservator types such as diaphragm, capsule and corrugated conservator, and is not limited by the detection environment.

1. Introduction
Currently, oil immersed power transformers are adopted by most of the power transformers. The transformer oil plays the role of insulation, heat dissipation, cooling and arc suppression during the operation of oil immersed power transformer. Due to the transformer oil possess large specific heat capacity and good thermal conductivity, and its insulation strength is much higher than that of air. Moreover, transformer oil can decompose a large amount of gas under the high temperature of arc, which can improve the arc extinguishing capacity of medium, so as to achieve good arc extinguishing effect [1-2]. The oil level of transformer conservator is of great significance to the reliable operation of power transformer.

The transformer insulating oil will inevitably volatilize and leak during maintenance and operation, resulting in the decline of its oil level. Besides, the oil level will also be too high under high temperature and high load, which has become a major hidden danger for the safe operation of the transformer. The transformer oil level is generally checked by remote observation of the oil level gauge. After long-time operation, the inner and outer surfaces of the oil level gauge will be polluted and the indication may become blurred, or the oil level gauge can not really reflect the oil level due to a fault, resulting in the inability to accurately evaluate the transformer oil level. When the indication of the oil level gauge is not clear or accurate, the oil level can only be preliminarily judged through the infrared temperature measuring of bushing at night. There are some limitations on infrared temperature measurement. First, it is possible to evaluate the oil level only when the temperature are quite different between the oil temperature and the environment, so it is generally conduct at night.
Second, the oil level only roughly estimated by infrared spectrum. Third, this method is not applicable to corrugated conservator.

Trip will caused by excessive higher or lower of the transformer oil level, and even damage the transformer. In 2020, there is a tripping fault of a 220kV transformer caused by high oil level in high load conditions, which have attracted the attention to study the on-line detection technology of oil level in main transformer in their whole power system for the grid company. According to incomplete statistical data, 1728 substations of 110kV and above in the whole power system are investigated by night infrared detection. It is found that 15 substations with oil level lower than 30%, accounting for 0.87%, 33 substations with oil level of 80-90%, accounting for 1.91%, 48 transformers with hidden oil level, accounting for 2.78%, and the oil level of some transformers cannot be detected. In 2021, to carry out the on-line detection technology, an 110kV substation which have all types of transformer conservator including diaphragm type, capsule type and inner oil ripple type was selected by the grid company.

2. On-site inspection
The 110kV substation was put into operation in 2001 and has been expanded twice. The conservator structures of three main transformers are different, including diaphragm type, capsule type and corrugated type. In July 2021, operations staff checked the oil level of the conservator of three main transformers on site and found that the capsule conservator oil level gauge could not be seen clearly, as shown in Figure 1. And the other two oil level gauges display normally, while whether they are distorted are uncertain.

![Figure 1. The capsule conservator level gauge in the 110kV substation.](image)

3. Oil level detection based on infrared temperature measurement

3.1. Principle of oil level detection by infrared temperature measurement
The infrared radiation temperature measurement is based on theory that all objects whose temperature is higher than zero are constantly sending infrared radiation energy to the surrounding space. The infrared radiation energy of an object and its distribution by wavelength are closely related to its surface temperature. Therefore, by measuring the infrared energy radiated by the object itself, its surface temperature can be measured. The internal insulating oil as the medium of transformer cooling cycle should constantly take away the heat generated inside. When the transformer is under high load in a specific period of time and the external ambient temperature is low, usually at night ,there is a temperature difference between the upper gas and the lower insulating oil of the oil level boundary in the conservator. So that infrared temperature measurement can be used to detect the oil level boundary [3-4].

3.2. On-site inspection
Infrared temperature measurement was carried out on the oil conservator of three main transformers
on-site at night. It was found that the oil level boundary could not be detected by the inner oil corrugated oil conservator, as shown in Figure 2. Yet the other two oil conservators can be measured clearly. It maybe caused by that the insulating oil of this type of conservator is completely enclosed in the corrugator, and the temperature of insulating oil diffuses to the whole conservator through thermal radiation, so that the temperature of the whole conservator is consistent, and the oil level boundary can not be detected by infrared temperature measurement.

4. Oil level detection based on ultrasonic technology

4.1. Principle of ultrasonic technology

The propagation speed of ultrasonic wave in the air is about 340m/s, which is much slower than that of light, so the signal processing of ultrasonic wave is relatively easy. The ultrasonic technology does not need protection compared with radioactive technology, and ranging in a short range is not affected by light and the color of the measured object compared with infrared or laser. Meanwhile, ultrasonic technology has the characteristics of non-destructive, real-time and penetrability, so ultrasonic detection is an ideal detection method.

The ultrasonic generation methods can be divided into two categories. One is generated mechanically, such as liquid whistle, air flow whistle, etc., and the other is generated electrically, including hysteresis telescopic type, electric type, piezoelectric ceramic type and so on. The ultrasonic distance measurement is carried out by transmitting and receiving ultrasonic signals through the ultrasonic sensor. In the process of ultrasonic distance measurement, the ultrasonic sensor transmits a series of pulse square waves, and then starts the timer to start timing. It reaches the receiving end of the obstacle and reflects back to the ultrasonic wave sensor through air transmission. And the single chip microcomputer stops timing immediately after receiving the first echo pulse. Thereinto, the distance is calculated by using the time difference and the propagation speed of ultrasonic in the air, and then sent to the nixie tube for display.

4.2. Selection of ultrasonic sensor type

Since the oil conservator is a metal tank containing transformer oil, the ultrasonic propagation mode is to penetrate the metal shell and transformer oil, and the ultrasonic will produce total reflection (partial scattering can be ignored) at the interface between transformer oil and air. After receiving the reflection wave, the ultrasonic receiver will return the signal to the equipment through the sensor and display the height of the oil level through calculation. Considering the great difference of ultrasonic propagation velocity between metal and transformer oil, how to ensure the measurement accuracy has become the difficulty of ultrasonic probe selection.

The ultrasonic sensor has three characteristics of frequency, directivity and impedance. The frequency characteristic is the relationship curve between ultrasonic frequency and sensitivity for the
receiving end of the sensor, and it is the relationship curve between frequency and sound pressure energy level for the transmitting end of the sensor. Generally 40 KHz selected as the frequency is suitable for most ultrasonic sensors whether transmitting or receiving. At the same time, the resonant frequencies of the transmitting part and the receiving part should match in the sensor system [5].

There are two types of common ultrasonic sensors include special type and compatible type. The special type is that the ultrasonic transmitting end and ultrasonic receiving end are separated, and the compatible type is a sensor integrating the transmitter and receiver [6]. The compatible type of ultrasonic sensor is recommended for conservator oil level measurement, which is convenient for the implementation of on-site detection.

The center frequency of ultrasonic sensor directly determines the applicability of ultrasonic sensor. The selection of center frequency of ultrasonic sensor mainly considers the measurement distance, measurement accuracy, sensor size and cost. The longer the measurement distance, the greater the energy loss of ultrasonic wave propagation in the medium. Meanwhile, absorption of ultrasonic wave by the medium is directly proportional to the square of frequency, and the center frequency of ultrasonic wave source must be reduced in order to reduce the energy loss. The higher working frequency can supply the higher measurement accuracy and the better directivity of ultrasonic. When the center frequency was low and a long distance was measured, to maintain the smaller energy loss and good directivity, the size of the sensor must be larger and the cost must be higher [7-8]. Considering that the distance of conservator is within 1m, under comprehensive considering the measurement accuracy and the cost, it is appropriate to select a low-frequency ultrasonic sensor with a center frequency of 2.0 MHz.

4.3. Design of verification device

In order to ensure the measurement accuracy, it was necessary to design a standard verification device to check the ultrasonic detection device. The standard measuring device apply transformer oil tank to contain transformer oil, and the design diagram was shown in Figure 3.

![Figure 3. Design diagram of the verification device for ultrasonic measurement.](image)

In order to simulate the shell of transformer oil tank, the material of the calibration device bottom used Q235 that commonly used in transformer oil tank. And the cylinder adopted transparent PVC material to facilitate observation and measurement. Firstly, the bottom plate was made from Q235 with size of 200×200×12 mm, and for installing bolt fixing device four through holes were made in the corner of plate with the diameter of each hole was Φ10 mm. The cylinder was made of PVC with size of Φ80×80×5 mm cylinder. Then, a size of Φ80×6 mm hole was processed accurately at the center of base plate and the cylinder was stick to the hole, and anti leakage test was conduct to ensure that sealability. Secondly, a size of 200×200×40 mm metal plate with the same through holes size as bottom plate at the four corners was used as the fixing plate. Finally, four Φ10×300 mm metal bar with 20 mm long threads at both ends was used as the support. After the above materials are assembled, a suspended cylinder with a height of about 260 mm away from bottom was formed, which
is convenient for calibration before inspection and test. It has verified that ultrasonic detection can detect the oil level and the optimal parameters are selected by this verification device.

4.4. On-site inspection of ultrasonic measurement
Since on-line detection work is required on site and the oil conservator of the main transformer was about 2 m away from the ground safety area, the ultrasonic sensor data line up to 3 m is selected. And to realize on-line detection, the sensor was fixed at one end by the insulating rod of which the hollow was used as the channel of the data line.

The oil level of diaphragm conservator was detected by modified low-frequency ultrasonic testing device. Since the insulating oil in the diaphragm conservator is in direct contact with the conservator shell, the ultrasonic sensor was placed at a flat and smooth place at the bottom of the conservator for detection, and the on-site detection data was 0.446 m, as shown in Figure 4.

![Figure 4](image)

Figure 4. Ultrasonic measurement of oil level of diaphragm conservator and structural diagram of conservator.

As shown in Figure 5, the insulating oil in the capsule conservator was also in direct contact with the conservator shell, only the conservator structure is similar to a horizontal cylinder, and the bottom of the conservator is a circular arc surface. The ultrasonic sensor should put at the lowest part of the conservator with coupling between the sensor and the circular arc surface. The height of oil level was 0.207 m according to on-site detection, as shown in Figure 5.

![Figure 5](image)

Figure 5. Ultrasonic measurement of oil level of capsule conservator and structural diagram of conservator.

Corrugated conservator is divided into external oil type and internal oil type. Thereinto, the inner part of the outer oil corrugated conservator is also a horizontal cylindrical structure. The change of the amount of insulating oil is realized by the expansion and contraction of the inner ripple in the horizontal direction. The insulating oil is also in direct contact with the conservator shell, and its oil
level changes in the horizontal direction, but it is a constant value in the up and down directions. Therefore, the oil level measurement of the external oil corrugated conservator should measure the oil level in the horizontal direction, as shown in Figure 6.

Figure 6. Structural diagram of external oil corrugated conservator.

The corrugated conservator of the 110kV substation is internal oil type, and the shell of the conservator is an expander, which is equipped with insulating oil. Therefore, the insulating oil is not in direct contact with the oil conservator shell, and there is also an expander wall and air inside. The low-frequency ultrasonic will reflect back at the interface when encountering the air, so the oil level measurement cannot be realized. During on-site inspection, it is found that there is a connected elbow at the bottom of the structural oil conservator, where a hole is opened in the oil conservator shell, leaving space for the sensor to contact the outer wall of the internal expander for inspection. If there is not enough space at the elbow hole of the conservator, the size of the sensor needs to be reduced. And the height of oil level was 0.529 m by on-site detection, as shown in Figure 7.

Figure 7. Ultrasonic measurement of oil level of inner oil corrugated conservator and structural diagram of conservator.

5. Conclusion
The insulation oil level of transformer conservator in substation cannot be correctly only judged by oil level gauge. Infrared temperature measurement technology can be used to judge the oil level of conservator in some structures, but there are problems of large detection workload and the limited detection environment. The on-line detection technology based on ultrasonic principle developed by this study can effectively check the oil level of all existing structural types of conservator, which is not limited by the detection environment with advantages of short detection time and high efficiency. Ultrasonic testing technology is a convenient, fast and efficient on-line oil level detection method for conservator.

References
[1] Rao R, Cheng L, Song H, et al. Research on detection method of transformer oil parameters
based on multi-frequency ultrasound technique[J]. Power System Protection and Control, 2016.

[2] Xiao L E , Yan-Yuan L I , Xiong Y J , et al. Research Status and Development Trends of Power Grid Fault Diagnosis[J]. Telecom Power Technology, 2015.

[3] Lin S N . Application of Infrared Detection Technology on Detecting Heat-fault in a Substation[J]. Electric Switchgear, 2011.

[4] He J , Xing X , Song X , et al. Partial Discharge Joint Detection Based on Ultraviolet, Infrared and Ultrasonic Technology: Measuring Technology and Instruments[C]// ICITEE2020: The 3rd International Conference on Information Technologies and Electrical Engineering. 2020.

[5] Zhang K , Liu G . Research on a Method of Improving Ultrasonic Ranging Precision[J]. Modern Electronics Technique, 2007.

[6] Al-N Aa Many A M , Meribout M , Busaidi K A . Design and Implementation of a New Nonradioactive-Based Machine for Detecting Oil–Water Interfaces in Oil Tanks[J]. IEEE Transactions on Instrumentation & Measurement, 2007, 56(5):1532-1536.

[7] Tapson J . High precision, short range ultrasonic sensing by means of resonance mode-locking[J]. Ultrasonics, 1995, 33(6):441-444.

[8] Scruby C B , Drain L E . Laser ultrasonics : techniques and applications. Adam Hilger, 1990.