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Surface Wear Monitoring System of Industrial Transformer Tap-Changer Contacts by Using Voice Signal

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Abstract: Surface wear of the tap-changer contacts of industrial transformers (due to frequent switching times) easily leads to operation failure of industrial transformers, which affects the safety and stability of the transmission network. In this paper, an intelligent voice signal monitoring system was proposed for the abnormal condition (surface wear) of tap-changer contacts. This monitoring system was composed of a voice signal acquisition system, voice analysis system and voice processing system. First, the voice signal of the tap-changer contacts was collected, and the collected voice signal was analyzed in the time domain and the frequency domain. Secondly, the characteristic curve of the voice signal was proposed, and the voice curve was compared with that of the normal operation state. In this case, the running state and surface wear abnormal situation of the tap changer could be monitored and determined, and the cause of the abnormal state could also be further analyzed. This method solved the surface wear problem of the tap changer in industrial transformers, which could be not monitored effectively in real time. This method improved the operational reliability of industrial transformers and had high economic and social benefits.

Keywords: surface wear; tap changer; industrial transformers; voice intelligent monitoring

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1. Introduction

Different from the power transmission transformer, an industrial transformer is a special transformer to meet actual production needs; electric arc furnace transformers and electrolytic transformers are used for the metallurgical industry and rectifier transformers are used for the chemical industry [1–3]. The on-load tap changer (OLTC) in industrial transformers is mainly used to adjust the voltage or current to orient it to the actual production [4,5]. Compared with the tap changer in the power transmission transformer, the tap changer in the industrial transformer operates more frequently, switches more times, and has a larger voltage regulation range. In this case, the contacts of the tap changer in the industrial transformer are more prone to surface wear, and the surface wear will have a greater negative impact on industrial production. Therefore, how to effectively monitor the surface wear and running state of the tap changer in industrial transformers becomes very important.

As the only moving part in the transformer, the tap changer has a high frequency of operation, and the surface is often damaged by wear caused by mechanical impact and arc ablation during operation, so the tap changer is one of the parts with the highest proportion of transformer failures [6–10]. Among them, more than 20% of transformer failures are caused by the tap changer. Therefore, monitoring the surface wear of tap-changer joints is critical. Previously, the tap changer was monitored offline. And the amount of burn loss of the tap-changer surface arc contact and the state of the mechanical mechanism was checked. This off-line monitoring method would cause industrial production to be suspended, resulting in economic losses. At the same time, this off-line monitoring method can not realize the real-time monitoring of the tap changer and can not assist in advanced prevention and hidden trouble investigations of the operation of the tap changer.

For many years, scholars have been committed to on-line diagnosis methods of the surface state of the OLTC [11–13]. Scholars have found that the OLTC diagnosis methods mainly include dissolved gas analysis (DGA), torque measurement, temperature measurement and vibration monitoring. Meanwhile, DGA is a method to determine the arcing and thermal breakdown of the diverter switch [14]; torque measurement is a method to determine the torque of the OLTC motor-drive [15]; temperature measurement is a method to determine the surface temperature of the OLTC [15]; and the vibration monitoring method is used to detect the faults (especially for surface wear) in the selector switch and diverter switch [16,17]. When the surface of the contact is worn, abnormal vibration signals will be generated. According to the frequency and amplitude changes in the vibration signal, the fault situation of the contact can be judged. The development of on-line monitoring technology for the OLTC through vibration signals has attracted the attention of numerous scholars.

For example, Singh [4] indicated the significance of on-load tap changing transformers in distributed energy systems and the industry has studied various smart wireless technologies through which their performance and possible failure might be monitored. Feizifar [18] developed one new arc-based model and condition monitoring algorithm for an on-load tap changer. This technique, obtained from computer simulation studies, demonstrated that the proposed algorithm accurately evaluated the electrical wear of OLTC contacts and determined the inspection or maintenance schedules of OLTC contacts. Meanwhile, Kim [19] proposed a digital twin approach for OLTCs using pre-processing of the vibration signal, data-driven dynamic model updating, and optimization-based operating condition estimation. This proposed method was applied to an OLTC vibration signal of both inactive and active power transformers. Simas [20] found that the vibration signals emitted during the tape changes were usually recorded and post-processed using spectral analysis and some pattern classifier technique. To reduce the complexity of the classifier, a new technique based on Genetic Algorithms was proposed by the authors. Li [21] investigated a novel strategy based on a Hidden Markov Model for the mechanical fault diagnosis of OLTC. With partition, normalization, and vector quantization of the power spectral density of the obtained vibration signals, a feature vector extraction methodology was presented for the discrete power spectrums, which, to the farthest extent, could retain the unique features and difference of various mechanical condition modes. However, up to now, most of the scholars focused on the vibration characteristics of the OLTC in power transformers, and the research on the vibration characteristics of the OLTC in industrial transformers is relatively limited; no perfect online monitoring system has been formed.

Based on the surface wear phenomenon of the tap changer in the process of switching, this study extracts the characteristic quantity from the sound signal of each switch vibration, so as to characterize the operating state of the switch. The extracted voice print curve of the sound signal was compared with the normal witching voice print curve, and then the minute fault inside the tap changer was found in time. In this way, the real-time monitoring function of the surface of the tap changer in the industrial field can be realized, and serious accidents caused by major faults (including surface wear) of the tap changer in the industrial transformer can be avoided. And, the safety and reliability of the transformer in the industrial field can be further improved.

2. Voice and Vibration Characteristics Analysis and Intelligent Monitoring System of Tap Changer Construction

2.1. Voice and Vibration Characteristics Analysis

The primary side of the industrial transformer is connected to the power grid, and the secondary side is connected to the power supply of the industrial production equipment. When the load on the production side changes, the voltage on the secondary side of the transformer changes accordingly. In this case, it is necessary to adjust the tap changer frequently to adjust the output voltage of the transformer. The tap of the transformer refers to a plurality of connection points on the primary winding of the transformer, and the tap changer is used to switch these connection points and complete the live switch. As shown in Figure 1, the tap is preselected on the selector and then switches the core for odd and even number switching. The numbers marked with 1, 2, 3, etc., are selector contacts, MSA and MSB in the changeover core are main contacts for live switching, and TA and TB are auxiliary contacts for live switching. When the MSA contact cuts to the TA contact, an arc is generated, which accelerates the wear of the contact surface. Moreover, in this study, the electric field distribution of tap-changer contacts during operation is simulated, as shown in Figure 2. As can be seen from the figure, the contact surface bears a strong field strength and is the weak insulation position in the tap changer. Therefore, the wear state of the switching contact directly determines the service life of the tap changer.

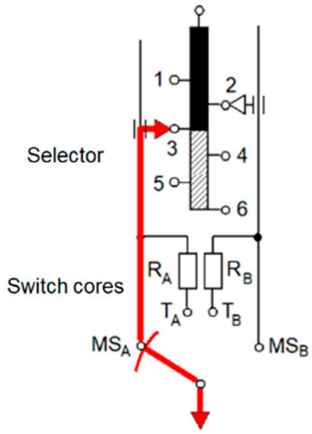


Figure 1. Schematic diagram for tap-changer switching.

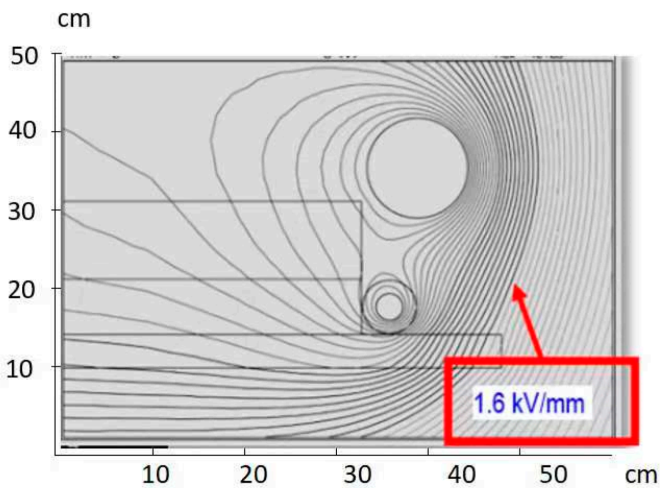


Figure 2. Electric field distribution for contact.

The mechanical structure of the tap-changer contact system is shown in Figure 3. As can be seen from the figure, each time the moving contact selects a tap, sliding friction will occur once. When the tap changer in the industrial transformer operates, the contacts gradually wear out. When the tap-changer contact is worn at more than 17mm, the field strength on the surface of contact is too concentrated. Figure 4 shows the electric field distribution after contact wear. Too much concentration of field strength on the contact surface would cause poor contact of static and static contacts, and then the switch resistance is too large when switching. In this case, the arc is elongated, and there is more gas production. So, the switch is considered to have reached the mechanical operating limit, and the switch contacts must be replaced. Moreover, in this study, as the currents for industrial transformers always are higher than 400A, the material of the contact was copper–tungsten, which can withstand erosion during switching.

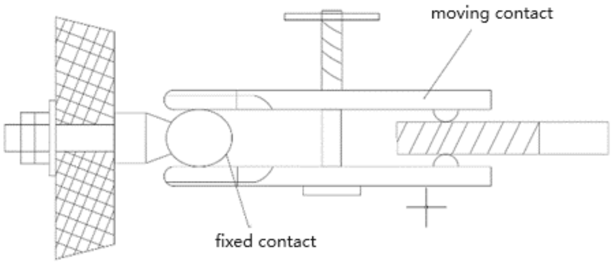
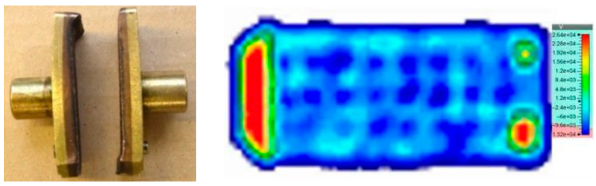


Figure 3. Schematic diagram of tap-changer contact system.



(**a**) (**b**)

Figure 4. Electric field distribution after contact wear: (**a**) real product picture and (**b**) electric field distribution.

In fact, contact wear is closely related to the number of times the tap changer is switched. Meanwhile, tap changers in industrial transformers operate very frequently every year. Table 1 gives the number of tap-changer switches in industrial transformers. In general, when the tap changer is switched to 100,000 times, a power outage repair is required. For example, the electric arc furnace transformer had just begun to be used before the power outage, and the wear of all the contacts of the tap changer must be repaired. The routine transformer maintenance workload is large, and the operation efficiency is affected. Hence, the online prediction of the wear of the tap changer in the industrial transformer is required, so as to reduce the number of major failures and outage maintenance in the operation of the industrial transformer.

Table 1. Switching times per year for industrial tap changer.

Types of Industrial Transformers	The Number of Times the Tap-Changer Is Changed per Year		
	Minimum	Average	Maximum
electrolysis	10 thousand	30 thousand	150 thousand
chemical engineering	1 thousand	20 thousand	70 thousand
electric arc furnace	20 thousand	50 thousand	200 thousand

Each time the tap changer in the industrial transformer is switched, it will be accompanied by the voice and vibration of contact collision. The voice information can be extracted to determine the online operation of the contact or tap changer. In this paper, a large amount of voice information about the normal wear of tap-changer contacts was first accumulated, and each subsequent switch was compared with the normal data. And, a warning standard is proposed to realize the real-time monitoring of the tap changer in the industrial field.

2.2. Intelligent Monitoring System of Tap Changer Construction

The intelligent monitoring system of the tap changer adopts high-resolution abnormal voice recognition technology in a complex voice environment. Based on the characteristic power spectrum tapping reconstruction theory, the wavelet transform optimization algorithm is adopted to greatly reduce the additional noise pollution caused by beam sampling. In such a setting, the weak voice source target recognition function can be realized under the background voice interference of the transformer application. At the same time, in order to construct the fault identification mode of the tap changer, the fault characteristics of the tap changer are studied experimentally, and the fault correlation map of the tap changer based on the voice and vibration signal is formed.

The voice intelligent diagnosis system is mainly composed of three subsystems. The first subsystem is deployed in the voice-sensing terminal near the tap changer, sensing the voice signal of the observation point and initiating preliminary signal processing. The second subsystem is deployed in the edge server of the transformer, comprehensively processing all voice information. The monitoring means of the equipment in the station are used to comprehensively research and judge the voice pattern to identify the fault information represented by abnormal sound. The third subsystem is deployed in the cloud server at the headquarters. According to the collected voice information of multiple tap changers, the voice database is built. Meanwhile, based on the deep learning algorithm model and expert experience, the voice intelligent diagnosis system is established to realize the intelligent voice inspection technology to replace or assist manual inspection and status judgment for transformers.

3. Implementation

3.1. Selection and Installation of Voice Sensing Probes

Based on the application background of transformers, the commercial wideband accelerated-vowel sensor probe was selected. The voice sensor was a voice pickup, which could pick up weak voices (which are indistinguishable from the human ear). And, the sensor could achieve a high signal-to-noise ratio and provided a reliable voice signal for fault diagnosis and identification of tap changers. The voice sensor could be integrated with other power station monitoring and inspection systems and provided a flexible software interface SDK. At the same time, the HTTP protocol could be used to set parameters, query the status and read data of the sensor. Meanwhile, in view of the noise interference in the operation of the transformer, after comparative analysis, the best position for the installation of the voice sensing probe was selected as the head cover of the tap changer, as shown in Figure 5. Because the threaded connection could achieve better acoustic coupling, the method of screw fixation was selected to install the voice sensing probe in the corresponding position.

Figure 5. Installation drawing of the voice sensing probe.

3.2. Voice Data Acquisition System

The voice acquisition system adopted a module with an acquisition card and voice signal transient recorder. By using an analog filter and sampling rate to reduce the signal spectrum, the acquisition system had good anti-aliasing characteristics. The acquisition system could accommodate four acquisition channels at the same time and had the ability to collect low-frequency sound signals for comparative analysis of fault signals. The main function of the acquisition software of the voice acquisition system was to configure the hardware channel to realize the synchronous acquisition, storage, playback and analysis of multi-channel noise. The acquisition software included related modules for voice signal analysis and processing, such as spectrum analysis, octave and other signal processing and analysis functions. Because of the large data flow of the tap-changer sound intelligent acquisition system, the acquisition software should also have the functions of recording, storing, managing and communicating with the common database.

3.3. Voice Data Analysis and Processing

In this study, the time and frequency information of the collected voice signal were then analyzed, and then the time and frequency associated with the voice signals could be given, as well as the relationship between the time and frequency of voice signals. Through the frequency and time information of the voice signal, all the voice signals appearing in the tap changer during the switching process were extracted.

The tap changer contact collided in an insulating medium to emit voice signals with a variety of frequencies. Subsequently, the voice signal propagated from the tap-changer contacted the sensing probe through a variety of media, such as transformer oil, metal and plastic parts, which also affected the frequency of the voice signal. But in any case, it could be confirmed that the voice signal transmitted from the tap-changer contacts was the broadband signal rather than a narrowband signal. In order to extract the voice signal during tap-changer switching, the wavelet transform method was used to analyze the time domain and frequency domain of the voice signal.

Typical analysis results of the voice signal during tap-changer switching are shown in Figure 6. In the figure, the horizontal axis represents the time of each tap-changer process, the vertical axis represents the frequency of the sound signal, and the signal level is in color. As can be seen from the figure, the switching process of the tap changer can be clearly identified through the voice signal. The voice signal from the tap-changer contact was generated with the operation of the mechanical mechanism, and its frequency band was between several thousand Hertz and more than one hundred thousand Hertz, while the frequency of the no-load and load noise of the transformer was several times that of 50 Hertz or 100 Hertz. As shown in Figure 6, the pre-selected split contact head, arc-rupturing contact and switch cores can be clearly indicated. In this way, the voice intelligent monitoring system of tap changers could easily filter the noise interference on the transformer side and extract and display the effective voice signal of the tap-changer switching operation.

When the voice signal sensing and analysis system was built, the sensor automatically recorded the voice signal emitted by the vibration of the contact during each tap-changer switching. And then, the analysis software was used to screen and organize the voice signal, thus obtaining the multi-series curve of the voice signal. By using self-learning software, the multi-series curves were compared and analyzed, and the envelope line was established according to the algorithm. Thus, the voice signal database of the tap changer was built. Since then, the voice signal emitted by each switch in the real operation of the tap changer was automatically compared with the envelope. Once an abnormal situation occurs, a reminder would be sent. In this case, the function of real-time monitoring of the tap changer was realized. Figure 7 shows the comparison of voice signal for tap-changer online monitoring.

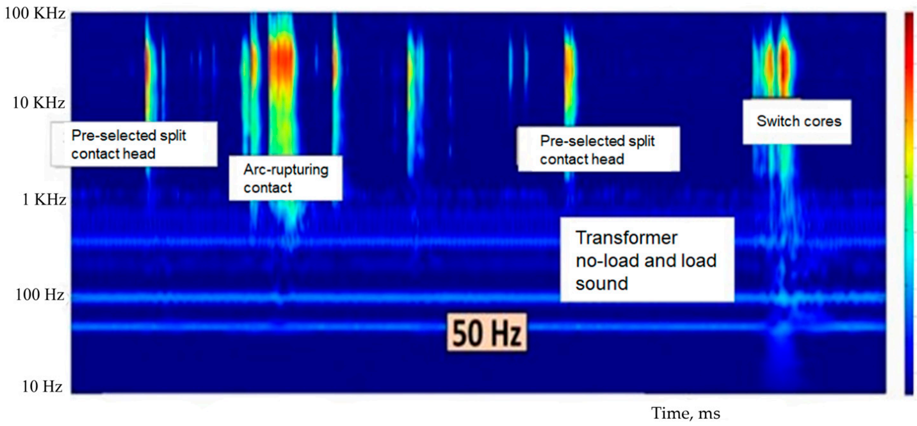


Figure 6. Voice signal analysis diagram of tap changer.

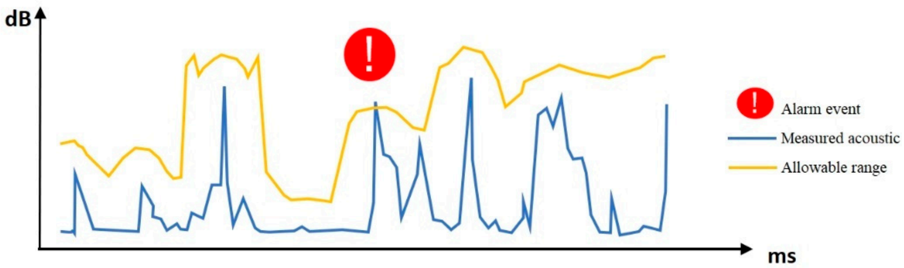


Figure 7. Comparison diagram of voice signal for tap-changer online monitoring.

Based on this intelligent monitoring system, the voice signal of the tap changer could be received in real time, and the voice change caused by the fault of the tap changer (excessive wear of contacts, aging of springs, loose fasteners and asynchronous switching) could be further extracted. In this case, the operation status of the tap changer in the industrial transformer could be effectively monitored under the non-power failure state, and the downtime maintenance time of the industrial transformer could be greatly reduced. In addition, the system could be used as a means of evaluating the suitability of tap-changer installation during transformer production.

4. Conclusions

Aiming to monitor the condition of the tap changer (where the frequent switching would cause the surface wear and other faults), an intelligent monitoring system was developed in this study, and the detailed conclusions are described as follows.

1. The monitoring system was composed of a voice signal acquisition system, voice analysis system and voice processing system.
2. The workflow of the monitoring system was as follows: First, the voice data of the tap changer were collected through a sensor mounted on the head cover of the tap changer. Then, the wavelet transform method was used to analyze the voice signal in the time domain and the frequency domain, and the noise outside the tap changer was effectively filtered, forming the standard switching voice curve of the tap changer. Next, each time the tap changer was switched during operation, the voice data were extracted and analyzed and compared with the standard envelope line, so as to realize real-time monitoring of the running status of the tap changer and timely detection of the tap-changer fault.
3. Based on the voice signal, the monitoring system monitored the potential failure of the switch contacts online, gave an early warning, found the abnormal state of the tap changer in real time, and discovered the cause of the abnormal state according to the voice signal.

This monitoring system greatly reduced the economic loss caused by power failure maintenance, reduced the operation and maintenance workload of personnel and reduced the detection cost and maintenance cost of the tap changer.

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