Recent Developments in Noise Assessment and Condition Monitoring of Ultra-High-Voltage Power Transmission Systems

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Abtract—**With increased utilization of ultra-high-voltage power transmission systems, systematic noise assessment and condition monitoring schemes have been developed in recent years to address the environmental and safety issues involved. This paper summarizes the progress in these areas and outlines the directions for further development.**

Keywords-ultra-high voltage; power transmission systems; noise assessment; condition monitoring

I. INTRODUCTION

Following the development of the first 1000-kV AC ultra-high-voltage (UHV) power transmission system in China in 2006, the rate of construction of UHV AC and DC power transmission stations has risen to around 4–5/year. Those systems, with the advantages of long-distance, high-capacity, and low-energy-dissipation transmission, have greatly enhanced the economy and regional industrial development. However, in parallel with this development is a concern about the environmental noise impact on nearby residents and personnel working in the stations and the operational risks of key power transmission systems, such as UHV power transformers and high-voltage (HV) reactors.

The importance of the control of noise from UHV power transmission systems can be understood in terms of the proportional relationship between the sound power level and the voltage level of the systems and how the specified sound pressure level at the boundaries of the transmission stations complies with noise regulations. Traditional condition monitoring and fault diagnosis of power transmission systems have been based on oil analysis and off-line detection of their health status. A simple, real-time, on-line detection method based on the vibration signature of a power transmission system has attracted the attention of the maintenance sector of UHV power transmission systems. The vibration-based condition monitoring method has demonstrated advantages in on-line identification of the early symptoms of mechanical faults, such as looseness of clamping pressure, deformation and tilting of the winding structure, and loss of the insulation elements.

In this paper, recent advances in noise assessment and condition monitoring of UHV power transmission systems are summarized, based on the work at the ZJU-UWA Joint Laboratory for Modern Acoustical Engineering, in collaboration with the China Electrical Power Research Institute. The future direction of research in the noise and condition monitoring aspects will also be outlined.

II. NOISE ASSESSMENT

A. Assessment of System Noise

One of the most important questions about the assessment and control of noise from power transmission systems is how to correctly determine the source characteristics (including sound power and directivity). Current methods for determining source characteristics are based on sound pressure, sound intensity, and vibration. General techniques and conditions for the methods have been specifically described in various standards [1,2]. Previous experiments have posed questions about the reliability and accuracy of those methods [3,4]. Indeed, it is not uncommon for the source characteristics of the same transformer measured in the manufacturer's workshop and in the on-site environment to be quite different. Furthermore, previous noise assessments of source characteristics were always conducted on an individual unit.

Figure 1 shows a typical layout for a UHV power transmission station. It is worth noting that each UHV transformer consists of three single-phase units (shown as A, B, and C) closely located and separated by firewalls. The same applies to the HV reactors (shown as a, b, and c), which are often closely located near the boundary of the station. Because of the firewalls and closely located units, noise interference occurs between the firewalls, at the locations where the radiated sound waves from the units meet. Figure 2 shows the measured sound pressure field in front of three units of a HV reactor system. This shows the interference patterns of those distributed fields, indicating that the sound pressure from any single unit cannot be directly separated.

FIGURE I. TYPICAL LAYOUT OF TRANSFORMER UNITS AND HV REACTOR UNITS IN A UHV POWER TRANSMISSION STATION.
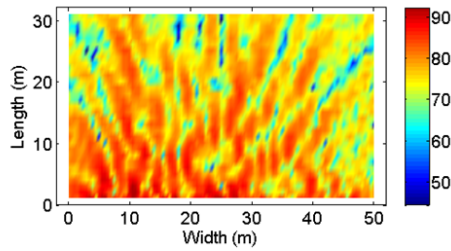

FIGURE II. INTERFERENCE IN THE SOUND PRESSURE FIELD IN FRONT OF THREE UNITS OF A HV REACTOR SYSTEM, AS DETERMINED BY THE DIRECT MEASUREMENT OF SOUND PRESSURE.

Figure 3 shows locations for measurement of sound pressure between two firewalls of the phase A unit of the HV reactor system. As expected, strong interference patterns are observed, as in Figure 4. The difference between the maximum and minimum sound levels is more than 10 dB. The interference patterns shown in Figure 4 are caused by the combined effect of reflection between the firewalls and the surfaces of the unit, and the radiation field from the vibrating unit. As a result, the particle velocity and sound intensity may have different directions and magnitudes at those near-field locations.
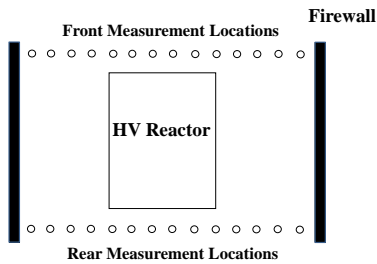

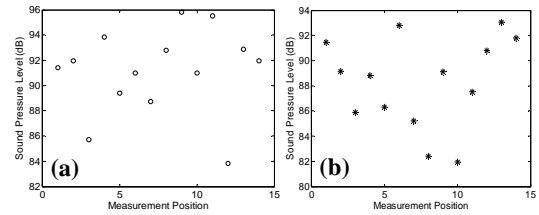FIGURE III. MEASUREMENT LOCATIONS BETWEEN TWO FIREWALLS.

FIGURE IV. DISTRIBUTIONS OF SOUND PRESSURE LEVEL AT (A) THE FRONT AND (B) REAR MEASUREMENT LOCATIONS OF A HV REACTOR.

It is also worth mentioning that the existing vibration method is based on statistical energy analysis of a radiating structure, which relates the radiated sound power from the structure to the structural vibration energy and radiation efficiency. Essentially, this method describes energy transfer in coupled systems with sufficient modal density and broad-band distribution of vibration and sound energy. For noise from transformers or reactors however, the sound energy is mainly contained at 100 Hz and its harmonics. As a result, errors in determining the radiated sound power by the spatially averaged transformer vibration occur right at the beginning of the formulation, where the basic assumption of a sufficient number of modes is not satisfied.

B. Analysis and Solution

The existing sound pressure and sound intensity methods are all based on the discrete measurement of sound pressure and intensity on closed contour(s) at a defined distance from the surface of the unit. However, interference causes a significant difference in the measured sound pressure level, even when the location of the sensor changes only slightly. The spatial interference of the sound field will also cause the sound intensity field to become direction-dependent. As a result, a slight variation in the orientation of an intensity probe from the normal direction of the contour may also cause a significant difference in measured sound intensity.

To obtain accurate sound power, a new measurement method is developed based on the Kirchhoff–Helmholtz (K-H) integral [5]. For this case, sound pressure p, at any location $\vec{r}$ and angular frequency ω in the space Σ enclosed by the boundary surface S and the surface at infinity S_∞, is expressed as:

$$p(\vec{r},\omega) = \int_S [\, p(\vec{r}_s,\omega)\frac{\partial G}{\partial n} + i\rho_o\omega v_n(\vec{r}_s,\omega)G\,]dS \,, \quad (1)$$

where $G = \dfrac{1}{4\pi|\vec{r}-\vec{r}_s|}e^{-ik|\vec{r}-\vec{r}_s|}$ is the free-field Green's function,

$\dfrac{\partial G}{\partial n}$ is the gradient of G on S, and v_n is the normal vibration velocity of the radiating surface. The advantages of this K-H integral method are:

(1) The boundary vibration velocity is the source of sound. For sound radiation from heavy vibrating structures, the effect of noise from other sources on the source velocity is negligible. This is because the sound and structural coupling is weak in this case.

(2) The boundary integral includes reflection from all the boundary surfaces (the first term on the right-hand side of Eq. (1)) and the re-radiation of sound from surfaces because of the non-rigid boundary surface.

Therefore, a determination of the source characteristics of a power transmission system can be converted to a measurement of the vibration velocity on the source surface and an estimation of the specific acoustic impedance of the non-rigid surfaces. Because of the aforementioned advantages, the application of the K-H integral method and a measurement of surface velocity allows for an accurate determination of the sound power. The observed interference in the radiated sound field is one of the outcomes of this method.

As a demonstration of the success of this method, the sound pressure field shown in Figure 2 is determined using the K-H integral method by measuring the surface vibration of the three units of a HV reactor system. Figure 5 is a photo of the reactor system, and the measured surface velocity at 100 Hz is shown in Figure 6. Note that the phase information of the distributed velocity has been taken into account because all the velocity measurements were conducted with respect to the velocity at the same reference location.

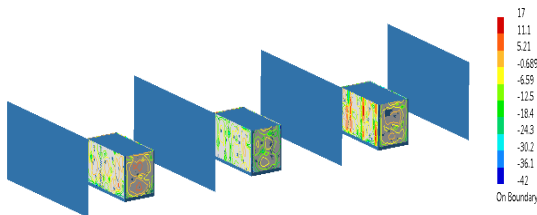FIGURE V.   A PHOTO OF THE THREE UNITS OF A HV REACTOR SYSTEM.

FIGURE VI.   ILLUSTRATION OF THE SURFACE VELOCITY ON THE SURFACES OF THE THREE UNITS OF A HV REACTOR SYSTEM.

The sound pressure determined by the K-H integral method is demonstrated in Figure 7, showing excellent agreement with that in Figure 2. An accurate determination of the entire radiated field is necessary for an accurate determination of the sound power. The dependence of the measured sound pressure and sound intensity on the location of measurement can then be explained by the interference in the radiated sound field.
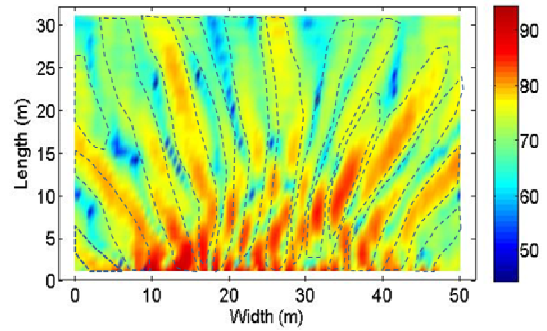

FIGURE VII.   INTERFERENCE IN THE SOUND PRESSURE FIELD IN FRONT OF THREE UNITS OF A HV REACTOR SYSTEM, AS DETERMINED BY THE K-H INTEGRAL METHOD.

III.   CONDITION MONITORING

Vibration-based condition monitoring also relies on the measurement of vibration at the surface of the UHV power transmission system. In this case, the aim is to relate the condition of the internal structure of the system to the vibration. The inputs to the system are the terminal voltages and load currents and possible environmental inputs. As a result, the system model of the condition monitoring system can be expressed as:

$$Y = [H]X ,$$
(2)

where X and Y are the electrical input and vibration output vectors, respectively, whilst $[H]$ is the frequency response matrix, including the characteristics of the mechanical and electro-magnetic components of the system. Typically, a change in mechanical conditions, such as reduced clamping pressure on the windings and core and deformation and tilting of windings, will cause a change in the resonance properties of the mechanical system. As a result, on-line, real-time measurement of $[H]$ and using the variation of $[H]$ from that of the healthy system is the central aspect of the vibration-based condition monitoring technique. For example, component health indicators can be defined as:

$$\varepsilon_{ij} = \left| \frac{[H]_{ij} - [H_o]_{ij}}{[H_o]_{ij}} \right| .$$
(3)

The severity of certain fault(s) can then be described by a combination of indicators and their correlations with the characteristics of the fault(s).

Establishing a correlation between component indicators and the characteristics of the faults is largely based on a mechanism study of transformer vibration. A great deal of experimental work on a single-phase distribution transformer and a three-phase power transformer has been conducted and the links between vibration output and electro-magnetic input have been established. For example, Figures 8 and 9 show the relationship between the core vibration components at 50 Hz

and its harmonics and the percentage change in clamping pressure on the core and winding of a single-phase transformer.
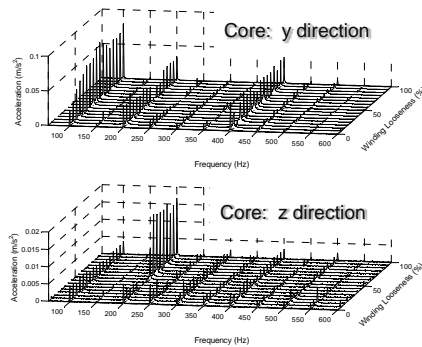

FIGURE VIII. EFFECTS OF A CHANGE IN WINDING CLAMPING PRESSURE ON A CORE'S VIBRATION COMPONENTS.
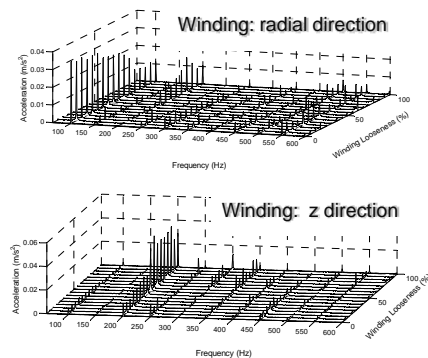

FIGURE IX. EFFECTS OF A CHANGE IN WINDING CLAMPING PRESSURE ON A WINDING'S VIBRATION COMPONENTS.

The experimental data shown in Figs. 8 and 9 have been used as models of the clamping-pressure-related faults for fault diagnosis in vibration-based condition monitoring. Recently, a mechanism study also included the effects of aging of winding insulation paper [6], local deformation of winding, and change in a core's clamping pressure on transformer vibration. These are all part of the aim to relate elements in $[H]$ to the characteristics of various faults.

IV. CONCLUDING REMARKS

Utilization of the Kirchhoff–Helmholtz integral method has allowed an accurate assessment of the source characteristics and radiated sound pressure field of ultra-high-voltage (UHV) power transmission systems. This method will also become a tool for the assessment of passive control systems for attenuating noise from UHV power transmission systems. The mechanism study of the correlation between mechanical faults in a transformer's windings/core and the vibration response provided important criteria for transformer fault detection and diagnosis using the vibration-based condition monitoring method. Because the forces and vibration in a transformer's windings and core are also the major sources of transformer noise, progress in this mechanism study may also deliver a new area of research and development in reducing the noise of power transmission devices from their sources and energy transmission paths.

As a direction for future research into noise control and effective condition monitoring of UHV power transmission systems, Figure 10 presents a block diagram showing the sources and transmission of mechanical-electromagnetic energy, where the magnetostrictive (MS) and electromagnetic (EM) forces are the causes of noise and vibration, whilst the structure-to-structure (S/S), structure-to-liquid (S/L), and liquid-to structure (L/S) couplings are the main paths of energy transmission.
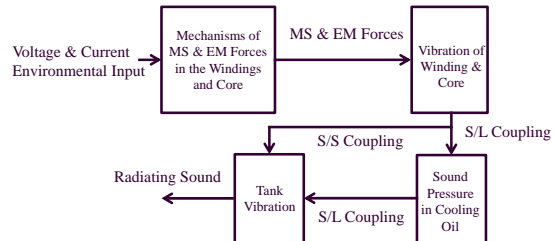

FIGURE X. ELEMENTS OF UHV POWER TRANSFORMERS FOR FUTURE NOISE CONTROL AT THE SOURCE AND STUDY OF FAULT MECHANISMS.

Based on Figure 10, directions for future research into UHV power transmission systems can be outlined as follows.

(1) It is necessary to understand the mechanisms of noise generation, transmission, and radiation of UHV power transmission systems, and the effects of various faults on these mechanisms.

(2) It is necessary to apply those understandings to minimize the radiated sound power of a UHV power transmission system at the design, manufacturing, and installation stages.

(3) It is also necessary to apply those understandings to the detection and identification of faults based on measured system vibration and electrical and environmental inputs.

ACKNOWLEDGMENTS

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