High-impedance spectroscopy methods
Electronic Infosystems

Topics:
1. Introduction
2. Measurement system
3. Diagnosis methods of high-impedance objects
4. Signals with designed shapes
5. Usage of sinc excitation
6. Example
7. Comparison of methods
Introduction

The photography of the cell for impedance measurement of anticorrosion coating on the high voltage

Cross-section of the anticorrosion coating and the cell
Introduction

When a coating is new and there is no penetration of the coating by electrolyte, there are only two elements in the equivalent circuit: capacity $C_c$ (of the order of tens - hundreds pF) and resistance $R_p$ (tens - hundreds GΩ), which model the properties of the coating material.

After some time the coating loses barrier properties, penetration of the coating by electrolyte occurs, but still undercoating corrosion does not take place. In this stage an influence of resistance of electrolyte in corrosion pits on $R_p$ appears. The value of $R_p$ decreases as more as the electrolyte penetrates the coating. Additionally the penetration of the electrolyte into the coating causes an increase of the dielectric constant, thus an increase of value of capacity $C_c$.

In the next stage a break of coating continuity occurs and undercoating corrosion takes place. In the equivalent circuit two new elements occur: the capacity of double layer $C_{dl}$ and the resistance of charge transfer $R_{ct}$. As corrosion progresses the value $R_p$ still decreases until the coating is destroyed.
An object $Z_x$ is excited with a signal $u_o(t)$ and signals proportional to voltage $u_x(t)$ across and current $i_x(t)$ through the object are measured. The excitation signal is generated by DAQ module U2531A and is applied to the object from DAC through $A_{out}$. The programmed resistor $R_L$ is used at the output of the amplifier $A_1$ in order to limit the maximum value of current flowing through the object. Response signals $i_x(t)$ and $u_x(t)$ are converted to signals $u_1(t)$ and $u_2(t)$ and applied to ADCs in the DAQ module through $A_{in1}$ and $A_{in2}$. Current $i_x(t)$ is converted to voltage $u_1(t)$ by current-to-voltage converter (CVC) realized with amplifier $A3$. The range of the CVC can be changed with resistor $R_R$ in order to fit the measured signal $u_1(t)$ to the range of the ADC.
Measurement system
Diagnosis methods of high-impedance objects

Single-frequency method

The conventional measurement technique used for impedance spectroscopy is based on single sine technique (SST).

An object is excited with a harmonic signal and two signals are measured: voltage across $u_x(t)$ and current through $i_x(t)$ the object.

FFT method is used to calculate spectrum of signals $u_x(t)$ and $i_x(t)$.

Impedance magnitude and argument are calculated on the basis of spectrum of signals.

Measurements are repeated for different frequencies in order to obtain the impedance spectrum in several decades.
Diagnosis methods of high-impedance objects

**Single-frequency method**

Nyquist plot

Magnitude

Argument
Diagnosis methods of high-impedance objects

Multi-frequency method
Diagnosis methods of high-impedance objects

Multi-frequency method

Excitation signal

Spectrum of signal
Diagnosis methods of high-impedance objects

Usage of square pulse excitation

\[ U_2(j\omega) \approx \sum_{n=1}^{N-1} \int_{t_n}^{t_{n+1}} \tilde{u}_2(t) \exp(-j\omega t) \, dt \]

\[ U_1(j\omega) \approx \sum_{n=1}^{N-1} \int_{t_n}^{t_{n+1}} \tilde{u}_1(t) \exp(-j\omega t) \, dt \]

\[
\begin{align*}
\text{Re} U_i(\omega) &\approx \sum_{n=1}^{N-1} \frac{1}{\omega} \left( u_i(t_{n+1}) \sin \omega t_{n+1} - u_i(t_n) \sin \omega t_n \right) \frac{u_i(t_{n+1}) - u_i(t_n)}{t_{n+1} - t_n} - \frac{u_i(t_{n+1}) - u_i(t_n)}{\omega^2} \cos \omega t_{n+1} - \cos \omega t_n \\
\text{Im} U_i(\omega) &\approx \sum_{n=1}^{N-1} \frac{1}{\omega} \left( u_i(t_{n+1}) \cos \omega t_{n+1} - u_i(t_n) \cos \omega t_n \right) \frac{u_i(t_{n+1}) - u_i(t_n)}{t_{n+1} - t_n} + \frac{u_i(t_{n+1}) - u_i(t_n)}{\omega^2} \sin \omega t_{n+1} - \sin \omega t_n 
\end{align*}
\]

\[ Z(\omega) = \frac{\text{Re} U_2(\omega) + j \text{Im} U_2(\omega)}{\text{Re} U_1(\omega) + j \text{Im} U_1(\omega)} R_\text{R}
\]
Diagnosis methods of high-impedance objects

Usage of square pulse excitation

Variable sampling frequency idea

Division into segments

Logarythmic method

\[ \log(f_s) \]

\[ f_s_{\text{max}} \quad f_s_{\text{min}} \]

sample number \((n)\)
Signals with designed shapes

Usage of half period of a signal

\[ x_k \left( \frac{T_k}{2} < t - \tau < T_k \right) = -x_k \left( 0 < t - \tau < \frac{T_k}{2} \right) \]

\[ \sin(2\pi f_k t + \Phi_k) = -\sin(2\pi f_k t + \Phi_k + \pi) \]
Signals with designed shapes

Excitation signals and their spectra

**Excitation signals**

- Square unipolar
- Square bipolar
- Triangle
- Sawtooth
- Sinc

**Spectra of signals**

- Square unipolar
- Square bipolar
- Triangle
- Sawtooth
- Sinc
Signals with designed shapes

Simulation research

Magnitude error

Argument error
Usage of sinc excitation

Excitation signals and their spectra

Excitation signal of type $\sin(x)/x$

Spectrum of signal $\sin(x)/x$

$$u_0(t) = U_0 \text{sinc} \left( 2\pi f_{\text{max}} (t - \tau) \right)$$

Conditions: $T > 1/f_{\text{min}}$

$$T = k f_{\text{max}}^{-1}$$

$k = 1, 2, 3, \ldots$
Example

Diagnosis of high-thickness rubber anticorrosion coating

\[ C_c = 400 \text{ pF}, R_p = 1 \text{ G\Omega}, C_{dl} = 10 \text{ nF}, R_{ct} = 5 \text{ G\Omega}; \]
\[ C_c = 300 \text{ pF}, R_p = 10 \text{ G\Omega}, C_{dl} = 1 \text{ nF}, R_{ct} = 50 \text{ G\Omega}; \]
\[ C_c = 100 \text{ pF}, R_p = 100 \text{ G\Omega}, C_{dl} = 10 \text{ pF}, R_{ct} = 500 \text{ G\Omega}; \]
Example

I stage – measurements on higher frequencies (> 0.1 Hz)

Excitation with sinewave signal

Magnitude characteristics

Argument characteristics

Impedance spectrum is evaluated for frequencies 100 mHz – 10 Hz
Example

II stage – measurements on lower frequencies (< 0.1 Hz)

Excitation with $\sin(x)/x$

Magnitude characteristics

Argument characteristics

Impedance spectrum is evaluated for frequencies 1 mHz – 100 mHz
Example
Combination of results

Magnitude characteristics

Argument characteristics
The most accurate, but the slowest is **single-frequency** method. Measurement time is at least a sum of all periods of components in spectrum.

A method with **half period of sinewave signal** enables to shorten measurement time in cost of accuracy of impedance spectrum calculation. Also there is a need to eliminate offset from measured signals.

A method with **multi-frequency excitation** enables for measurement of spectrum in a wide range of frequencies, but there is a limitation in selection of measurement frequencies. Minimum measurement time equals a period of lowest frequency component in spectrum.
Comparison of methods (2/2)

- Usage of **square pulse excitation** signal enables to significantly decrease of measurement time, but accuracy of impedance spectrum evaluation is poor. Duration of pulse excitation depends on value of impedance. Due to shape of spectrum of square pulse excitation there is a limitation in selection of measurement frequencies. There is a need to use changable sampling frequency, because of sudden changes of values of measured signals on the beginning and on the end of square pulse.

- In a metod with **sin(x)/x** excitation signal there is no limitation in selection of measurement frequencies in assumed range from $f_{\text{min}}$ to $f_{\text{max}}$. Accuracy of impedance spectrum evaluation in this range is constant. Efficiency of the method decreases along with extension of the range of measurement frequencies. Measurement time is the same as in the multi-frequency method. There is ease in selection of sampling frequency, which can be constant as opposed to method with square pulse excitation.