

CAPACITANCE AND DISSIPATION FACTOR METER FOR HIGH-VOLTAGE ELECTRICAL MACHINES

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Abstract - Measurement of the capacitance and the dissipation factor of the high-voltage machines insulation systems is one of several method used in the technical diagnostics. This paper deal with the development of instrument designed for measuring capacitance and dissipation factor of such machines. There is described principle of ratio measurement method as well as developed hardware based on FPGA application. Finally the measurement error analysis is given and its correction is presented.

Keywords: electrical capacitance, dissipation factor, impedance measurement, high-voltage machines diagnostics

1. INTRODUCTION

In the field of energetics there is an amount of high-voltage (HV) machines that lifetime is expected of the order of tens of years. As an example may be mentioned the power transformers and generators directly used in the production and the transmission of electricity. To achieve expected lifetime it is necessary to plan regular diagnostic examinations of these machines, thus the machine operator avoids unexpected shut down of the machine or the entire system [1].

The HV machines windings are constantly exposed to a combination of heat, electric and mechanical stresses [2], [3]. All of these factors have influence on the state of the machines winding insulation. The state of winding insulation is one of the studied parameter that can detect an upcoming failure. There is a few measurements methods used to winding insulation state assessment as electric resistance measurement using DC current, partial discharge measurement [4], [5], dielectric response measurement [6] or capacitance and dissipation factor measurement using AC current with a frequency of 50 Hz.

This paper is focused only on method for measuring capacitance and dissipation factor. This method uses the AC current of a frequency of 50 Hz. It is also necessary to perform the measurements at nominal voltage of the tested machines. These voltages can rise up to tens of kV. Therefore it is to choose an appropriate way of measuring the capacitance and the dissipation factor.

This paper describes a design of capacitance and dissipation factor meter (CDF meter) developed in

a cooperation with the ORGREZ company dealing with the high-voltage machines diagnostics.

2. CDF METER DESCRIPTION

2.1. Applied measurement method

The measurement of the capacitance and the dissipation factor leads to measurement of electrical impedance in general. There are few methods used to measurement of the electrical impedance, some of them are described in [7]. The main disadvantage of the described methods is a fact that they are suitable only for low voltage measurements.

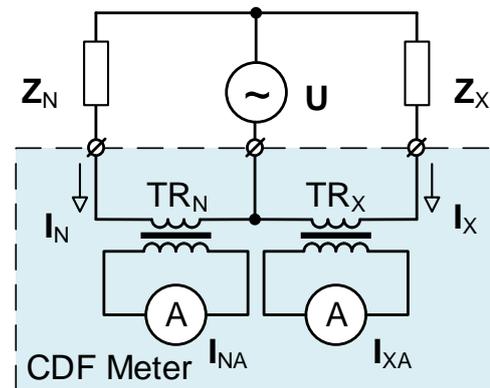


Fig. 1. Modified I-V method used in the CDF meter.

There is also described the I-V method in [7]. This method is based on Ohm law and it needs to measure the current flowing through the measured impedance and the voltage on the measured impedance. However, the method is dependent on the value of voltage. For this reason it was chosen modified I-V method that solves this disadvantage. It is shown in Fig. 1. The measuring circuit consists of HV power source U , the measured impedance Z_X , the reference impedance Z_N with known and stable parameters, the current transformers TR_N and TR_X and ammeters I_{NA} and I_{XA} . The blue rectangle shows parts that are implemented directly in the CDF meter the other parts are formed by external HV power source and reference impedance Z_N .

The measured impedance \mathbf{Z}_X could be expressed as

$$\mathbf{Z}_X = \mathbf{Z}_N \frac{\mathbf{I}_N}{\mathbf{I}_X} \mathbf{A} = \mathbf{Z}_N \frac{\mathbf{I}_{NA} p_X}{\mathbf{I}_{XA} p_N} \mathbf{A}, \quad (1)$$

$$p_N = \frac{\mathbf{I}_{NA}}{\mathbf{I}_N}, \quad p_X = \frac{\mathbf{I}_{XA}}{\mathbf{I}_X}, \quad (2)$$

where p_N is the transformer ratio of the TR_N , p_X is the transformer ratio of the TR_X , \mathbf{A} is an error correction factor that will be described in the section 3 and other quantities was explained above. As you can see in (1), the HV power source \mathbf{U} does not act in the equation. In other words, it is not necessary to measure voltage \mathbf{U} . On the other hand this method requires use of known reference impedance \mathbf{Z}_N constructed for high-voltage with stable parameters. In the case of CDF meter it was used a HV vacuum capacitor with known capacitance and dissipation factor.

If we are interested in capacitance and dissipation factor of \mathbf{Z}_X they could be expressed as

$$C_X = -\frac{1}{2\pi f \text{Im}\{\mathbf{Z}_X\}}, \quad (3)$$

$$D_X = \frac{\text{Re}\{\mathbf{Z}_X\}}{\text{Im}\{\mathbf{Z}_X\}}, \quad (4)$$

where C_X is capacity of impedance \mathbf{Z}_X , D_X is dissipation factor of impedance \mathbf{Z}_X and f is frequency of currents \mathbf{I}_N and \mathbf{I}_X .

2.2. Hardware description

There was described applied measurement method in the section 2.1. There was also derived the basic equations necessary to evaluate the capacitance and the dissipation factor. It should be mentioned all of the quantities used in equation (1) are vector quantities. It means the ammeter \mathbf{I}_{NA} and \mathbf{I}_{XA} have to be able to measure current amplitude and also its phase.

The block diagram of the CDF meter satisfying the requirements expressed in the previous text is shown Fig. 2. The diagram consists of several blocks. The red rectangles represent blocks of current measurements, the blue ones blocks of power source frequency and phase measurement, the yellow ones communication blocks and green one a control unit.

The blocks of current measurements form two measuring channel, one for C_N and one for C_X . Terminals C_N and C_X are used to connect the reference impedance and a device under test (DUT), see Fig. 1 where \mathbf{Z}_N belongs to C_N and \mathbf{Z}_X to C_X . The FPGA circuit was used as the key control component of the designed CDF meter. The measuring current flows from the terminal through a range switch to the current transformer (TR_N and TR_X in the Fig. 1). The transformers was designed to minimize their vector error. The transformed current is converted by an I/U converter to voltage that is filter by a low pass filter. The filtered signal is fed to a quadrature synchronous detector.

The synchronous detector produces voltages proportional to the real and imaginary part of currents I_{NA} and I_{XA} . These signals are digitalize using the 24-bit $\Sigma - \Delta$ AD converter.

The main role of the blocks of power source frequency and phase measurement (blue rectangles in Fig. 2) is to generate reference signals (sin, cos) for synchronous detectors. The reference signals have to have the same frequency as the HV power supply \mathbf{U} . Therefore it is necessary to measure the frequency of the \mathbf{U} . In practise it is used a HV power source with frequency and phase derived from a power supply source connected to the power grid. Hence, it is not necessary to provide the frequency measurement on the used HV power source. It is sufficient to measure frequency of the power line grid connected to the terminal U_f .

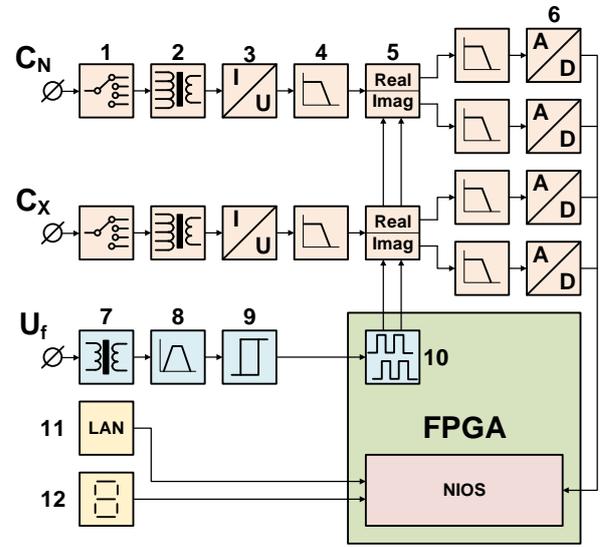


Fig. 2. Block diagram of the CDF meter. 1 - range switch, 2 - current transformer, 3 - I/U converter, 4 - low pass filter, 5 - synchronous detector, 6 - AD converter, 7 - voltage transformer, 8 - band pass filter, 9 - comparator, 10 - reference signal generator, 11 - communication element, 12 - display element

The U_f voltage is reduced using a voltage transformer and filtered by band pass filter with center frequency of 50 Hz. The signal is led to the comparator with hysteresis and led directly to the FPGA. The reference signal generator produces two reference signals phase-shifted by 90 degree for driving quadrature synchronous detectors.

Communication and display blocks are used to controlling the meter and displaying the measured values. The meter could be control via the TCP/IP protocol over the 1 Gbit Ethernet interface or using an built-in coloured graphical display having touch screen.

The role of the control unit takes FPGA of family Cyclone IV. The FPGA allows to implement embedded 32-bit processor NIOS that is used to processing the data from AD converters and communication service. The real time operating system is implemented in the processor. Other functions such as AD converter driver and reference signal generator are implemented using VHDL by logical elements

outside the processor. It allows to decrease the processor computational load.

A six layer printed circuit board (PCB) implementing all of the elements except the range switches and the current transformers was designed. The board was also equipped with auxiliary components such as SDRAM memory for booting the processor and EEPROM memory to saving the operating settings.

2.3. DUT connection

The CDF meter is constructed for capacitance and dissipation factor measurement of insulation of connected DUT. The DUT can be represented by a HV transformer or a generator. There is shown a basic DUT connection to the CDF meter in Fig. 3. In this case the DUT is represented by transformer with one primary winding H a two secondary windings A and B . The are also marked the studied capacitances in the figure. The red capacitor C_{HA} represents parasitic capacitance between windings H and A , capacitor C_{HB} between windings H and B and capacitor C_{HG} between winding H and ground.

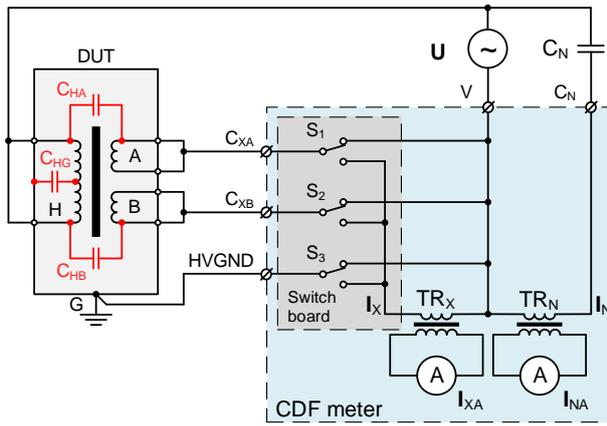


Fig. 3. Connection of the DUT to the CDF meter

The DUT is connected to the CDF meter current transformers using a switch board, see Fig. 3. The switch board consists of couple of switches. The full schematic is shown in Fig. 4. The switches allow to choose one or more of the capacitances C_{HA} , C_{HB} or C_{HG} to be measured without the change of the DUT wiring. Corresponding switch positions are documented in Table 1.

Table 1. Measuring modes.

Measured capacitance	S_1	S_2	S_3
C_{HA}	ON	OFF	OFF
C_{HB}	OFF	ON	OFF
$C_{HA} + C_{HB}$	ON	ON	OFF
$C_{HA} + C_{HB} + C_{HG}$	ON	ON	ON
$C_{HB} + C_{HG}$	OFF	ON	ON
$C_{HA} + C_{HG}$	ON	OFF	ON
C_{HG}	OFF	OFF	ON

2.4. Measuring ranges

To achieve the wider measuring range the current transformers are realized with four primary windings. Switching the windings allows to change the transformers ratio p_N and p_X described in (2). The complete transformers connection using the switchboard is shown in Fig. 4. The switches S_7 to S_{14} are used to change the transformers ratio. They allows to change the ratios in the range of 1:600 to 1000:600. All measuring ranges with maximum current limits are presented in Table 2. The maximum capacitances are calculated assuming the the voltage source U reaches the value of 12 kV. There is also a power limitation of the voltage source. The measuring range 1:600 with the maximum capacitance of $4,2 \mu F$ is presented informatively. For excitation the capacitor it is needed much more power source as is conventional used.

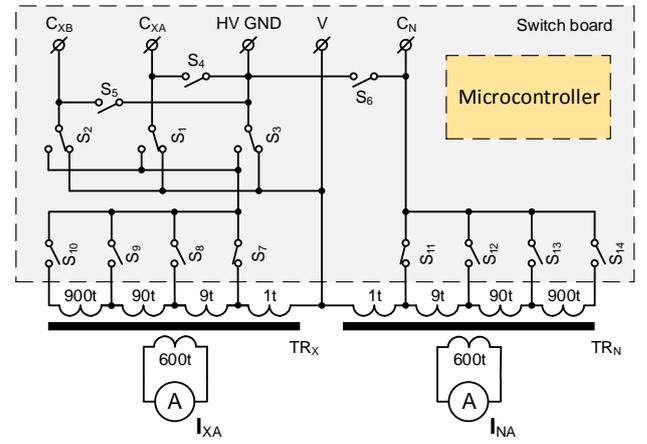


Fig. 4. The current transformers connection.

Table 2. Measuring ranges.

Measuring range	$I_{Xmax} [A]$	$C_{Xmax} [nF]$
1000:600	0,016	4,2
100:600	0,16	42
10:600	1,6	420
1:600	16	4 200

There is a risk of HV presence on the meter terminals during the range or mode switching. If the measuring circuit is open the meter input impedance increase. For example the switches S_2 and S_7 are turned on which means that the terminal C_{XB} is floating. In that case the HV appears through the capacitance C_{HB} which may cause a damage of the device. Therefore there are also switches S_4 to S_6 that are turned on during the switching range or mode. These switches ensure that the measuring circuit is always closed an the input terminals are not floated. This switching procedure is provided by a microcontroller situated on the switchboard.

3. ERROR MODEL

To achieve the highest measurements accuracy it is necessary to determine an error model of the meter and correct the errors. Let's assume a vector error of the vector ammeters I_{NA} and I_{XA} . The measured values could be expressed as

$$I_{NA} = \overline{I_{NA}} E_N, \quad I_{XA} = \overline{I_{XA}} E_X, \quad (5)$$

where $\overline{I_{NA}}$ and $\overline{I_{XA}}$ are measured values by vector ammeters, $\overline{I_{NA}}$ and $\overline{I_{XA}}$ are real values of the current and E_N and E_X are the vector errors. The vector errors E_N and E_X contains vector error of used ratio current transformers as well as vector errors caused electronic circuit used for analogue signal processing (filtering, gain settings, etc.). Substituting into the equation (1) we get

$$Z_X = Z_N \frac{\overline{I_{NA}} E_N p_X}{\overline{I_{XA}} E_X p_N}, \quad (6)$$

hence the error correction factor A from the equation (1) could be expressed as

$$A = \frac{E_X}{E_N} \quad (7)$$

and the equation (6) reduces to

$$Z_X = Z_N A \frac{\overline{I_{NA}} p_X}{\overline{I_{XA}} p_N}. \quad (8)$$

3.1. Correction factor determination

Correction factor A is obtained by determination of both ammeters errors E_N and E_X separately. These errors could vary depending on the set measuring range hence the used current transformer winding. Therefore it is necessary to determine the vector error for each winding, together eight values.

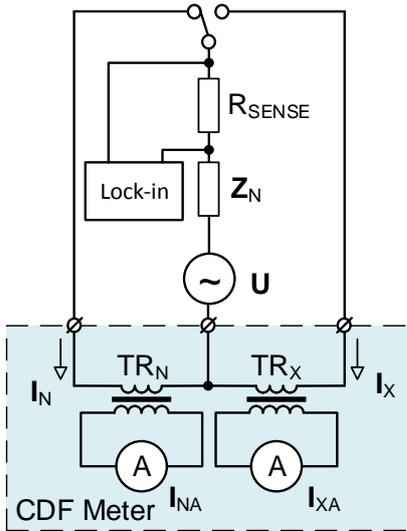


Fig. 5. Circuit for vector errors determination

In the Fig. 5 there is shown a measuring circuit for determination both of the vector errors. The circuit contains

of the HV source U , the normal impedance Z_N , a sensing resistor R_{SENSE} and a lock-in amplifier. The frequency reference signal of the lock-in amplifier is derived from 230 V power grid. The vector error could be expressed from (5) as

$$E_N = \frac{I_{NA}}{\overline{I_{NA}}}, \quad E_X = \frac{I_{XA}}{\overline{I_{XA}}}, \quad (9)$$

where the real currents $\overline{I_{NA}}$ and $\overline{I_{XA}}$ may be consider the value measured by the lock-in amplifier. Both of the values are measured separately for each winding and measuring range.

3.2. Accuracy improvement

The CDF meter is in general an instrument for measuring the electrical impedance. But its main application is measuring capacitance that leads to impedance vector with small real part and high imaginary part. Especially when the capacitors with small dissipation factor are measured the imaginary part of the impedance and the measured current is close to zero while the real part rises up to AD converter saturation.

The imaginary part of impedance could be influenced by high measurement error due to the low signal level on the AD converter. It seems to be preferable to ensure approximately the same voltage levels of the imaginary and real parts on the AD converters that reduces the influence of offset error and increases the signal to noise ratio. This situation is illustrated in Fig. 6. The vector I represent the current vector corresponding to the impedance with the capacitance character. The vector I_T represent target current vector with the equal imaginary and real parts with the phase shift φ to the vector I .

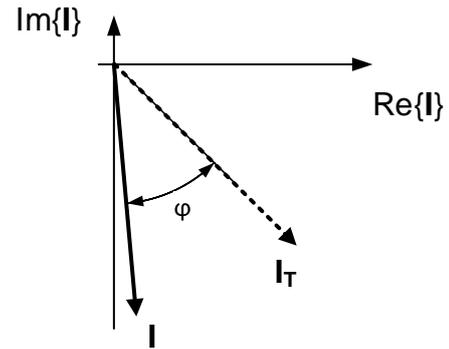


Fig. 6. Measured current phase shift

The one way to achieve the situation described in Fig. 6 is to rotate the Cartesian coordinates by the angle of φ . The CDF meter implements the rotation in the block reference signal generator shown in Fig. 2. A detailed diagram of the generator is shown in Fig. 7. Conditioned signal with the same frequency and phase as the power grid is leaded to the input of the generator. The signal is shifted by the angle φ using the phase shifter to achieve the rotation shown in Fig. 6. The reference generator produces two

reference signals used for the synchronous detectors. These two signals are mutually shifted by the angle of $\pi/2$.

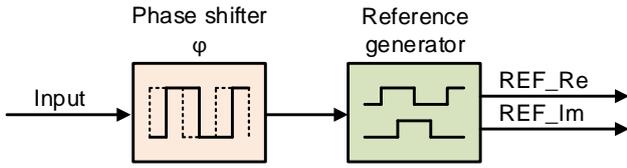


Fig. 7. Measured current phase shift

Due to additional phase shift in the measuring channel it is necessary to revise equation (5). The measured current vectors should be expressed as

$$\mathbf{I}_{NA} = \overline{\mathbf{I}_{NA}} \mathbf{E}_N e^{-j\varphi}, \quad \mathbf{I}_{XA} = \overline{\mathbf{I}_{XA}} \mathbf{E}_X e^{-j\varphi}, \quad (10)$$

where $e^{-j\varphi}$ is a correction of the Cartesian coordinates rotation. Substituting into the equation (6) we get

$$\mathbf{Z}_X = \mathbf{Z}_N \frac{\overline{\mathbf{I}_{NA}} \mathbf{E}_N e^{-j\varphi} p_X}{\overline{\mathbf{I}_{XA}} \mathbf{E}_X e^{-j\varphi} p_N}. \quad (11)$$

Assuming that the phase shift φ is identical for both of the measuring channel, the correction factor $e^{-j\varphi}$ has no effect in the equation. Hence, the value of the phase shift φ does not impact calculated value of the measured impedance \mathbf{Z}_X .

4. CONCLUSIONS

This paper deals with the non-destructive method to diagnostic the insulation of the high-voltage electrical machines. Especially the method of the measurement of the capacitance and the dissipation factor was discussed. The paper describes a design of the CDF meter for HV measurements. The suitable measuring method was noted. The hardware requirements and simplified device block diagram was introduced. There is also described way how to connect the DUT to the CDF meter using the switch board. Application of switch board allows to measure all important main or parasitic capacitance and dissipation factor without any reconnection of the DUT.



Fig. 8. The front panel of the CDF meter

To reach the highest measurement accuracy the simple error model has been created and the method of error correction is proposed. The error model calculates with the vector error for each measuring range. According to the preliminary results the CDF measures the capacitance better than 0,1 %. In the case of the dissipation factor the accuracy is better than 1 %.

Fig. 8 shows a front panel of the assembled CDF meter. The meter allows to perform the measurements under the high-voltage in the order of tens of kilovolts. The maximal measured current is limited up to the 16 A that allows to measure capacitances in the order of thousands of nano farads (dependent on the output power of used HV source). The minimal measured dissipation factor is limited to the value of 0.0001.

To achieve much more measuring accuracy and signal processing flexibility it is planned to design fully digital vector ammeters. The existing sigma-delta AD converters will be replaced by ones with sampling frequency up to 250 MHz. The synchronous detectors will be implemented at the firmware level. Also the wide frequency range is expected that involves to use the meter in the field of the dielectric spectroscopy.

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