AN ACTIVE MEASURING IMPEDANCE FOR SENSITIVITY IMPROVEMENT AT PARTIAL DISCHARGE MEASUREMENT IN POWER CABLES

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REZUMAT. In lucrare se analizează rolul pe care îl are impedanţa de cuplaj asupra sensibilităţii schemei de măsurare a descărcărilor parţiale (DP) în cablurile electrice, prin compararea diferitelor soluţii de realizare a acestora. Se descriu caracteristicile de frecvenţă ale unor impedanţe de cuplaj clasice ca filtre trece-sus pasive constatindu-se o rejecţie redusă a tensiunii de incercare de joasă frecvenţă cât şi utilizarea unei impedanţe de cuplaj active bazata pe un filtru trece-sus de tip Butterworth de ordinul IV care permite extragerea impulsurilor de descarcare parţială chiar la nivele reduse ale intensitatii acestora .

Cuvinte cheie: cabluri electrice de putere, descărcări parţiale, filtru trece-sus, impedanţă de cuplaj

ABSTRACT. The paper analyses the role of the coupling impedance on the sensitivity of the measuring diagram of partial discharge (PD) in power cables by comparing different solutions for achieving them. The frequency characteristics of some classical coupling impedances as high-pass filters are described finding out a low rejection of the low frequency test voltage the use of some active coupling impedances based on high-pass filter type Butterworth a 4-th order allowing partial discharge impulse extraction even for low intensity ones.

Key words: power cables, partial discharges, high-pass filters, coupling impedances,

1. INTRODUCTION

The safety in operation is very much dependant on the material quality and manufacturing technology used, on their laying quality and on the electric and mechanic stresses they are subjected to during operation. In the case of electric cables, unlike other electric power equipments as power transformers, the sensitivity of PD classical detection methods is relatively low due to the high electric capacity of the cables. In order to improve the sensitivity, some high capacity coupling capacitors should be used that is not a cost effective solution for on-site tests.

The paper analyses the role of the coupling impedance on the sensitivity of the measuring diagram by comparing different solutions for achieving them when a modern method for on-site test voltage generation is used namely oscillating wave test system (OWTS).

The test diagram, its components and the frequency characteristics of some classical coupling impedances as high-pass filters are described finding out a low rejection of the low frequency test voltage hindering in this way the detection of some PD considered dangerous for insulation condition.

Therefore, the paper proposes the use of some active coupling impedances based on a 4-th order high-pass Butterworth filter allowing partial discharge impulse extraction even for low intensity ones.

The study is achieved by means of the numerical simulation of the whole testing diagram operation that assumes the modelling of: studied cable, tests voltage generation equipment, PD source, disturbance sources inductively and/ or capacitively coupled with the test diagram etc. The active filter was optimised so that to provide a much higher rejection of the spurious low frequencies existing in the distribution posts or stations in comparison with the systems used so far. The active filter protection is achieved by electromagnetic screening for radiated disturbances and by an optoelectronic chain for common mode conducted disturbances.

The results and proposals presented in the paper have a general character namely they may be applied without restriction also in the case when the AC test voltage is applied permanently and irrespective of the test object.

2. SENSITIVITY ANALYSIS OF THE CIRCUIT DIAGRAM FOR MEASURING PD IN POWER CABLES

Determining the sensibility of the measurement circuit of PD in power cables

The classic circuit measurement of PD contains a coupling capacitor (C_k), an measurement impedance (Z_m), the cable for transmitting data and the electrical measuring instrument. Usually, the measurement impedance used in the PD detection circuit is formed of passive electrical circuits components. In the classic diagrams, the measurement impedance may be coupled in series with the coupling capacitor (C_k) (fig. 1), thus forming a passive high-pass filter, with the role of rejecting the low-frequency components from the alternative power supply voltage, as well as its harmonics. A high-pass high-quality filter must present zero attenuation for the useful signal provoked by the presence of the partial discharges and very high attenuation for the carrying component. The rejection factor, defined as the proportion between the alternative voltage when entering the measurement impedance and the output voltage, must be as high as possible, in order for the sensitivity of the circuit for measuring PD to be at maximum value. At a limit, it would be ideal that only the voltage pulses corresponding to the PD signal passed through the measurement impedance.

In analysing the sensibility of the circuit diagram for measuring PD, a capacitive model was considered for a portion of a cable that suffered an internal defect, as presented in fig. 1 in which C_z is the sound parallel capacity (untouched by any defects), C_x represents the equivalent capacity of the cavity (defect) and C_y stands for the capacity of the sound layers in series with the defective area, and it started from the fact that the partial discharges that appear by short-circuiting the inclusion capacity, C_x lead to a drop in voltage of the terminals for the object tested:

$$\Delta U_a = \frac{C_y}{C_z + C_y} \Delta U_c \ll \Delta U_c \qquad (1)$$

The expression (1) is valid for the condition: $C_z \gg C_x \gg C_y$

Connecting the object tested C_t to the alternative or damped ac voltage by means of a separation impedance Z symbols that only the circuit formed of the coupling capacitor C_k and the testing object C_t practically exists.

In the ideal situation $C_k \gg C_t$ in which the C_t capcity of the object tested contains both the sound part and the defective area, the coupling capacitator C_k has the role of a power capacitor (stable voltage source) during the short period of producing the PD. It discharges a current equivalent to the current absorbed in the PD area, which compensates for the drop in voltage ΔU_a.

In these conditions, the q charge, given by the expression (2), represents the apparent charge of the PD pulses, fundamental measure in the PD measurements in conformity with IEC 60270.

$$q = C_y \Delta U_c \qquad (2)$$

In the actual situation of measuring PD in electric cables, the relation between C_k and C_t is totally different from the case previously analysed, namely $C_t \gg C_k$ (C_k being of the nF order, and C_t of the order of hundreds of nF). In this case, the electrical voltage from the terminals of the two capacitors C_k and respectively C_t is no longer constant and as a resultit is obtained, considering the relation (2):

$$\Delta U = \frac{C_y}{C_z + C_y + C_k} \Delta U_c = \frac{q}{C_z + C_y + C_k} \qquad (3)$$

The electric charge q_m measured by the electrical measuring instrument from the circuit diagram for determining PD, considering the expression (3) and the relation between C_z and C_y, namely $C_z \gg C_y$, has the expression:

$$q_m = C_k \Delta U = \frac{C_k}{C_z + C_y + C_k} q \cong \frac{C_k}{C_z + C_k} q \qquad (4)$$

In order to establish the sensitivity level of the circuit diagram for measuring PD, the values obtained for the apparent charge q prodused by PD in the defective area and the q_m charge measured by the electrical measuring instrument from the circuit determining PD, are analysed, by reporting q_m to q, thus obtaining :

$$\frac{q_m}{q} = \frac{\dfrac{C_k}{C_z + C_k} q}{q} = \frac{C_k}{C_z + C_k} \cong \frac{C_k}{C_t + C_k} \cong \frac{C_k}{C_t} \qquad (5)$$

Analysing the result from the expression (5) it is evident that in the situation of measuring PD in the electrical cables, the sensitivity of the basic measurement circuit diagram is very reduced (C_t >>C_k), by using a passive high-pass filter. For this reason, as it is futher demonstrated, it is suggested to further use an active filter together with the passive filter in the circuit diagram for measuring PD, which would ensure a superior rejection of the low-frequency signal collected from the passive filter. The active filters have simple circuit diagrams, are easy to realise and thus lead to a simple, economic and efficient solution as to increase the sensitivity in detecting PD in the MV cables.

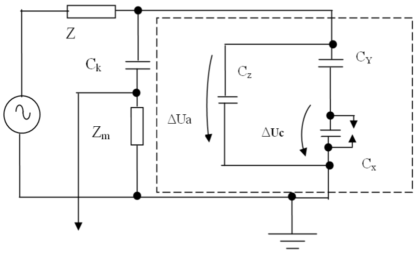

Fig. 1. Circuit diagram for measuring PD

The OWTS methods of testing electric cables

This off-line and on-site method which is succesfully used in diagnosting electric cables and accessories, principally consists in generation a damped ac voltages – DAC with a frequency between 50-500 Hz.In fig. 2 [1,2], the basic diagram for using OWTS in testing electric cables is presented. The system is powered from a variable voltage source of c.c. that supplies the tested cable for a *t* period of time, counted in seconds, an ascending voltage up to the value of the testing voltage. When reaching the testing voltage, the capacity of the cable, C_{cable} is discharged on an air coil (L=1 H and R= 19 Ω) with the help of a static switch of HV, with a very short closing time (under 1 μs), thus forming an attenuated oscillant voltage.

The *f* oscillation frequency is determined with the expression [1,3]:

$$f = \frac{1}{2\pi\sqrt{LC_{cablu}}} \qquad (6)$$

3. IMPROVING THE CIRCUIT DIAGRAMS FOR MEASURING PD IN CABLES

Comparative analysis concerning the high-pass filters

In the electric circuits for testing electric MV and HV cables, measurement impedances with passive circuit components are used (resistors, coils and capacitors).

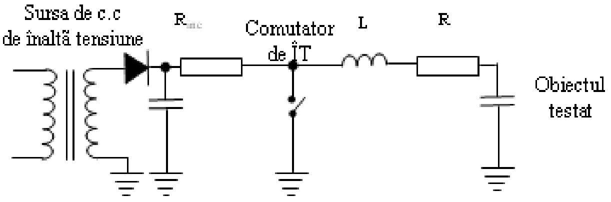

Fig.2. The basic diagram for producing OWTS

In the fig. 3a a passive filter R-C is presented, and in fig. 3b [4], a passive high-pass filter in the industrial circuit diagram measurements is presented.

As it was presented in previous paragraph., these types of high-pass filters, with measurement impedances with passive circuit components, present a low sensibility in case of PD measurements concerning electric cables that embody a predominantly capacitive character.

In view of increasing the sensitivity of the circuit diagrams for measuring PD in testing the alternative or oscillated attenuated voltage, it is considered necessary to introduce an active high-pass filter in the measurement circuit.

A high-pass active filter type Butterworth of the 4th order was chosen as it responds well to the requirements of a measurement equipment: a) it presents zero attenuation in the passing area (fig.5, characteristic1), which ensures the unaltered reproduction of the measured signal; b) presents a high attenuation in the blockage area (80dB/dec), which ensures the a sufficient rejection of the low-frequency signal; c) it is very easy to implement in practice; d) it ensures a safe functioning.

In fig. 4 [5] the diagram of a filter type Butterworth of the 4th order that is suggested to be used in similar electric circuit diagrams is presented.

In view of the comparative analysis of the behaviour of high-pass filters, both in low-frequencies as well as in high frequencies, using the SPICE software, the frequency characteristics for the passive high-pass filters presented in fig. 3.a and b and for the active high-pass filter from fig.4 were raised.

The results obtained are presented in fig.5.

From analysing the characteristics presented in fig.5 it is observed that, concerning low frequencies (ensure a strong attenuation, thus an increased rejection of the low-frequency components from the voltage supply, as well as its harmonics), the filter type Butterworth of the

4th order (characteristic 1 from fig.5) behaves the best. Similarly, regarding high frequencies (at the level of frequencies from a PD signal), it is also the filter type Butterworth of the 4th order that behaves the best as it presents a zero attenuation in all the passing area.

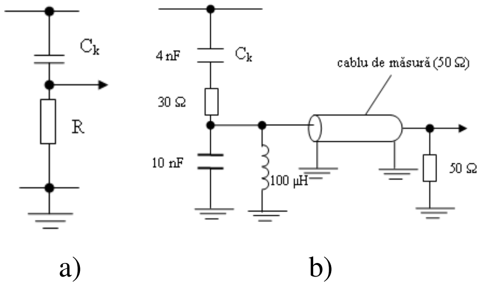

Fig.3 High-passive filters with passive circuit elements a) filter type R-C b) high-pass filter used in industrial circuit diagrams

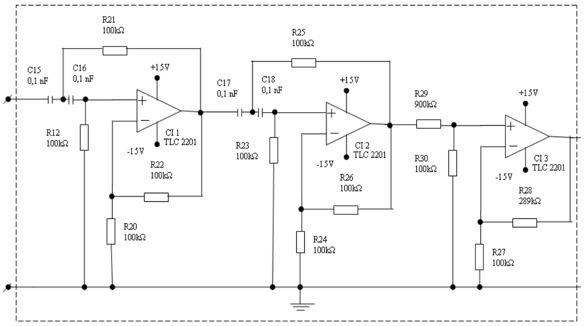

Fig.4. The electric circuit diagram of the active high-pass Butterworth type filter of the 4th order

Modelling the PD measurement with the OWTS testing

In view of studying the behaviour of the circuit diagram for measuring PD in MV cables with internal defects using OWTS, a SPICE model of the testing system [5,6] was achieved. An MV cable of NA2XSY type, with XLPE isolation and a 120 mm^2 section, U_N = 12 kV and a length of 700 m was considered that was modelled by using a quadripole type-model in symmetrical Π (pi), divided in fourteen identical cells. For the defect, a capacitive type model was used, presented in fig.6 in which C_y represents the sound part of the cable and C_x represents the part affected by the defect.

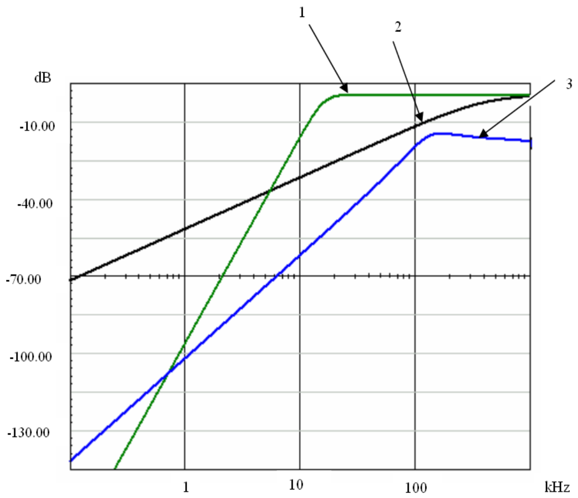

Fig. 5 Frequency characteristics for diferent high-pass filter
1. active high-pass filter type Butterworth of the 4th order;
2. passive high-pass R-C type filter (fig. 3.a);
3. passive high-pass filter for industrial use (fig.3 b)

In view of a comparative study, three dimensions of internal defects were considered, from low values, ≤ 1mm, to values that are considered high of 10 mm, for which the corresponding values for C_x and C_y were calculated, considering capacitors of a parallel plan type, in table 1.

Table 1

Small dimension defect	**Medium dimension defect**	**High dimension defect**
C_x = 0.088 pF C_y = 0.5 pF	C_x = 0.442 pF C_y = 2.5 pF	C_x =0.884 pF C_y = 5 pF

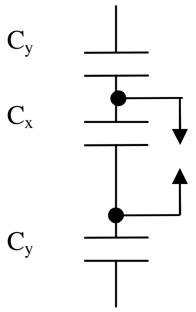

Fig. 6 Capacitive model for the defect in isolation of the cable

In view of studying the behaviour and stability of the sensibility of the circuit diagram of measuring the PD signals, an unfavourable case to the measurement process was chosen, namely a defect located closer to the free end of the cable, thus which is located farther from the measurement point, taking into consideration that the PD signals, of high-frequency, are attenuated in the propagation process.

The modelling results are presented in fig. 7 and fig. 8 [5].

From analysing the results (fig.7), it is observed that the passive industrial type high-pass filter achieves a good adaptation of the signal acquired, the amplitude of the attenuated voltage being of 10-15mV, however insufficient for assessing the presence of the PD signals produced by the medium and small dimension defects (curves 3 and 4)

The analysis of the results presented in fig.8 shows, in case of using the active filter type Butterworth of 4th order, a very good filtration of the attenuated alternative voltage (zero line), which underlines the presence of the PD signals, in this case the signals for high dimensions defects being well visualized (curve 2), as well as the small and medium dimension defects (curves 3 and 4).

The results of these computerised modelling are in concordance with the estimated behaviour of the respective types of high-pass filters, as they are in conformity with the form of the frequency characteristics presented in fig. 5.

In fig. 9, a modern and efficient circuit diagram is presented that is applied in practice for measuring PD by using active filters similar with the one suggested.

This circuit diagram (fig.9) provides at the exit from the classic coupling impedance (C_k, Z_m) a chain of optical separation which ensures the elimination of common type disturbances as to protect the active filter (FA). The optical chain (block E/O, optical fiber, block O/E) is capable of transmitting broad band analogue signals (DC-2.5 MHz) on optical fiber. The electric signal from the output of the optical chain is transmitted simultaneously to the active filter (FA) described above, as well as a low-pass filter (FTJ) for measuring the alternative tension applied to the testing cable. Both signals are visualised on a PC screen.

The diagram also provides protection by installing a spark gap (D).

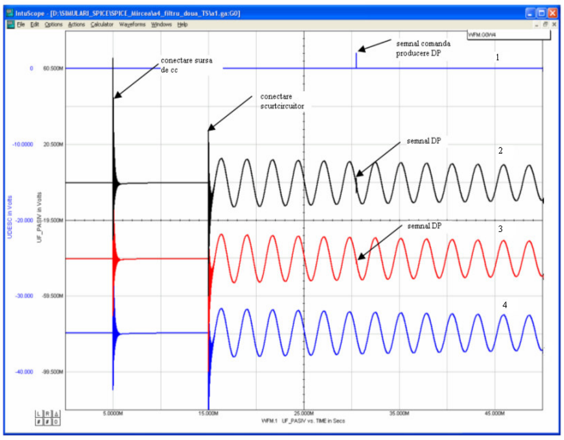

Fig.7 The PD signals taken over when leaving the passive industrial type high-pass filter (fig.3 b)
1) the command signal for PD; 2) the signal for high dimension defects; 3) signal for medium dimension defects; 4) signal for small dimension defects.

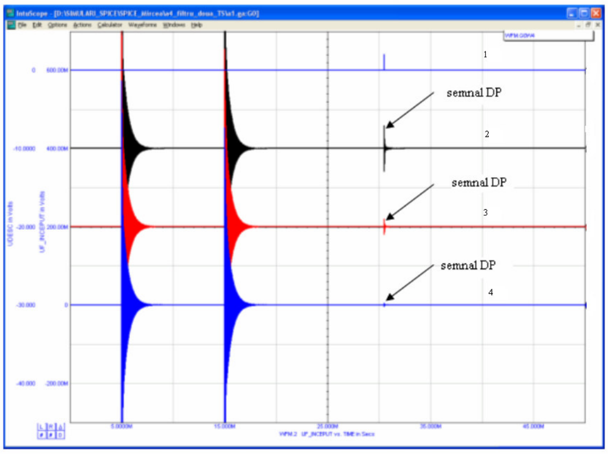

Fig. 8 The PD signals taken over when leaving the active filter type Butterworth of the 4th order
1) the command signal for PD; 2) the signal for high dimension defects; 3) signal for medium dimension defects; 4) signal for small dimension defects.

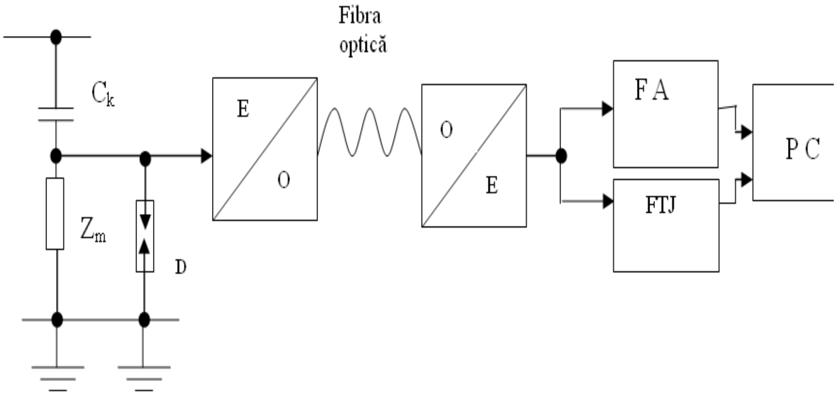

Fig. 9. Circuit diagram for measuring PD using optical fiber transmission

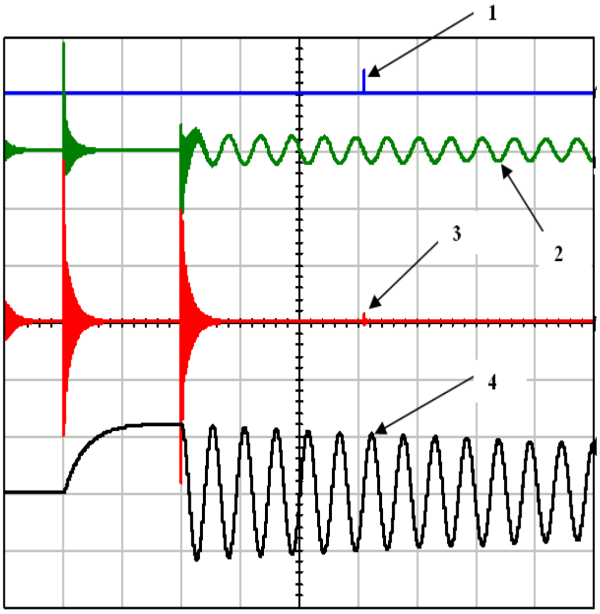

Fig.10. The results obtained in case of perturbations produced by an electro-magnetic induction along the cable

1) commanding signal for PD; 2) signal in the output from the passive industrial filter (fig.3); 3) signal in the output from the active filter type Butterworth of the 4th order;
4) the form of DAC voltage applied to the cable.

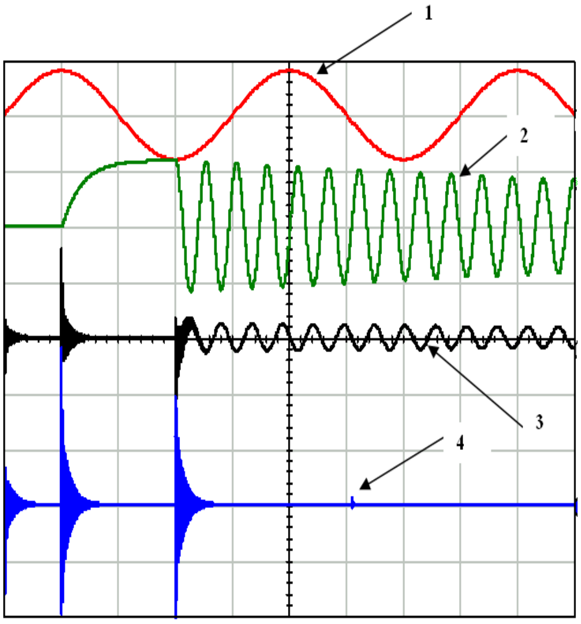

Fig. 11. The results obtained in case of perturbations produced by an external electrical field (f=50Hz)

1) the form of voltage produced by the external 50 Hz frequency perturbing source; 2) the form of DAC voltage applied to the cable; 3) the signal in the output of the passive industrial filter (fig. 3). 4). signal in the output from the active filter type Butterworth of the 4th order

4. THE INFLUENCE OF ELECTROMAGNETIC PERTURBING FIELDS IN THE PD MEASURING PROCESS

In concrete situations from the current practice of evaluating the isolation state of the MV and HV cables by measuring the PD level, the measurements may be influenced by the existence of the electromotive perturbing fields in the respective areas.

In view of studying the influence that these electric and magnet low frequency fields may embody (the frequency of the 50 Hz network) upon the circuit diagram for measuring PD, the SPICE model of testing electric cables with OWTS was considered, which is described in [5], taking into consideration that in the tested cable, a medium dimension defect exist (table 1).

Two possible situations were analysed, namely: 1) a case in which in the tested cable, in all its length, perturbations are induced at a 50 Hz frequency from the magnetic field of a cable in function and the proximity of the one tested; 2) perturbations, upon the terminal of the cable connected to the circuit diagram measurement, produced by the electric field of the HV equipment existent in the power station.

The perturbations produced by the electric field of the MV or HV equipment existent in the power station were simulated in SPICE by means of a voltage source with f=50 HZ and a coupling capacitor C=10 pF, connected to the terminal of the cable where the measurement performed, thus resulting a perturbing electric filed E= 2,000 kV/m.

The results obtained are presented in fig.10 and fig.11.

The analysis of the results obtained and presented in fig.10 and fig.11 show a good behaviour of the high-pass filters studied regarding the rejection of low frequencies (50 Hz) introduced by external perturbing sources, illustrating the perfect functioning of the active Butterworth type filter of 4th order which ensures a good attenuation of the low frequencies signals and a superior filtration at a high frequency (PD signals of high frequency may be evidenced).

5. CONCLUSIONS

The evaluation of the PD level in the isolation of electric cables and accessories (junctions and terminals) constitutes a modern and efficient modality in the prophylactic activity of discovering defects in the isolations of electric equipments, of observing their evolution in time and the ageing degree.

The usual industrial circuit diagrams used for measuring the PD values utilise a high-pass filter with measurement impedance achieved with passive elements (fig. 3a and b) which have the role of rejecting the low frequencies introduced by the voltage supply, as well as its harmonics, to let the PD high-pass frequency signals enter, as well as a voltage divider for the input signal in the electrical measuring instrument.

In this paper a studio was presented which evidenced the fact that, in case of electric cables, which have a powerful capacitive character, the classic diagrams with measurement impedances with passive elements utilised at PD measurements are not able to ensure the necessary sensitivity for properly measuring the high-frequency signals.

The improvement of these circuit diagram measurements require the introduction along the high-pass filter and an active high-pass filter achieved with operational amplifiers. In this paper an active filter type Butterworth of the 4th order is proposed (fig. 4).

The analysis of the frequency characteristics for the passive and active filters studies evidenced a good functioning of the active filter which ensures a powerful attenuation of the low-frequency signals, as well as a zero attenuation in the domain of the high frequencies (in the domain of the frequencies characteristic to the PD signals).

Following the SPICE modelling of testing electric cables with internal defects, by using OWTS, the previous conclusion regarding the behaviour of the passive measurement impedances has been better illustrated. Thus, taking into consideration three dimensions for the existent defect in the cable isolation, the low sensitivity of the circuit measurement diagram that used the passive impedance for measuring (only PD signals for large defect could be evidenced) was observed, compared with the results obtained at the output of the active filter proposed (PD signals were evidenced, even for small dimension defects, as well as incipient defects, fig. 8).

The results of the SPICE modelling of testing electric cables with OWTS in the conditions of certain existing low-frequency perturbing factors (electric field or voltage produced by magnetic induction) are relevant by the fact that these factors do not influence the sensitivity of the circuit measurement diagram, as it behaves similarly to the ideal case where these perturbing factors are absent.

In this paper a modern circuit diagram for industrial use (use of optical fiber, active filter etc) is presented when measuring PD by means of an alternative voltage or damped ac voltage.

The results obtained in this paper by SPICE modelling are important for the analysis of real situations which may arise in the actual practice of PD measuring in electric cables, situations which are difficult, sometimes impossible to achieve and also very expensive in the trial performed in lab conditions.

The results and proposals presented in the paper have a general character namely they may be applied without restriction also in the case when the AC test voltage is applied permanently and irrespective of the test object..

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