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# On-Site Surveillance of Potential Transformers by Means of PD-Measurements

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## ABSTRACT

A method is proposed and described to execute electrical partial discharge measurements on potential or combined potential/current transformers placed within outdoor substations in situ. The method was developed for a periodic surveillance of such instrument transformers, which may be useful if there is reason to assume that the life-time of the instruments draws to a close. Due to practical experience in applying this method in substations up to 420 kV nominal voltage, a PD-sensitivity of at least 10 pC can be reached.

Keywords: On-site surveillance; partial discharges; instrument (potential, current) transformers.

## Introduction

In general, the potential and current transformers or combined PT/CT's are reliable components of our outdoor h.v.-transmission and -distribution system, and there is no need for any sophisticated surveillance system during operation. In spite of this fact, there are many situations in which a periodic quality control of the insulation systems for such components is adequate. For example, a lot of quite old PT's are in operation and even with new types of equipment efforts for an additional quality control are justified if, for example, an unexpected high failure rate can be related to certain types of equipment, in which some fundamental design erros have to be assumed to have caused the breakdowns.

Some years ago, the unusual increase in the failure rates of PT's in some outdoor substations of the Swiss power transmission system /1/ initiated the request for an easy-to-apply diagnostic test of the electrical insulation systems. There was general agreement between utility companies and manufacturers, that such tests should always be made "on-site" to reduce the time and expenses for testing as much as possible.

Dissolved gas analysis, dissipation factor measurements and PD-measurements have been taken into consideration for such surveillance tests, i.e. methods which are able to indicate at least a badly aged insulation system. A periodic dissolved gas analysis /2/ is, indeed an acknowledged method, now being increasingly applied also to measuring transformers. As far as dissipation-factor measurements are concerned, it is well known that the sensitivity may not be high enough to indicate the early stages of degradation of insulation. The methods for performing such measurements on-site, however, have been developed /3/. As for such measurements, the PT's have to be disconnected from the transmission voltage, the idea to perform much more sensitive electrical PD-measurements was also supported, though the first efforts to solve the necessary noise-suppression by means of pulse discrimination systems have not been successful. Investigations related to the PD-current pulses emanating from partial discharges in h.v. potential transformers, made under laboratory conditions, however, showed that on-site testing should be possible by applying well known balanced circuits. Results achieved in such investigations may well be omitted here, as the following presentation of the method finally applied can well be understood.

The first successful on-site PD-tests on PT's were made in 1984 in a 220-kV-substation close to the city of Zürich/Switzerland. Since this time, enough experience has been gained to promote this method in general. However, no advice can be given up to now as far as the interpretation of the results is concerned, i.e. whether or not a certain level of measured PD-quantity (in pC) may be too dangerous for the apparatus. This question is still under consideration and it could only be answered finally after some further years of experience, i.e. by correllating the results with real life-time of the PT's.

## The Test Circuit

The main difficulty in performing PD-measurements on-site within an outdoor installation is introduced by electromagnetic interference and noise, the origin of which is well known. The measures taken to suppress all significant types of noise are best explained by presenting the applied test circuit in advance, as shown in Fig.1: In general, a set of 3 single-phase potential transformers, which are erected on supports within the substations, will form a h.v. measuring group. As it would be too expensive to remove the PT's from their posts, and as proper PD-measurements should be made as a function of voltage magnitude, up to some higher voltage levels than nominal, it is necessary to disconnect the h.v. connecting cables to the busbars, which can easily be tied back or removed. The first of some essential methods to suppress interference is now to establish between two of the three units each the h.v. arm of a balanced PD-circuit, which can be easily done at the h.v. terminals of two instrument transformers standing side by side, by linking both with a cylindrical high voltage connection, which can be of telescopic type. This bar should have a diameter such that it is PD-free, during voltage application. As the insulation system under test is always related to the primary or h.v. winding of a PT, the low voltage ends of these windings, which are earthed during normal operation, are the terminals to be connected to the low voltage arm of the bridge circuit. In general, these terminals are terminated on small bushings and readily available, so that the earthed transformer housings need not be isolated from ground.

This balanced PD-testing circuit established so far can be excited by an additional h.v. testing transformer as is usually done during a PD-test in laboratories. As, however, PT's or combined potential/ current-transformers can be much more economically self-excited by its secondary- or lower voltage windings, only this method has been applied up to now, as shown in Fig. 1. The voltage ratios of PT's of equal construction are always equal und thus either parallel or series connection of the low voltage windings is possible. In both cases, only general purpose, low voltage regulating transformer ("variacs") are necessary, which in general may be fed from any low voltage power point (mains socket), available in every substation. Thus, excitation of the PT's made by its nominal frequency (but see below). The power rating necessary for the variac is not high (∿ 10 kVA), though at least PT's for high nominal voltages (i.e. 400-kV-systems) need currents up to some 10 Ampères if testing voltages become much larger than the nominal voltages. As these currents are mainly capacitive wattless currents, the power rating of the variac can still be small if reactive power compensation is made by means of a low voltage inductance (choke), as can be seen in the circuit diagram. Such chokes for low voltages are small and inexpensive.

If tests shall be performed with voltages much higher than nominal, the magnetic core of PT's will be saturated with nominal frequencies. Therefore we use quite often instead of a variac a small motor-generator unit to excite the test circuit with higher frequencies (up to about 100 Hz). The higher frequencies are generated by coupling the a.c. motor with the a.c. generator by a variable gear unit. Voltage regulation is made with the generator.

A further, very essential step for noise reduction is now to introduce an effective line filter within the low voltage circuit and to provide an excellent shielding of this circuit behind the filters. The filters should be placed behind the variable voltage source, i.e. between the variac or motor-generator and the choke. By this, the filters, which are more expensive than the other low voltage components, are unburdened from most of the reactive power, and the noise voltages in general produced by the variac during operation are effectively reduced, as well as the noise from the mains and low voltage power cables. The filters used in our test circuit are rated for 380 V, 25 A, and provide attenuation of at least 100 dB in the frequency range between 14 kHz and 10 GHz.

The metal housings of the filters are now an integral part of a metal shield surrounding the choke and all wiring necessary to connect the choke and the low voltage windings of the PT's. As the length of these connections may be as long as 10 meters highly corrugated and thus very flexible metal tubes of commercial type are used for an effective shielding. The inner diameter of these tubes is large enough to run the flexible conductors through them. We use BOA-tubes (BOA AG, Luzern/ Switzerland), designed for mechanical applications (high pressures and temperatures; vibrations), made from stainless steel, with inner diameters of about 35 mm.

It is unnecessary to mention that these flexible shielding tubes must be tightly connected to the solid metal box made from copper plates containing the choke, thus forming a transportation unit. The other end of the flexible tubes are again connected as tightly as possible to the PT terminal boxes, which are in general, at ground potential. For further illustration, the design of the connection on both ends of the corrugated tubes are demonstrated in figures 2 and 3.

As mentioned before, balancing of the objects under test is an essential step for noise reduction. The application of a high-frequency "Schering bridge" as sketched in Fig.1 is very well suited for this purpose, though the effective reactance of the h.v. winding of the PT's is not at all a simple capacitor. This statement is confirmed by presenting a typical measurement result from laboratory investigations, during which external pulse-interference has been simulated in such a balanced circuit and the noise-currents at the low voltage end of the h.v. winding have been measured directly, by means of high bandwidth amplification (-3dB points: 50 kHz and 55 MHz respectively). Fig. 4 shows such a typical current-pulse (Fig. 4a), together with its normalized amplitude frequency spectrum calculated by FFT. Though different kinds of real PD's within the transformers and external noise sources will excite different shapes of these current pulses, they will be transmitted to the low voltage arms of the balanced circuit, the reactance of which is mainly due to the resistors ($G_L$, $G_R$, see Fig. 1). These resistors convert the currents into voltages, the difference of which is zero if both currents are equal in magnitude and shape. As for such short current pulses, the measuring cables interconnecting the bridge with the PT's are transmission lines and thus voltage reflections may occur, it is therefore very essential to use equal length of this coaxial cables. The capacitance, C, in the Schering bridge circuit (see Fig. 1) is, under ideal conditions, i.e. for complete symmetry of the whole circuit, not necessary. However, the balancing process shows that small values of C are necessary to achieve best noise suppression when $G_R$, $G_L$ are equal.

The frequency components of the noise-or PD-currents may be significant up to quite high frequencies, see Fig. 4b. An actual design of a high frequency Schering bridge, with its conductances $G_R$ and $G_L$ parts of which must be both step-wise and continuously variable, is not able to balance frequencies higher than some 100 kHz. As, however, the voltage across both bridge arms is the input quantity for bandpass-amplifiers, which integrate these voltage pulses to quantify the "apparent charge" (see /4/ and /5/), unsufficient balancing is not essential for frequencies, for which the bandpass-amplifier ist not sensitive. As so-called "wide- band" PD-detectors are made with upper cut-off frequencies not higher than 200...400 kHz, only the lower end of the spectrum (see Fig. 4b) is quantified. But this most essential part of the spectrum contains the "apparent charge" q of the PD-pulses /5/, so that no difficulties can arise. The same statement can be made for tunable narrow-band PD-detectors if a center frequency is used, which is still within the range of possible balancing (about 50 kHz to 1 MHz). As is shown later, the application of narrow-band-detectors in combination with such a bridge circuit is sometimes of great advantage. The design of a new commercial type of a PD-detector was partly influenced by experiences made during such on-site tests /6/.

A description of the test circuit explained so far may be completed with reference to the coaxial measuring cables linking the PT's with the bridge circuit: This cables must be of high quality and double shielded, with an adequate insulation between the two braided shields. Due to grounding of the shields at least at the PT-ends, the outer shield will conduct cable shield (noise) currents, and the so called "coupling impedance" of the cables /7/ must be small enough to avoid noise signals otherwise induced into the signal path. If simpler cables are used, one should provide an additional shield, for instance with corrugated metal tubes as done for the power supply cables.

## Measuring and Calibration Process

As the equipment necessary to perform the measurements is neither large nor too heavy, a general purpose van fits all requirements for transportation and control of the equipment (PD-bridge-detector, variable transformer, filters and chocke etc.). The small van can easily be placed alongside the PT's to be tested, and if the PT's have been disconnected from the busbars before, the necessary connections and measurements can be made within a short time (see Fig. 5).

PD-measurements are carried out following IEC-270 recommendations: The bridge circuit is first balanced by a standard calibrator placed between the center of the high voltage connection bar and ground potential. The calibrator, however, should be able to withstand some hundred volts a.c. which can be induced at the h.v. terminals due to capacitive coupling from the h.v. busbars of the substation. After removal of the calibrator, the rejection ratio may easily be quantified by setting the bridge to a straight detection mode, i.e. by short-circuiting $G_L$ or $G_R$. The remaining noise level can then be measured by the calibration of the circuit as usual, i.e. the calibrator is connected across the h.v. winding of one of the PT's only (see Fig. 1). Experience shows that the quantified noise level is always well below 10 pC; even with heavy corona at nearby busbars.

The origin of the noise can well be evaluated by displaying the noise-signals on a cathode-ray oscilloscope and synchronizing the display with test voltage or h.v. busbar voltage frequency. Many PD-detectors provide the possibility of doing so. If, with a convential wide-band amplifier applied, the noise signals recorded are continuous and "modulated", still strong broadcast radio interference may be present. Then, a narrow-band amplifier should be used which can be tuned to a center frequency not occupied by broadcast. This will always be possible within a frequency range between about 50... 500 kHz. Note, that the bridge must then again be balanced for the center frequency used to take advantage from best noise rejection.

## Additional Remarks to Noise Reduction

As mentioned above, noise levels during PD-measured can be reduced such that partial discharge levels of at least 10 pC or lower can well be detected. This result is based upon measurements made on more than 30 instrument transformers (PT or PT/CT-combinations) rated for nominal voltages between 220 and 420 kV. This surprisingly low disturbance level, however, can only be reached if the instruments are not wetted by rain, and if the metal housings and h.v. electrodes are free of PD's up to the testing voltage applied. Therefore, after rain the porcellain bodies have to be dried and if metal parts produce external partial discharge, additional electrodes for field stress control must be provided. Such external partial discharges which are strongly electrically coupled to the inner insulation can, of course, not be distinguished from inner PD's by this or any other bridge circuit.

The disturbance levels of even quite strong corona discharges appearing at the busbars of the substations, however, are effectively reduced by the bridge circuit. This can well be understood as these impulsive disturbances are only capacitively coupled to the whole circuit under test. Induced voltages at the high voltage part of the circuit are thus common-mode voltage pulses across the balanced circuit and are, therefore, very well attenuated, as the impedances effective for both bridge arms are identical. As all wirings of the low voltage power and measuring circuits are well shielded, the noise currents induced by the electrical field coupling will also not disturb the measurements.

If a so-called "wide-band" PD-detector is used in combination with the balanced circuit, there remains only one main source of disturbance level, provided by radio transmission, i.e. by electromagnetic waves. It is well known that radio waves are travelling by the interaction of the magnetic and electrical fields, and that the electrical field components for waves in the frequency range which would disturbe wide-band PD-detection (i.e. about 100 kHz - 2 MHz) are orthogonal to the ground surface, whereas the magnetic field components are in parallel. Therefore, the electrical field component induces common-mode voltages only which are suppressed by the circuit. The magnetic field, however, will induce circular currents within the loop established by both instrument transformers standing side by side. Depending upon direction of this loop with reference to the travelling direction of the electromagnetic wave (EMW) the magnitude of induced voltages and currents can be low or high. As EMW's may arrive from divergent directions, and as it would be too difficult to turn the loop in a most convenient direction providing lowest induced voltages, application of a tunable narrow-band PD-instrument is the simplest way to get rid of disturbances of such a kind. Therefore, the combination of a blanced circuit with a tunable narrow-band instrument /6/ is an excellent solution for on-site PD-measurements.

## Literature

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## RESUME

Le nombre de transformateurs de mesure est grand dans le réseau haute tension, mais les dépenses pour chaque transformateur particulier ne sont pas trop élevées. Donc l'effort technique pour le contrôle courant ou périodique de ces transformateurs ne peut pas être poussé trop loin. Cependant, si les transformateurs de mesure en service sont déjà bien agés ou si le taux de défaillance des transformateurs nouveaux est plus élevé que la normale /1/, il s'avère opportun de vérifier la rigidité diélectrique si possible sur les lieux d'installation (normalement des installations extérieures).

De nos jours les contrôles périodiques sur les lieux d'installation se font ou bien par une analyse des gaz dissolus dans l'huile isolante /2/ ou bien par une mesure du facteur de pertes /3/. Comme cette dernière méthode ne donne que des résultats très discutables sur l'état des transformateurs de mesure, on essait aussi de mesurer les décharges partielles sur les lieux d'installation.

La présente contribution décrit en détail une méthode de mesure basant sur les décharges partielles pour les transformateurs de mesure (tension ou tension et courant combinés, voir fig. 1). Les transformateurs de mesure ne doivent pas nécessairement être retirés des lieux, mais la connexion au réseau haute tension (ou à la barre collectrice) doit être enlevée. L'excitation des transformateurs de mesure se fait par une basse tension à fréquence variable appliquée au côté secondaire. On reçoit une réjection de la tension de perturbation très poussée en soignant le blindage du circuit excitateur et en faisant usage d'un montage en pont en utilisant deux transformateurs semblables reliés au côté haute-tension du pont. Des détecteurs de décharges partielles à large bande ou à bande étroite ajustable peuvent être utilisés comme "indicateur de zero". Les raisons qui mènent à l'emploi de l'un ou de l'autre détecteur sont décrits ainsi que tous les détails nécessaires pour la construction des circuits d'épreuve et de mesure (voir fig. 2, 3 et 5).

Avec ce principe le niveau de bruit peut être réduit nettement au-dessous 10 pC, ce qui permet la détection de décharges partielles avec une sensibilité d'au moins 10 pC, et cela dans des installations extérieures jusqu'à 420 kV.

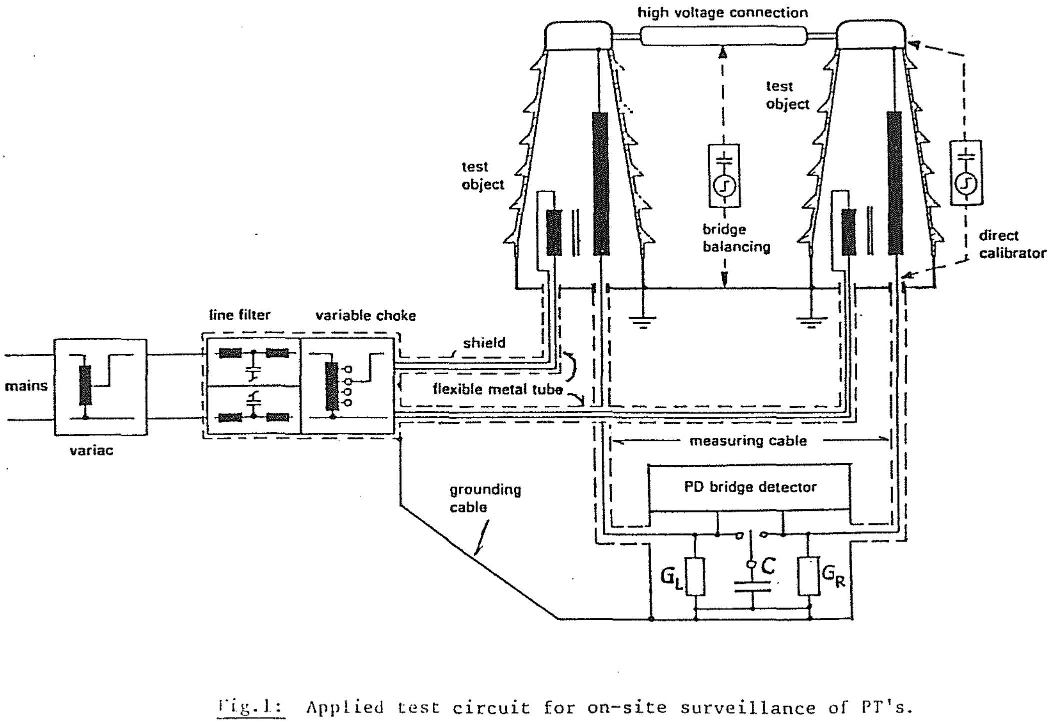


Fig.1: Applied test circuit for on-site surveillance of PT's.

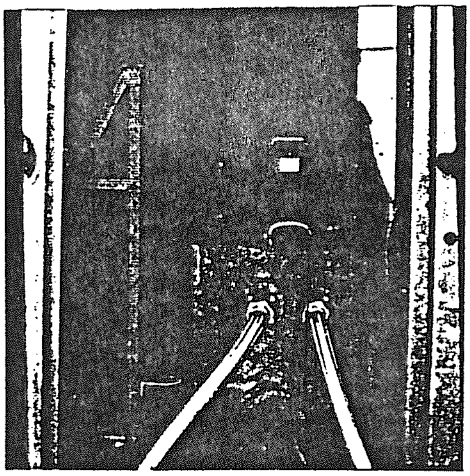


Fig. 2: Connection of flexible metal tubes with metal housings for filters and choke.

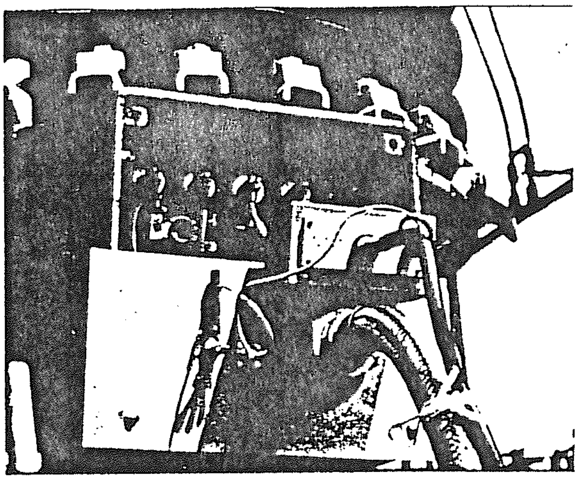
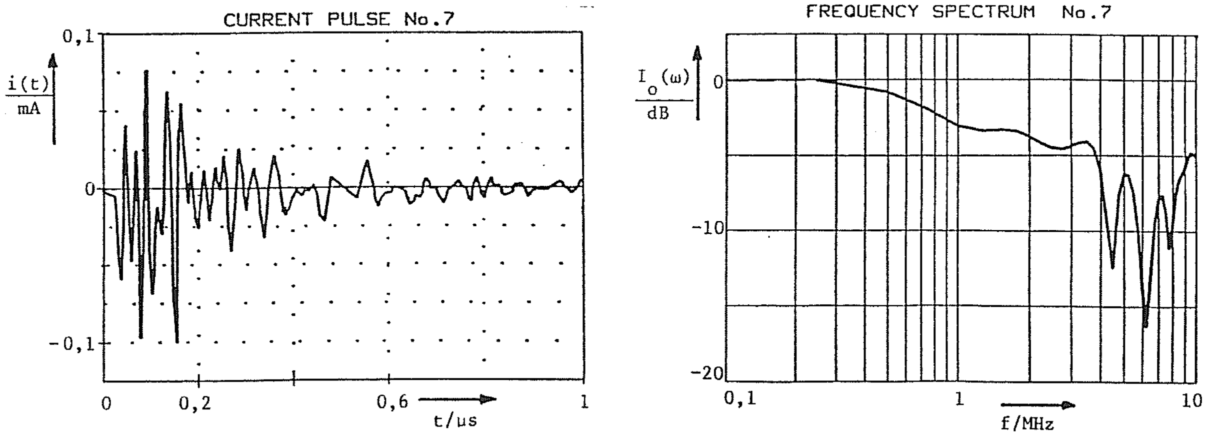


Fig. 3: Connection of flexible metal tubes and measuring cable with earthed PT-housings.



a)

b)

Fig. 4: Typical interference current pulse (a) and its normalized amplitude frequency spectrum (b) measured at low voltage end of the h.v. winding of a PT.

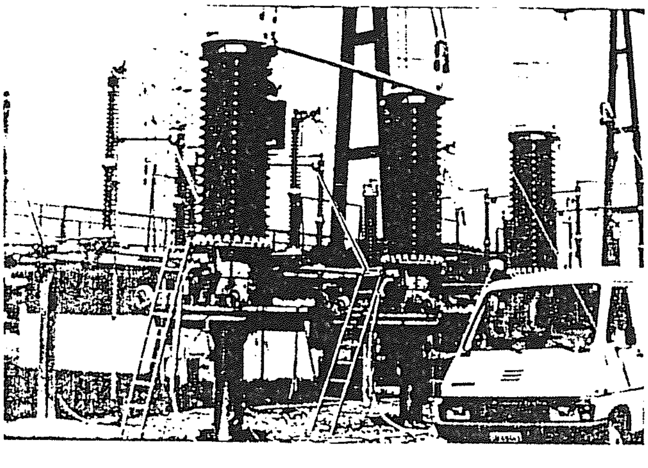


Fig. 5: The van used for transportation and control in front of a group of instrument transformers (combined PT/CT, 245 kV) within a 245/420 kV outdoor substation.