Advanced Methods of UHF EM Diagnostic of Discharge Activity in High Voltage Transformers Dielectric

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Abstract— One of the crucial aspects of high voltage power transformer is the quality of its dielectric oil filling. Partial discharges represents significant problem which can lead to serious transformer failure and accident. Variety of methods for early detection of partial discharge has been developed over time. The most progressive is the UHF method. The article reports on the results obtained by the application of new Discrimination of Disturbed Acquisition detection approach within the UHF method. Further, proposal of novel modification of sensors are described. The approach consists in the adjustable signal filtration before processing, which can significantly improve the reliability of partial discharge signal identification.

1. INTRODUCTION

The reliable and economical production and distribution of electrical energy and safety impacts of these processes are crucial aspects of sustainable development in industry and generally the human society. The energy production and distribution chain comprises of various blocks with specific functions and the safety and reliability of each of the blocks are under intensive monitoring. The key component of the chain is the block transformer in the power plant. It is carrying high electrical power under very high voltage conditions. Therefore, the condition of its oil dielectric is carefully watched in order to prevent the development of partial discharges (PD). PD in oil represents an electrical discharge activity at the microscopic nonhomogeneities — e.g., released microbubbles of dissolved gasses. The oil degeneration due to PD activity rapidly deteriorates its insulating properties which can lead to subsequent intensive arc and catastrophic transformer failure.

Various methods have been developed over time [1]. Currently the most advancing is the ultra-high frequency (UHF) method which is based on the real-time detection of electromagnetic radiation generated by PD [2, 3]. Moreover, this approach allows also the time-difference-of-arrival (TDOA) localization of PD source [4]. We have previously reported the development of PD diagnostic system based on the UHF method, including TDOA localization and we have presented results of real field measurement on the nuclear power plant's transformers [5]. Despite of the common view of the UHF method, which assumes excellent sensitivity due to transformer's vessel shielding properties against outer interference, we have noted low-level signal detection difficulties [6]. They are caused by the influence of discharge activity in the encapsulated feeding lines which connect the transformers with turbo-generator system. We have developed a new method for weak PD signal detection which utilizes discrimination of disturbed signal acquisitions. The method was verified by field measurement of very weak injected artificial impulse signal. The results indicate that the sensitivity down to tens picocoulombs can be achieved [6].

In the article we report on results obtained be the new detection method application. The steps of procedure of method application will be described also. Further advances of the method represents the discharge radiated signal filtration with the goal of separation of the frequency band which are typical for rapid PD and the suppression of frequency bands occupied by components of different electrical discharge types. This advancement further enhances the sensitivity and reliability of the UHF method with discrimination of disturbed signal acquisitions approach.

2. PD DIAGNOSTIC SYSTEM

We have developed a diagnostic system for UHF EM detection and localization of PD in high voltage power plant transformers. The system consists of main unit (Fig. 1(b)) and five RF sensors. Four sensors are designed for installation in the inlets in the transformer vessel (Fig. 1(a)). The fifth sensor serves as outer sensor (Fig. 1(c)). The system is equipped with diagnostic software (Fig. 1(d)) which displays impulse signals waveforms, occurrence in phasor, elliptical and sine diagram. The software and also computes the signal source localization by means of time-difference-of-arrival (TDOA) methods.

The PD sources electromagnetic RF radiation with spectral range from hundreds of MHz to units of GHz. The above described system has analog bandwidth of 1 GHz, which is sufficient for PD impulse signal acquisition. Since the lower bound of PD apparent charge is very low (tens of picocoulombs (pC)) a cascade of amplifiers is installed in the RF sensors, together with variable attenuator and signal limiters. Careful shielding of the main unit and sensor casing and triaxial transmission cables are used in order to achieve highest EM imunity.

3. LOW LEVEL PD IMPULSE SIGNAL DETECTION

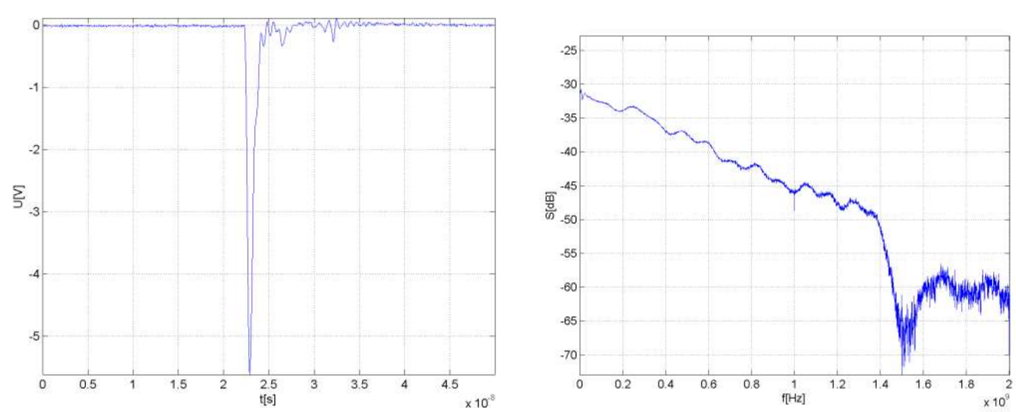
It is often mentioned in the literature that the metal transformer vessel ensures convenient shielding and hence the low level PD signal is easy to detect. However, we have realized within our experiments and real field measurement that serious problems are caused by the discharge activity in bushings. The interference can also penetrate via bushings expansion collars and via slits around the sensor case connection. Therefore a good shielding has utmost importance.

The PD occurrence in the transformers dielectric is a serious condition. Therefore the PD activity is carefully monitored. The initial PD activity exhibits very weak EM signal, hence the diagnostic sensitivity and selectivity has to be maximized by means of advanced methods. For testing and calibration of the system, a source of artificial impulsed signal has been developed. The negative going impulse with fall time under 300 ps and FWHM (full width at the half of maximum) of 700 ps has a peak value of −5.9 V. The impulse waveform is shown in Fig. 2(a). The radiated impulse has simulated the EM signal generated by PD in view of its waveform, time duration and spectral characteristic also. The calculated amplitude spectrum of the impulse is shown in Fig. 2(b). The impulse generator has been built into the shielding cover and equipped with the same antenna as the sensor.

Since the artificial impulse simulates the PD transmitted EM signal, it is possible to assign an apparent charge to it. In order to evaluate the equivalent apparent charge a simple, straightforward calculation was performed. It assumes that the PD represents a charge transport through certain

(a) (b) (c) (d)

Figure 1: (a) RF internal sensor, (b) main system unit, (c) external sensor, diagnostic software.



(a) (b)

Figure 2: The waveform of (a) the artificial impulse signal and (b) its magnitude spectrum.

impedance. The similar case is the charge transport through the input impedance of impulse transmitting antenna. The difference is that the electromagnetic radiation effect will be more efficient in case of PD, since the antenna reflects some portion of the signal due to non-perfect matching. If we for simplicity consider a real character of antenna's input impedance Z_i, we can deduce the current waveform through this impedance $i(t) = u(t)/Z_i$. The waveform will be same as in Fig. 2(a). The current is defined as the transported charge during a time interval $i(t) = dQ(t)/dt$. It can be deduced from previous relations that the total charge transported through the antenna's input impedance is $Q = (1/Z_i) \int u(t)dt$. This rapidly transported charge causes an electromagnetic wave radiation as in case of PD. If we apply the charge relation on the voltage waveform in Fig. 2(a), we find the charge value $Q = 94\,\text{pC}$ in case of perfect antenna matching. In real case, we obtain radiated wave, which equivalent apparent charge is lower than 94 pC. For given antenna with known reflection coefficient the estimated apparent charge will be 30–50 pC.

In standard mode of the system operation the artificial impulse signal was not detected due to presence of strong impulse interference. Therefore novel detection method has been proposed and tested.

4. DISCRIMINATION OF DISTURBED ACQUISITION METHOD

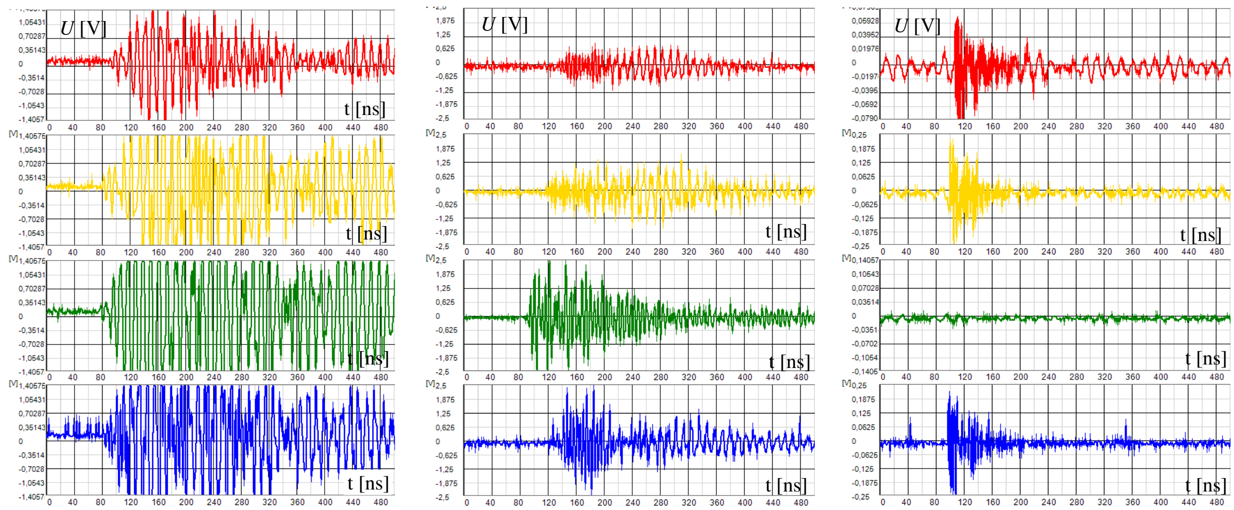
In order to allow the detection of the low level EM impulse signal with the presence of strong impulse disturbance a new Discrimination of Disturbed Acquisition (DDA) method has been proposed, tested and implemented in the diagnostic software.

The DDA method exploits the multi-trigger ability of the diagnostic system — the signal acquisition can be triggered by the signal threshold-crossing in any of the four channels simultaneously. The external sensor is connected on the one input of the main unit, instead one of the internal sensor. Now only three internal RF sensors are utilized for localization. Nevertheless, this is sufficient for the signal source localization. The external sensor is positioned as best near the place where the outflow of impulse disturbance is expected. Typically near the expansion collar in the feeding bushings. Further, the signals acquisition procedure is initiated and the RF sensor gain is set on suitable level. The strong disturbing impulse signal propagates inside the vessel to the internal RF sensors and also outside the vessel, where is captured by the external RF sensor. The strong signal may override the weak PD signal on the internal sensor. Subsequently the signal gain of the internal sensor is increased in such ratio that also weak signal begin to trigger acquisition. In order to resolve the relevant acquisitions a sorting operation is performed — the acquisitions which were triggered by the external sensor (acquisitions with strong disturbance) are discriminated from further processing. The remaining acquisition containing the desired weak signal are displayed and utilized for localization computation.

The examples of captured signals are shown in Fig. 3. Fig. 3(a) shows acquired waveforms of disturbing signal in the standard detection mode using four internal RF sensors. In the external sensor mode, the external sensor is connected to the third channel and it is positioned near the expected source of disturbance (bushings expansion collar). The waveforms acquired in this setup are shown in Fig. 3(b). It is apparent that: 1) the signal in the third channel comes first to the external sensor; 2) has greatest magnitude; 3) the other signals are dispersed in time. The first and second point causes the fact, that the external sensor was correctly positioned near the source of disturbance. The third point indicates that the disturbing impulse signal propagates through longer path to the internal sensors (through the bushing). The different mechanisms of propagation for different spectral components lead to different propagation speeds and the impulse is therefore dispersed in time. The frontal part of the impulse waveform is also only slowly rising due to strong attenuation of high frequency components of the impulse spectrum. When the DDA system mode is activated and the sensors gains are properly adjusted, we can detect the weak artificial impulse signal. The artificial signal waveforms are shown in Fig. 3(c). They have apparently shorter time duration in compare to disturbing impulse signals. This is because they propagate only in the transformers vessel and they don't undergo dispersion. They frontal part is also very steep in compare to disturbing signal.

It has to be noted that above described measurement has been conducted under full working condition of the high voltage transformer in the nuclear power plant. A very strong interference was present in this environment. Despite these conditions the very weak EM impulsed signal has been successfully detected and localized.

The efficiency of the DDA method depends on proper position of the external sensor and correct adjustment of the trigger threshold in the third channel. However the efficiency can be improved via



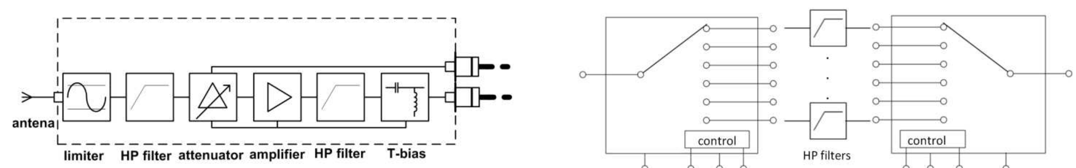
(a) (b) (c)

Figure 3: Acquired waveforms of disturbing impulse signal (a) in system's standard mode, (b) in the mode with external sensor connected to the third channel and (c) waveforms of detected artificial impulse in DDA mode.

combination with other supporting methods and improvements as described in the next chapter.

5. PRE-PROCESSING SIGNAL FILTRATION

The main differences between the impulse disturbing signal waveforms and artificial impulse signal waveforms were described above. These differences can be utilized in order to improve the reliability of PD signal detection. The differentiation in view of overall pulses duration has been implemented in the diagnostic software and it was successfully verified. Waveforms of disturbing signals have longer time duration because of the experienced dispersion. This approach disqualifies the impulse signals with long duration from further processing. Another approach can utilize the different spectral composition of the disturbing and the PD impulse signal. Since the disturbing signal lacks high frequency components a high pass filter might be utilized for its suppression. In fact a high pass filters are installed in each RF sensor as shown in simplified sensor block scheme in Fig. 4(a). However, they have relatively low corner frequency 80 MHz, which is not sufficient for attenuation of the disturbing signals.



(a) (b)

Figure 4: (a) Simplified and (b) its magnitude spectrum.

Therefore it has been proposed to complete the sensors with filters with suitable corner frequency. Since it is not possible to exactly determine the optimal value of the corner frequency, the adjustable filter has been proposed. In the intended frequency band (hundreds of MHz) is not trivial to fabricate a tunable filter. Therefore a set of switchable filters shown in Fig. 4(b) is intended for implementation in the sensors.

In order to examine the potentialities of adjustable signal filtering a numerical filtration of signal with disturbing component and also with the artificial component has been performed. The signal was acquired by the internal RF sensor installed in the transformer vessel at the sampling rate was 8 GSps. It has been further designed a set of nine FIR high pass filters with corner frequencies between 100 MHz and 900 MHz. The signal was processed by the filters and is has been examined the influence on the ratio between disturbing signal and artificial signal magnitudes. The results are shown in Fig. 5. Fig. 5(a) depicts signal without numerical filtering. Figs. 5(b), 5(c) and

5(d) depict signal after processing by filters with corner frequency 200 MHz, 300 MHz and 500 MHz respectively. The significant attenuation of the disturbing signal is obvious. Basically, in Fig. 5(d) only the artificial impulse signal is present and time of its occurrence can be determined by proper set threshold.

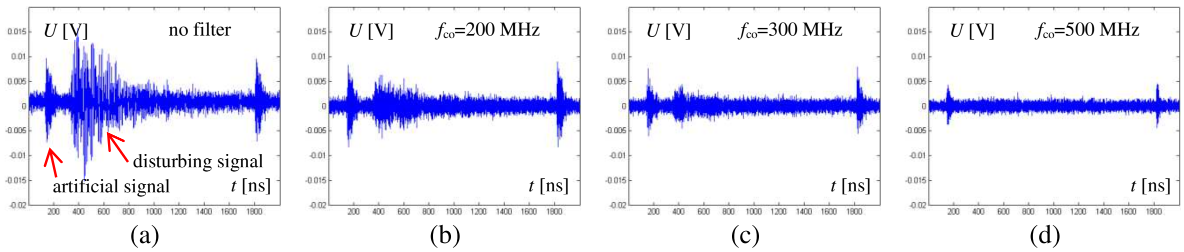


Figure 5: (a) Original signal with artificial and disturbing component and results of processing by filter with corner frequency (b) 200 MHz, (c) 300 MHZ, and (d) 500 MHz.

6. CONCLUSION

The UHF method is a very advantageous method for watching the PD activity in the high voltage power transformers. However, it has to be taken into account the influence of surrounding electromagnetic disturbance, which can baffle the PD signal detection. In order to avoid this problem a new method based on the discrimination of disturbed acquisitions (DDA method) has been proposed, verified and implemented. The DDA method has allowed detection of weak impulse signal and its source localization in conditions with intensive impulse disturbance. For further improvement of this PD identification approach a pre-processing signal filtration with adjustable corner frequency has been proposed a verified. The research work will continue toward the physical implementation of switchable UHF HP filter and its in-field verification.

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