NOVEL SENSOR SOLUTIONS FOR ON-LINE PD MONITORING

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ABSTRACT

The electric utility industry is going through significant changes caused by new regulation models, distributed generation, increased competition and requirements for continuous improvement in the quality of power supplied to the customers. To minimize outages and supply interruptions, utilities must be able to monitor and locate faults more quickly and to develop condition monitoring in a more preventive direction. On-line continuous partial discharge (PD) measurement is an excellent way to determine the overall health of the medium voltage (MV) cables. Essential parts of a PD monitoring system are the sensors for measuring the high frequency PD signal. The continuous on-line PD monitoring of MV cables is a problem, primarily because no adequate cost-effective sensor solution is available for permanent installation. The goal of this paper is to develop a low-cost, sensitive and robust sensor solution for continuous on-line PD monitoring of MV underground cable networks.

INTRODUCTION

As underground cables in cities are aging and cabling of medium voltage networks is increasing also in rural areas condition monitoring is becoming an important measure in preventing unplanned and long lasting interruptions. Especially, in rural networks it may be difficult to maintain the power supply via alternative network configurations during the fault location and repair. Thus, it is important to detect and locate incipient faults before they cause a supply interruption. Also legislative actions and regulatory measures are forcing the network companies to increase proactive network monitoring in order to prevent unplanned and long lasting interruptions. The best way for detecting incipient faults in underground cable networks is continuous on-line PD monitoring.

A Partial Discharge is an electrical discharge that only partially bridges the insulation between two conducting electrodes. Generally, such discharges appear as sharp pulses having time duration of less than 1 µs [1]. Partial discharge activity occurs at defects, such as air-filled cavities within the insulation material when the electrical field strength exceeds the breakdown strength of the insulation material. PD may deteriorate the electrical strength of insulating material which ultimately leads to the complete breakdown of the cable. PD detection is an important monitoring tool to avoid catastrophic failures of power networks and high voltage equipment.

Conventional off-line PD testing has been used for many years to evaluate the health of the cable. The significant disadvantage of carrying out off-line test is that they require power interruption. In contrast, on-line monitoring allows the network to operate in normal condition during the measurements. It is also more effective way to detect rapidly developing faults and thus prevent unplanned outages and possible equipment failure. On-line PD measurements for condition monitoring has not been economically possible in medium voltage networks because of the high cost of the equipment and resources needed [2].

Soft ferrite cores are used for effective coupling between electric current and magnetic flux. The most popular combinations are manganese and zinc (MnZn) or nickel and zinc (NiZn). These compounds show good magnetic properties. Ferrites have an advantage over other types of magnetic materials due to their high resistivity and low eddy current losses over a wide frequency range. These characteristics along with their high permeability make ferrite ideal for applications where the high frequency currents are measured.

This paper presents the design and testing of novel ferrite based low-cost high frequency current transformer (HFCT) sensor for continuous on-line PD monitoring. The main results of a series of laboratory measurements conducted on different ferrite cores with different winding constructions for sensing high frequency PD signals are presented. Measurements to characterize and compare the different HFCT constructions were conducted using a network analyzer, impulse source and digitizer and 50 Hz AC source. The effect of HFCT core material, winding configuration and air gap on the amplitude response, transfer impedance (sensitivity) and saturation characteristics are analyzed. In the end the performance of the developed HFCT sensors are compared with commercially available HFCT sensor and a sensitive Rogowski coil with active integrator.

Types of PD sensors

There are number of coupling techniques available for monitoring PD activity including coaxial cable sensors which can be installed at the cable joints [3], inductive HFCT transformers which can be clamped around the cable [4], directional couplers which can be placed on either side of the cable joint [5] and the Rogowski coil [6]. These coupling techniques work on different frequencies, ranges from tens of kHz to several hundred MHz. For the capacitive coupler and directional sensor, outer metal earth screen should be removed to obtain a discharge measurement. The inductive couplers on the other hand measure the magnetic field inductively and provide galvanic insulation. They can be installed without interrupting the power supply which makes it a popular choice for on-line PD measurement.

High frequency current transformer sensors

The basic principal of current transformer is to produce an alternating current in its secondary winding which is proportional to the alternating current flowing through its primary winding. HFCT sensors consist of a wound toroidal ferromagnetic core unlike the Rogowski coil which has an air core but both detect current pulses caused by PD through magnetic field. HFCT sensors may suffer from saturation if they are installed around the phase conductor and the phase current is high. The Rogowski has an air core so it does not saturate but their transfer impedance is poor when compared to HFCT sensor. The Rogowski coil also needs a digital integrator to obtain the primary current waveform. In contrast, HFCT has good frequency range and transfer impedance but poor saturation property. An effective PD sensor should be compact and easy to install, sensitive to tens of pC of PD level and have a high saturation performance.
Sensors are characterized by suitable frequency response for measuring fast and sharp PD pulses, transfer impedance which is the ratio between the secondary voltage and the primary current and the saturation current of the sensor in order to measure the PD pulse properly.
A series of laboratory measurements were performed on different ferrite cores to develop the best possible sensor.

SENSORS STUDIED

Novel HFCTs developed at Tampere University of Technology (TUT) were studied and compared with a commercially available HFCT and a Rogowski coil and analogue integrator developed earlier at TUT [6]. All the novel HFCTs were wound using an enamel wire of diameter 0.19 mm on different MnZn (M1…M3) and NiZn (M4) ferrite cores. The windings were spread evenly around the core. All the sensors were terminated into 50 ohm during the measurements.

AMPLITUDE RESPONSE

Measurement setup with the network analyzer

All the measurements were carried out using Agilent 4395A Network Analyzer combined with an S-parameter test set. The output of the network analyzer, port 1, was passed through the sensor and terminated into 50 ohm. Sensor's output was connected using a coaxial cable to the network analyzer's port 2. A full 2-port calibration was performed before the measurements in order to correct the systematic errors of the network analyzer [7]. After calibration, the S_{21}-parameter or forward transmission coefficient from 10 kHz to 100 MHz of each sensor was measured. It is important to characterize the performance of each sensor over wide frequency ranges to select the best possible option for PD measurement. The S_{21}-parameter describes how well a signal is coupled from sensors input to its output thus, it corresponds to the frequency response of the measured sensor [7].
Figure 1 presents the amplitude responses of HFCTs wound on 4 different ferrite materials with different winding configurations. For the sake of simplicity, materials are named as M1, M2, M3 and M4. All materials were studied with different winding configurations. For clarity only 3 configurations i.e. 4 turns, 9 turns and 20 turns are included in this paper.
As shown in Figure 1, the amplitude responses of all materials with 4 turns winding configuration are not as flat over higher frequencies as with 9 and 20 turns but their sensitivity is still better than other winding configurations. Amplitude response of M1…M3 with 20 turns configurations have similar flat response over wide frequency range until the sensitivity start to increase 3 dB to 4 dB, respectively then drops and finally resonance frequencies are reached. M4 with 20 turns has flat amplitude response only above 500 kHz. In comparison, response of M1…M3 with 9 turns winding configurations have flat amplitude response over wide frequency range until it reaches resonance frequency. Moreover they also exhibit good overall sensitivity and low resonance peaks when compared to other winding configurations. However, M4 with 9 turns has flat amplitude response only above 1 MHz and the resonance peak is also high. It is also evident from the curves that the resonance peak of all the materials regardless of their winding configuration appears in the frequency range 75 – 90 MHz which already gives quite good frequency range in the higher end to measure PD signals.

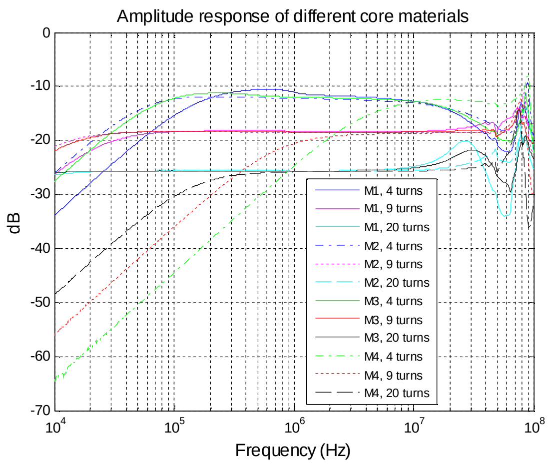

Figure 1. Amplitude response of different ferrite cores with different winding configurations

A good sensor should have high enough sensitivity and flat frequency response over wide usable bandwidth. It can be concluded from the curves presented in Figure 1 that M1 with 9 turns winding configuration seems to be the best choice among the materials as well as the number of turns. It exhibits high enough sensitivity, flat amplitude response between 30 kHz to 45 MHz as well as low resonance peak which is an excellent choice for PD monitoring.

Closed vs. split core

Closed core HFCTs cannot bear high current because of the core saturation. Split core increases saturation but it affects the frequency response and sensitivity of the sensor. Figure 2 depicts the comparison of the amplitude responses of M1 with closed core and split cores with 3 different air gaps size. The same 9 turns winding configuration was used in all cases. It is quite visible from the graph that air gaps affect the amplitude response of the core. Lower -3dB cut-off frequency which was around 30 kHz in case of closed core increases to around 100 – 200 kHz but still the amplitude response is quite flat over the frequency range of interest with air gaps of 0.1mm to 0.3mm. The working frequency range of M1 (as set by the lower and upper -3dB cut-off frequency) is between 100 kHz to 45 MHz which is quite promising to detect PD signals.

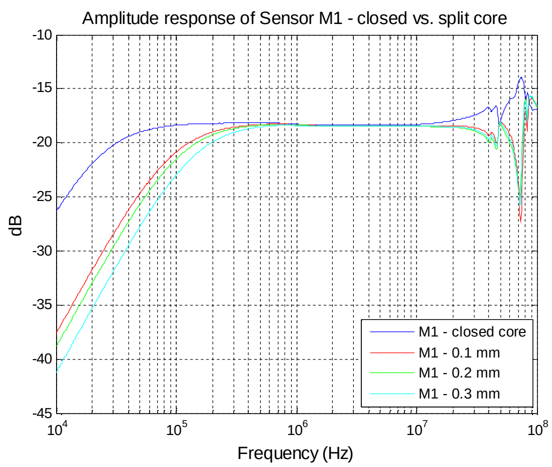

Figure 2. Amplitude response of Material 1, closed vs. split core with different air gaps size

Sensitivity and amplitude response

In the following section, sensitivity and amplitude response of the Rogowski coil, commercial HFCT and sensors developed at TUT using different core materials with 0.3 mm air gaps size are compared. With reference to Figure 3, M1 has good sensitivity as well as flat amplitude response which extend up to 45 MHz when compared to other core materials, commercial HFCT and the Rogowski coil. Commercial HFCT has flat amplitude response up to 15 MHz. However, the sensitivity is considerably lower when compared to M1 and M2 in the frequency range 90 kHz to 15 MHz. In comparison, the Rogowski sensor has the lowest overall sensitivity and unstable amplitude response at higher frequencies.

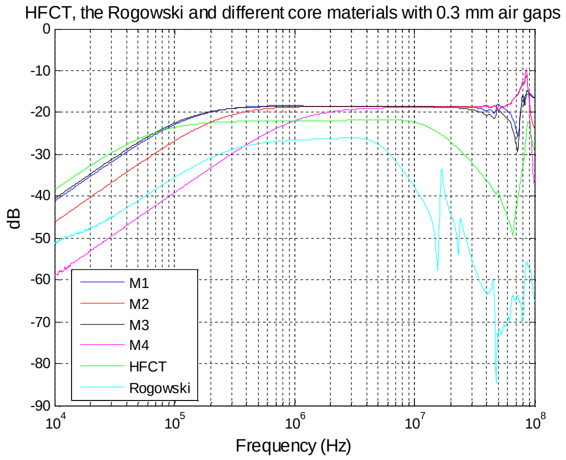

Figure 3. Amplitude response of commercial HFCT, the Rogowski coil and different ferrite cores with 0.3 mm air gaps

PASSBAND TRANSFER IMPEDANCE

The length of the air gap is the key parameter of the sensor design because it directly affects both the sensitivity of the sensor and the lower cut-off frequency as presented in Figure 2. The smaller the air gaps the higher the sensitivity and the lower the lower cut-off frequency. The sensors are characterized by their transfer impedance which is the ratio of the voltage across the secondary winding terminated into 50 ohm to the current of the primary winding. Passband transfer impedances of the sensors developed at TUT were measured to investigate the effects of inserting air gaps between the ferrite cores. In addition, a comparison with commercial HFCT and the Rogowski coil is also made to study the sensitivity of the developed sensors. All developed sensors use 9 turns winding configuration and 0 mm refers to the split core without spacer.

Transfer impedance measurement was setup using a signal generator and an oscilloscope. A sinewave with 1 MHz characteristic frequency was generated using a function generator and passed through the sensors using the BNC connector and terminated at 50 ohm. Sensor's output was measured at the oscilloscope.

Table 1. Transfer Impedance of commercial HFCT, the Rogowski coil and developed sensors with different air gaps size

	Air Gap (on one side of the core)			
Sensor	Closed	0 mm	0.2 mm	0.3 mm
HFCT-M1	6.20 Ω	6.05 Ω	5.95 Ω	5.90 Ω
HFCT-M2	6.02 Ω	5.93 Ω	5.80 Ω	5.72 Ω
HFCT-M3	6.05 Ω	5.95 Ω	5.93 Ω	5.88 Ω
HFCT-M4	4.74 Ω	4.70 Ω	3.85 Ω	3.80 Ω
HFCT	-	-	-	3.45 Ω
Rogowski	-	-	-	1.45 Ω

Table 1 shows the transfer impedance against different air gaps size using 1 MHz as a characteristic frequency. It should be noted that the Rogowski coil has an air core and commercial HFCT has an air gap of approximately 0.25 mm. Both are shown in the right most column of the table.

The results suggest that the sensitivity of the developed sensors reduces as the size of air gaps increases. In comparison, developed sensors and commercial HFCT sensor has much higher transfer impedance than the Rogowski coil. However, the sensitivity of the developed sensors is still much better when compared to the commercial HFCT sensor.
The purpose of the air gaps is mainly to reduce the saturation of the magnetic materials which is the state when an increased magnetic field cannot increase the magnetization of the material further. Air gaps tunes the permeability of the core so that the saturation takes place for a higher current [8]. High current saturation test is also performed and demonstrated in the next section to support the argument.

HIGH CURRENT SATURATION

A high current test was set up using a VARIAC to increase the 50 Hz current. 10 primary turns around the developed sensors and commercial HFCT was used to yield high current. The overall test setup is shown in Figure 4.

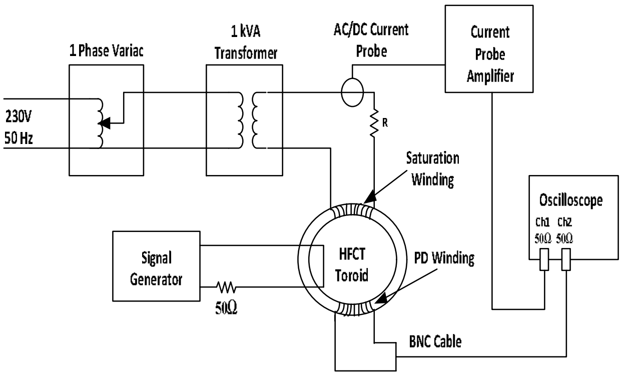

Figure 4. High current test setup

Table 2 shows the saturation current recorded for commercial HFCT sensor, the Rogowski coil and developed sensors with different air gaps size. All developed sensors use 9 turns winding configuration. The Rogowski coil does not saturate and the commercial HFCT has an air gap of approximately 0.25 mm. The saturation value for commercial HFCT sensor is shown in the right most column of the table.

Table 2. Saturation current of commercial HFCT, the Rogowski coil and developed sensors with different air gaps size

	Air Gap (on one side of the core)			
Sensor	Closed	0 mm	0.2 mm	0.3 mm
HFCT-M1	10.0A	12.5A	68.0A	100.0A
HFCT-M2	3.0A	13.5A	55.4A	67.3A
HFCT-M3	6.6A	21.0A	60.0A	65.2A
HFCT-M4	18.8A	28.0A	31.0A	35.3A
HFCT	-	-	-	64A
Rogowski	-	-	-	-

It is clearly visible from the table that air gaps increase the saturation current of the core. The saturation current of all the developed sensors except M4 with 0.3 mm air gap is higher than the commercial HFCT sensor. All these sensors have high saturation performance as well as wider working frequency range when compared to the commercial HFCT sensor.
The effect of 50 Hz saturation on one of the developed sensors is demonstrated in Figure 5 by inputting a 1Vpp, 3 kHz pulse (channel 2 - green) into 50Ω with simultaneous primary 50 Hz current (channel 1 - pink) through the HFCT. Saturation can be seen to occur when the amplitude of the 3 kHz pulses starts to decrease at the peaks of the primary sinewave current.

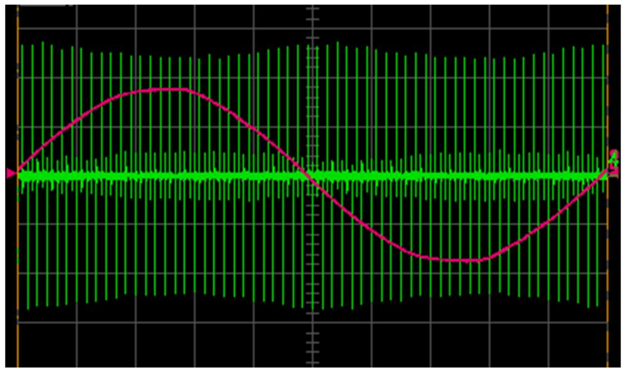

Figure 5. High current saturation test

IMPULSE RESPONSE

A sensor should be able to reproduce the shape of the PD pulse as close as possible. All sensors were also tested using a PD calibrator to determine the sensitivity of the developed sensor as shown in Figure 6.
Calibrator pulse of 10 000 pC was fed through each sensor and the RMS value of the sensors' output was measured using an oscilloscope. A calibrator pulse of 10 000 pC fed through the HFCT was terminated at 50 ohm. With reference to the Figure 6, M1 output (red) reproduces the calibrator waveform quite accurately. The signal-to-noise ratio is high enough and the sensitivity is sufficient to prevent the signal from vanishing under the background noise.

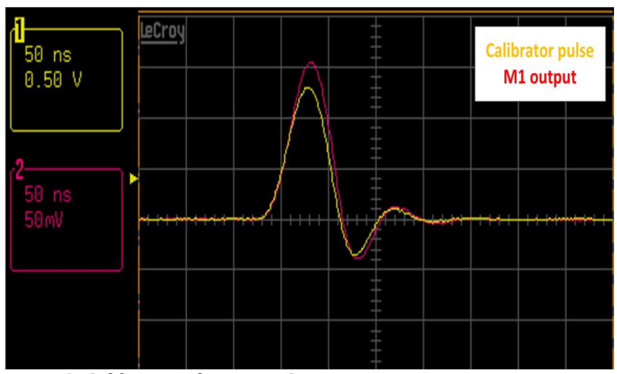

Figure 6. Calibrator pulse vs. HFCT output response

CONCLUSION

Ferrite cores offer a cost-effective and accurate solution for developing inductive sensors which can cover a wider bandwidth. Four different ferrite materials were studied and series of measurements were performed to choose the best possible option based on frequency range, transfer impedance and saturation current. Closed core sensors provide flat amplitude response and higher transfer impedance but their saturation performance is poor. On the other hand, split core sensors provide higher saturation performance on account of frequency range and transfer impedance. Thus, it is a trade-off between the transfer impedance and the saturation current of the sensor.

All Sensors except M4 with closed core and 9 turns winding configuration have frequency range of 30 kHz to 45 MHz as shown in Figure 1. However due to poor saturation performance, they are not feasible for monitoring PD signals in the real power network. Split version of all sensors with 0.3 mm air gaps size and 9 turns winding configuration improves the saturation performance of the core by compromising slightly over frequency ranges and transfer impedances. However, their frequency range and transfer impedance as shown in Figure 3 and Table 1, respectively are still better when compared to the commercial HFCT sensor. The working frequency range of all sensors except M4 (with respect to lower and upper -3dB cut-off frequency) is between 130 kHz to 45 MHz whereas commercial HFCT sensor has frequency range of 70 kHz to 15 MHz. The saturation current of sensor M2 and M3 closely matches the saturation current of the commercial HFCT sensor which is 64A but their transfer impedance is still better than the commercial HFCT sensor.

In comparison, sensor M1 seems to be the best candidate because of its higher transfer impedance and saturation performance as shown in Table 1 and Table 2, respectively when compared to other developed sensors as well as commercial HFCT sensor and the Rogowski coil. Sensor M1 has a saturation current of 100A, highest of all the sensors and lower resonance peak. Moreover, it has a transfer impedance of 5.9Ω (at 1 MHz) which is around 1.7 and 4 times more sensitive than the commercial HFCT sensor (3.45Ω at 1 MHz) and the Rogowski coil (1.45Ω at 1 MHz), respectively.

Consequently, split core sensor M1 with 9 turns winding configuration can be used on MV cable carrying current up to 100A without saturation over the frequency range of 130 kHz to 45 MHz to measure PD signals. Thus, novel low-cost HFCT sensor solutions presented in this paper will be used for continuous on-line PD monitoring without interrupting the power delivery. A modified version of real-time monitoring device as discussed in [9] along with the low-cost HFCT sensor solutions presented in this paper can be used for permanent installation to monitor MV cables especially in rural networks. This will prevent unplanned outages and help early detection and possible prevention of equipment failure, especially catastrophic failure.

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