DOI 10.5162/SMSI2023/P25

Resistive Sensor for Online Assessment of the Insulation Condition of High Voltage Capacitive Bushings

Marcos V. H. Rambo[1], Aguinaldo G. de Melo[1], Daniel Benetti[1], Ivan J. Chueiri[2], Vóldi C. Zambenedetti[2], Edgard Jamhour[2]
[1] COPEL Geração e Transmissão S.A. (COPEL GeT), Brazil,
[2] Pontifícia Universidade Católica do Paraná (PUC-PR), Brazil
marcos.rambo@copel.com

Summary:
The main purpose of this work is to present a new resistive sensor for online assessment of the insulation condition of high voltage capacitive bushings. Capacitive bushings are one of the most critical components of power transformers and online monitoring can prevent explosions, that may result in damages ang power outages. The proposed sensor can online determine the absolute values of the capacitance with absolute errors that enable a qualitative analysis. Future studies may use this sensor to also determine the resulting sum of currents through three phase sensors and the insulations' power factor.

Keywords: High voltage capacitive bushings, capacitance, power factor, resistive sensor.

Introduction

High voltage capacitive bushings are the third most common source (17%) of failures of power transformers [1]. Bushings' insulation is degraded as consequence of aging and thermal, electrical, and mechanical stresses, and can cause catastrophic events, such as explosions, damages to adjacent equipment and power outages. One of the biggest power outages in Brazilian electrical grid, in the last years, was originated from a bushing failure [2]. Therefore, power utilities have invested in online monitoring of bushings' insulation [3]. Offline assessment is more accurate but must switch off the power transformers and may not identify insulation failures that develop quickly. In this way, this paper presents a new resistive sensor, which is installed in a 230/138 kV autotransformer.

Capacitive Bushings Equivalent Impedance

High voltage bushings are mainly capacitive due to their structure in layers. Each layer is made of insulation paper, impregnated with insulation oil, and have a conductive foil to promote a better distribution of the electric field along the insulation. Thus, the bushings impedance may be represented as a set of capacitors in series (see Fig. 1). Dielectric losses may be represented as resistors in parallel to the equivalent capacitances. Since the testing tap must be grounded, when the power transformer is operating, C_2 may be neglected.

The bushings' insulation capacitance (C_1) state may be labeled according to Tab. 1.

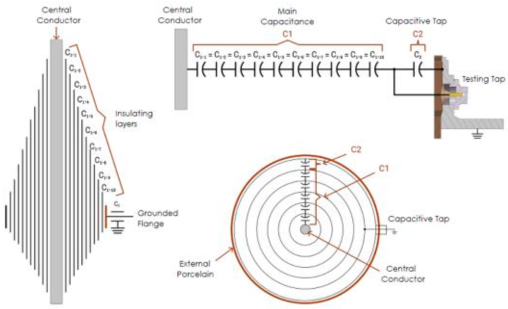

Fig. 1. Equivalent main capacitance (C_1) and tap capacitance (C_2) of high voltage bushings.

Tab. 1: Bushings' state, where C_p and PF_p denotate the nominal capacitance and power factor values [4].

State	Capacitance (C)	Power Factor (PF)
Good	$C_p \leq C < 1.05 \cdot C_p$	$PF_p \leq PF < 2 \cdot PF_p$
Alert	$1.05 \cdot C_p \leq C < 1.1 \cdot C_p$	$2 \cdot PF_p \leq PF < 3 \cdot PF_p$
Replacement	$C \geq 1.1 \cdot C_p$	$PF \geq 3 \cdot PF_p$

Nominal values of Power Factor are in the range of 0,3 to 0,4% [5], thus C_1 may be measured neglecting the current flowing throw the dielectric losses, i.e., the absolute current circulating through the sensor may be considered as the current that flows through C_1.

Proposed Bushing Sensor

The electrical schematic of the proposed sensor is presented in Fig. 2 (a). It is encapsulated in an aluminum casing that must be connected to the testing tap of high voltage capacitive bushings (see Fig. 2(b)).

Six sensors were installed at the bushings of a 150MVA 230/138kV power transformer in Bateias Substation of COPEL GeT.

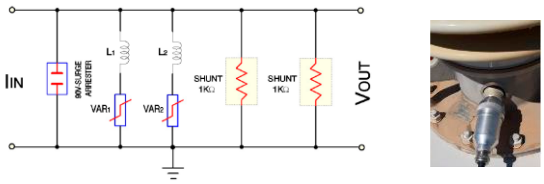

Fig. 2. Proposed resistive sensor. (a) Electrical schematic. (b) Sensor installed at Bateias Substation.

Results

The equivalent impedances of the resistive sensors were measured using a Keysight LCR Meter, model E4980A (see Tab. 2).

Tab. 2: Measured Impedance of the resistive sensors, where H is used for the sensors that were installed at 230kV level and X for 138kV.

Voltage level-Phase	Absolute value (|Z|) [Ω]	Phase [º]
H-A	496.68	0.11
H-B	496.33	0.10
H-C	496.85	0.10
X-A	496.24	0.11
X-B	496.47	0.11
X-C	496.33	0.11

Prior to sensors installation, the bushings insulations parameters were measured with Omicron CPC 100 (see Tab. 3).

Tab. 3: Nominal values (C_p and PF_p) and values measured with Omicron CPC 100 (C_o and PF_o) for C_1.

Bushing	C_p [pF]	C_o [pF]	PF_p [%]	PF [%]
H-A	277	271.11	0.35	0.3827
H-B	296	289.77	0.39	0.3989
H-C	290	283.72	0.36	0.3760
X-A	231	229.19	0.46	0.3999
X-B	230	227.01	0.37	0.3721
X-C	230	226.36	0.46	0.3597

After energization of the power transformer, the resulting voltages (*Vout*) at the sensors' outputs were acquired with a Tektronix TPS 2014 Oscilloscope (see Fig. 3).

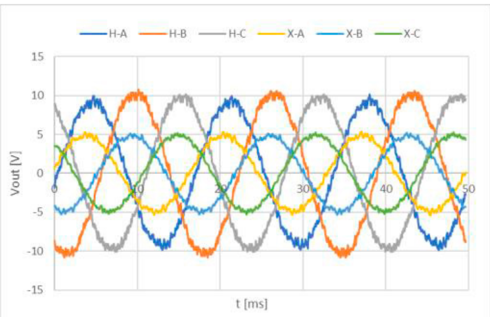

Fig. 3. Voltage signals at the resistive sensors' outputs.

The voltage signals of Fig 3 were filtered by a bandpass 256 tap FIR filter using MatLab, to preserve only the fundamental frequency (60Hz), and the root mean square (RMS) value of each filtered signal was calculated ($Vout_{RMS}$). The current (Ic_{RMS}) through C_1 was then calculated by dividing $Vout_{RMS}$ by the resistance of the sensor (|Z| in Tab. 2). The phase voltages at the bushings' main conductors (V_{MRMS}) were obtained from the substation Supervisory Control and Data Acquisition (SCADA). The voltage drop at the resistive sensors were not considered when calculating C_1, because the capacitive reactance (X_C) is higher than MΩ for the six bushings. The measured capacitances (C_M) were finally obtained from I_{CRMS} and V_{MRMS} (see Tab. 4).

Tab. 4: Currents and voltages at bushings' C_1 and their determined value (C_M). Relative errors E_1 and E_2 are related to C_p and C_o (see Tab. 3), respectively,

Bushing	$\|Ic_{RMS}\|$ [mA]	$\|V_{MRMS}\|$ [kV]	C_M [pF]	E_1 [%]	E_2 [%]
H-A	13.21	135.4	258.8	6.56	4,53
H-B	14.77	135.5	289.2	2,29	0,19
H-C	14.01	134.6	276.1	4,80	2,69
X-A	7.01	80.7	230.4	0,25	0,53
X-B	6.99	81.1	228.7	0,59	0,72
X-C	7.04	80.7	231.3	0,55	2,17

Conclusions

The preliminary results of Tab. 4 indicate that the proposed resistive sensor can be used to determine the state of capacitive bushings' insulation using a qualitative analysis. Further investigation with the sensor of H-A bushing must be conducted. Its errors are close to the thresholds of Tab. 1. If they are constant and enable the assessment of the capacitances changes, they may be compensated by the data acquisition system. Finally, the proposed sensor may also be used in future studies to determine the sum of currents through three phase sensors and to measure the power factor together with the synchronized measurement of the bus-bar voltages using potential transformers.

Acknowledgment

The present work was financed by the R&D Program of the Brazilian National Electric Energy Agency (ANEEL) - code PD 6491-0373/2015.

References

[1] CIGRE Brochure 755, WG A2-43, "Transformer Reliability Survey" (2019); ISBN 978-2-85873-457-3

[2] BRANDÃO, Marcelo; LEAL, Aline. "Apagão no Amapá não foi provocado por raio, diz laudo: Incêndio no transformador foi provocado por superaquecimento" (2020); <https://agenciabrasil.ebc.com.br/geral/noticia/2020-11/apagao-no-amapa-nao-foi-provocado-por-raio-diz-laudo>.

[3] M. Koch and M. Krüger, "A new method for on-line monitoring of bushings and partial discharges of power transformers", *IEEE International Conference on Condition Monitoring and Diagnosis* (2012): doi: 10.1109/CMD.2012.6416378.

[4] I. E. Comission, "Insulated bushings for alternating voltages above 1000 V" IEC 60137 Edition 6.0 (2008).

[5] Institute of Electrical and Electronic Engineers, "IEEE C57.19.01 – Standard for performance characteristics and dimension for power transformer and reactor bushing" (2017).