A NEW INSTRUMENT FOR THE COMPLIANCE CONTROL OF CAST RESIN INSULATED WINDINGS

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Abstract - In this paper, a new instrument for the compliance control in the production process of windings is proposed.
It has been specifically designed for windings of MV-LV cast resin transformers, by implementing a SFRA (Sweep Frequency Response Analysis) based measuring technique. The proposed instrument was designed to be suitable for in line industrial production measurements. In this paper, the developed hardware and software features are presented, with particular respect to the pass-fail test execution.

Keywords: frequency response; power transformers; compliance control; measurement system; custom instrumentation.

1. INTRODUCTION

Cast resin transformers are used in a different kinds of applications, such as energy distribution, naval and railway transportation, AC/DC conversion as well as for other special requirements. The time required for assembling a cast resin transformer can be quite long, and the testing of each unit is always performed at the end of the production chain. If the final test fails, up to ten hours to could be needed for disassembling the machine and repair the fault. One of the possible causes of non-compliance are flaws in the windings: in this paper, a low cost customized instrument for in line quality control of the production process of cast resin transformer windings is presented. The main purpose of the instrument is to intercept any non-compliance on the windings before they are mounted on the transformer core, allowing time-to-market reducing and then lowering production costs.
The proposed instrument has been developed as a cooperation between the Department of Industrial and Information Engineering and Economics of the University of L'Aquila and BTicino Legrand group, a leader manufacturer of cast resin transformers which are produced in the plant of Castellalto, Italy.
IEC 60076-18 standard imposes on manufacturers of transformers to add to test reports the results of SFRA characterizations starting from June 2012, but some concerns can be raised for the interpretation of the results and their relationship with insulation defects, because the large part of existing literature refers to the SFRA test applied to oil filled transformers. Typically, the SFRA method consists in acquiring frequency responses of each winding of a transformer under test and then comparing them with the one of a new and healthy machine; any deviation between the two responses can reveal damages or incoming faults. It is also possible to compare the frequency responses of windings of the same transformer or evaluate the deterioration of a winding by repeating the SFRA over time.
In a recent paper [1, 2], the application of a SFRA based technique to unmounted transformer windings has been investigated, with promising results. The measurements have been performed with general porpoises instruments, without regard to the duration of the tests and to the investigation on algorithms for the automatic quality assessment of each winding.
The innovative features introduced by the instrument are measuring speed, compactness and versatility that make it suitable to be used in an industrial environment, as well as ability of managing measurements for different typology of windings (Fig.1).
In fact, although on the market is it possible to find instruments dedicated to the SFRA analysis, the decision algorithms are oriented to the analysis of non-compliance on assembled transformers and not on the windings.
This paper is focused on the description of the hardware architecture and the specific algorithm of the developed instrument; the first experimental results are also shown.

2. HARDWARE AND MEASUREMENT SETUP

2.1. Windings characterization using SFRA technique

SFRA measurements on a winding are performed by applying a input sinusoidal signal between one winding terminal and the ground, and measuring both the input signal and the output one between the other terminal of the winding and the ground (Fig.2).
The input signal frequency is variable, and it is swept from 20 Hz to 2 MHz at discrete intervals. Measurement connections are made with three coaxial cables respectively connecting: i) the signal generating section output to the input terminal of the winding under test; ii), the winding
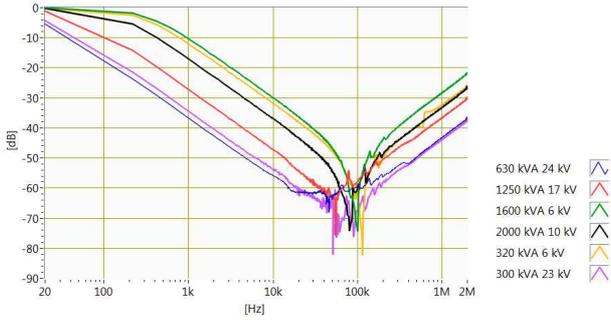
Fig. 1. Experimental TFs for windings of various size

input terminal to the first channel of the data acquisition section; iii) the winding output terminal to the second channel of the data acquisition section. According to the requirements in [3], the specifications of the measuring system to be complied are: i) accuracy of the ratio Vout/Vin better than of ± 0.3 dB in the range +10 dB -40 dB; ii) accuracy of the ratio Vout/Vin better than ± 1 dB in the range +10 dB/-80 dB; ii) accuracy of the ratio Vout/Vin better than of ± 0.3 dB in the range +10 dB -40 dB; iii) 10 Hz max bandwidth for frequencies below 100 Hz and less than 10% of the measured frequency above 100 Hz; iv) phase measurement accuracy better than ± 1° in the range +10 dB/-40 dB; v) input voltage up to 50 Vpp; vi) characteristic impedance 50 Ω and less than 0.3 dB attenuation at 2 MHz for the input and output coaxial cables; vii) internal impedance of the generator, input impedance of the acquisition inputs and characteristic impedance of the cable of 50 Ω ± 2% for the entire measuring range.

It is also necessary that the test duration must not exceed 90 seconds, in order to be suitable with the industrial process needs: the acquired waveform cycles number has been reduced in the frequency band between 20 Hz and 1 kHz, in order to speed up the test. The waveform cycles reduction can introduce a S/N reduction but this effect is negligible in the considered frequency interval for each winding typology. (Figure 1). A decimation of the frequency can be applied by the operator: the instrument allows to choose the test speed
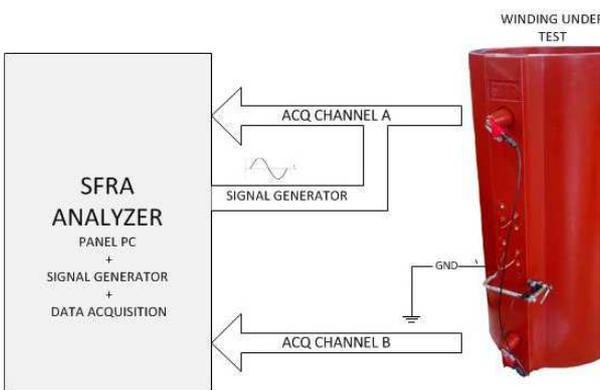

Fig. 2. Block diagram of the measurement setup

on the user interface so the minimum test duration can be 52 seconds. The total duration of the test (measurement and

connections) is about 15 minutes for all standard transformer windings for the fastest test mode.

2.2 Hardware architecture

The proposed instrument has been carried out by means of a COTS-based approach; a Picoscope 5442B, a 4-channel oscilloscope that includes an arbitrary waveform generator has been used for signals generation and acquisition. It has been connected via USB to a PCLOG 8SC fanless touch screen PC, rugged for the use in industrial applications and equipped with Microsoft Windows embedded operative system. The measurement software, developed ad hoc in NI LabVIEW environment [4, 5], manages the Picoscope: the software drives the generator that applies to the DUT a 4V
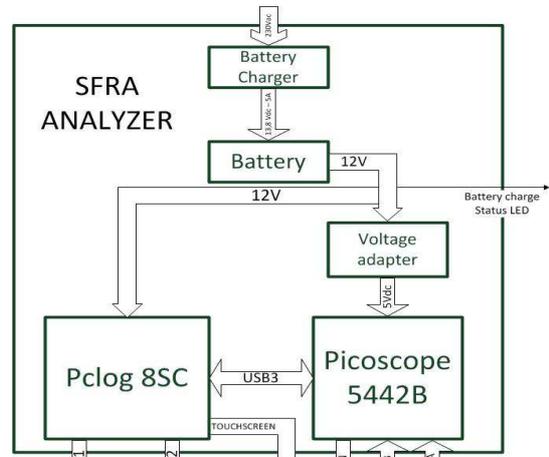

Fig. 3: Architecture of the proposed hardware.

peak-to-peak sinusoidal voltage. Output signal frequency increases gradually in discrete values which are pre-loaded into an array of frequencies stored in calibration files.

Table 1: Signal generator characteristics

Sinusoidal waveform generator characteristics	
Standard signal frequency	DC to 20 MHz
Output frequency resolution	<50 mHz
Output voltage range	±2 V with ±1% DC accuracy
Output impedance	50 Ω

Channel A of the Picoscope acquires the input voltage V_{in}, while channel B acquires the output voltage V_{out}. The maximum resolution of the ADC is 15 bit over 2 channels; oversampling and averaging techniques have been applied to increase the S/N ratio. The data are sampled at the maximum sampling rate of 60 MSample/s, and they are initially stored in the 16 MS internal buffer of the Picoscope; then, data are transferred at a 10 MS/s streaming rate to the PC.

Input impedances of the input channels have been adapted to the output impedance of the source, by inserting a 50Ω

resistance in parallel. Differently from standard SFRA, which is referred to the transformer core as a ground, an external ground plate must be introduced. The accurate choice of the ground plate geometry ensures the required measurement repeatability. The overall cost of the proposed instrument is about € 2500.

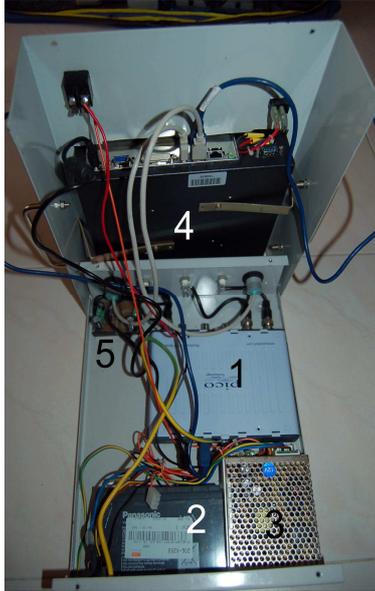Figs. 3 and 4 show the architecture and the components of the instrument.

Fig. 4. Instrument components: 1)Picoscope 5442B 2)12V Battery 3)Battery charger 4)PCLOG 8SC. 5)Voltage adapter

2.3 Data acquisition and processing software

As a critical issue, the reduction of electromagnetic noise effects on the final TFs have been investigated; in fact, an unmounted winding behaves like an antenna, because of the absence of the transformer core. The noise that is usually present in an industrial environment can heavily affect the measurement results. This issue can be successfully approached by implementing the following FFT based technique: i) simultaneous acquisition of the input Vin and output Vout signals, ii) Hanning windowing of both signals, iii) FFT processing of Vin and identification of its amplitude and position in the spectrum; iv) FFT processing of Vout, and identification of its component having the same position of Vin fundamental component. The advantages of this techniques consist in the ease detection of the Vin fundamental component, whose amplitude during all the test has been set to 4 Vpp, with negligible noise effects.

To acquire the desired number of waveform cycles for each generated waveform, the sampling frequency is updated dynamically: the sample interval is calculated with the following relation:

$$SI = \frac{TB-2}{125000000} \qquad (1)$$

where SI is the time interval in seconds and TB is the timebase integer value that is automatically set in the specific Picoscope API function [6]. SI, and so the sampling frequency, are updated when the frequency of the signal generated changes by varying the TB value in the LabVIEW application. As TB is an integer value, it is not always possible to acquire a fixed number of integer waveform cycles; this problem is overcome by the application of the windowing technique.

The number of cycles to be acquired has been defined after an experimental tuning: for input signal frequency from 20 Hz to 1 kHz, 20 cycles are acquired; for higher frequencies up to 2 MHz, 400 cycles. On the host PC the measurement software is executed, by applying a Hanning window and then FFT is applied on both input signal. The maximum FFT value is calculated and then is calculated the V_{out}/V_{in} ratio in dB for each frequency. The instrument allows the user to download via USB the data in Microsoft Excel format. An additional software devoted to the off-line analysis of measurement data on a remote PC has been also developed, according to the requirements of BTicino technical staff.
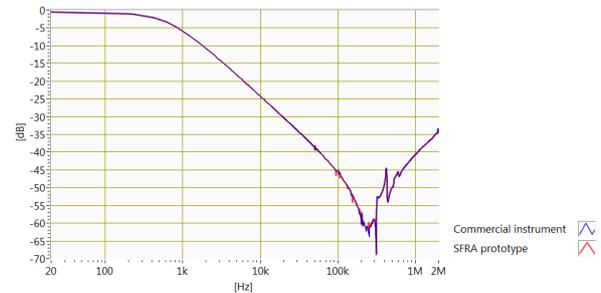

Fig. .: Comparison between commercial SFRA analyzer and the prototype

The instrument performance has been compared with the commercial SFRA analyzer N4L PSM1735 NumetriQ, by acquiring the TFs of the same DUT with both instruments. The obtained results show that TFs are practically superimposable in each comparative test, as shown in Figure 5, according to the accuracy requirements in Section 2.1.

2.3 The compliance control software

For the compliance control, a pass-fail test is performed by evaluating the TFs deviations between a reference curve and the one of the DUT [7]. The reference curve is defined by considering the envelope of a significant number of TFs measured on healthy windings of the same class. As a first requirement, the software must recognize if a particular class of windings has already been measured. The system updates the reference curve every time a test on a winding is performed. The reference curve is the average of N healthy windings curve, so for each frequency:

$$RTF(f_i) = \frac{\sum_{j=1}^{N} TF_j(f_i)}{N} \qquad (2)$$

where:

- RTF(f_i) is the reference transfer function sample at the frequency f_i

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- TF$_j$ is the j-th transfer function sample of a healthy winding at the frequency f$_i$
- N is the number of measured healthy windings

If the TF of Nth winding under test is satisfactory, the new RTF(f$_i$) is updated as:

$$\frac{N*RTF(f_i)+TF(f_i)_{N+1}}{N+1} \qquad (3)$$

where TF$_{N+1}$ is the measurement of the new winding. The measurement spreadsheet file must include the number N of TF involved in the RTF. The developed software performs all the following operations:

- Acquisition of TFs at different speed decimating the array of frequencies of the acquired signals;
- Analysis of the TFs of windings under test by comparing them with the reference curves for the corresponding windings classes. The software calculates the Pearson's correlation index (IC) and the standard deviation (SD) in 7 sub bands between 20 Hz and 2 MHz. The sum of σ in sub bands between 10 kHz and 130 kHz is performed. This is done to take into account the windings tolerances and the measurement noise.
- Storage and management of the measurement data. The measurement files are stored in folders organized by winding code. Usually, MV windings are equipped with tap changers, for the offline transformation ratio regulation; each data folder has been automatically structured with sub folders, one for each possible regulation tap.
- Setting up of the test threshold parameters such as IC and SD for each sub band. It is also possible to load a custom array of frequencies. These operations are performed by the user with an ad hoc front panel dedicated to parameters setup.

For each operation a panel in the GUI has been developed. When the system starts up, the main front panel is launched (Fig 7): some buttons allow the operator to choose the action to be performed.
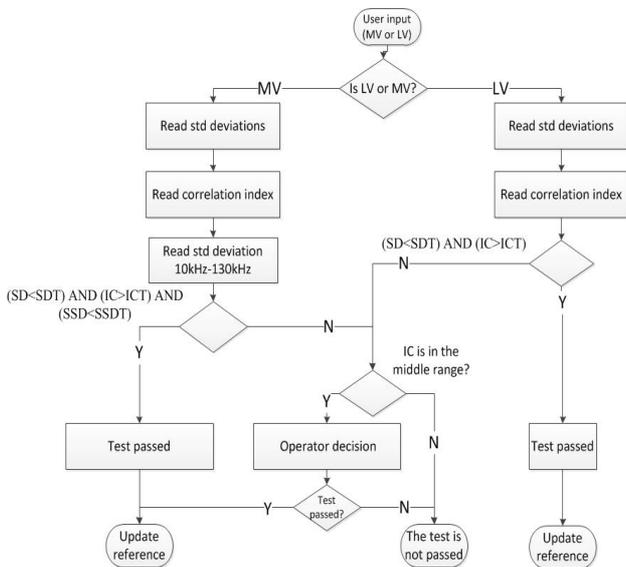
The threshold parameters adopted in the decisional algorithm have been set after a wide series of measurements, to take into account the effects that the craftsmanships during the production process can introduce in the TF of healthy windings: IC is an indicator the shape of the TF [8] and ρ indicates the TFs magnitude difference.

The decisional algorithm and the adopted threshold are shown in Fig. 6 and Table 2, where SD is the Standard Deviation, SDT is the SD threshold, IC and ICT are the correlation index and the threshold respectively. Moreover the frequency interval between 10 kHz and 130 kHz has been divided into 10 kHz wide sub bands: it is calculated the SD and the sum of SDs in each sub band. The maximum SD in a single sub-band must not exceed 5 dB and the sum of SDs must be less than 25. This operation has been implemented to take into account the craftmanships tolerances.

Table 2: Pass-fail parameters

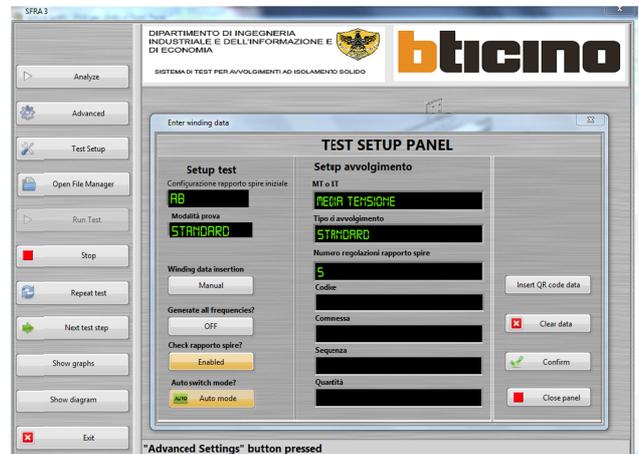| Sub-band	Tresholds LV	Tresholds MV	
	SD T [dB]	ICT	SDT [dB]
20 Hz – 20 kHz	0,4	0,85	1
20 kHz – 300 kHz	2	0,9	2
300 kHz - 700 kHz	1	0,9	1
700 kHz – 1.1 MHz	3	0,9	1
1.1 MHz - 1.4 MHz	3	0,9	1
1.4 Mhz - 1.7 MHz	3	0,9	1
1.7 Mhz – 2 MHz	0,8	0,9	0,8

Fig. 6. Decisional algorithm for a generic test

Fig. 7. Main GUI

The test of tap is possible by analyzing the inductive section of the SFRA TFs, usually in the frequency range 20 Hz - 10 kHz [9]: the impedance increases according to the turns number, so the instrument can be used for test on both uncoated or coated windings [10]. This feature allows to identify non compliances in the winding turns or tap changer configuration at a very early stage of the production process. The underlying principle is the change in inductive impedance due to the inclusion or exclusions of turns for each different tap charge connection. The TF amplitude decreases when the inductive impedance increases, due to the inclusion of a larger number of turns. The instrument processes the whole TF when the connection of the tap-changer includes the maximum number of turns, successively a portion of TF in the range 20 Hz – 10 kHz for the other tap-changer configurations. This procedure is performed in order to optimize the test duration: for higher frequencies the TFs of a DUT can be considered superimposable because of the capacitive behaviour of the windings (Fig. 8). The frequency of 10 kHz has been considered as the threshold within which all windings have. An inductive behaviour .
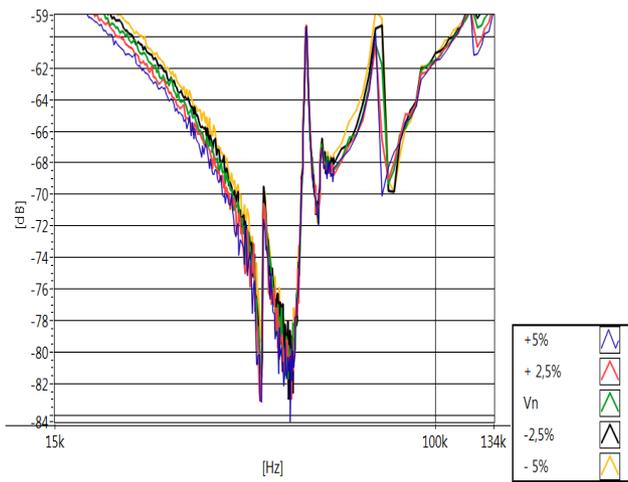
In Fig. 9 the TF obtained with measurements on a same winding, for different tap-changer connection, is shown: the difference between the TF with the maximum number of turns and the one with the minimum is about 10 dB, at the most. The curve moves upward because both inductance and resistance decrease (Fig. 9) . The mean value of each TF is calculated in the frequency interval mentioned above, then a comparison is performed Some LEDs in the software GUI allow the user to verify the results of this important test.

2.4 Experimental results

Some windings faults have been detected during the test for the validation of the instrument performance. In detail, short-circuit and axial decentralization faults are presented in this paper. The short-circuit fault is invisible from outside and it generates a lowering of the TF, because of the inductive impedance reduction: the measured TF is shown in Fig. 11. It is important to notice that variation affect only the band which has an inductive behaviour. The related parameters in Table 3 shows that this change mostly affects the SD because the IC is an indicator of the shape of the TF.

Fig. 8. The TFs are superimposable for frequencies above 10 kHz
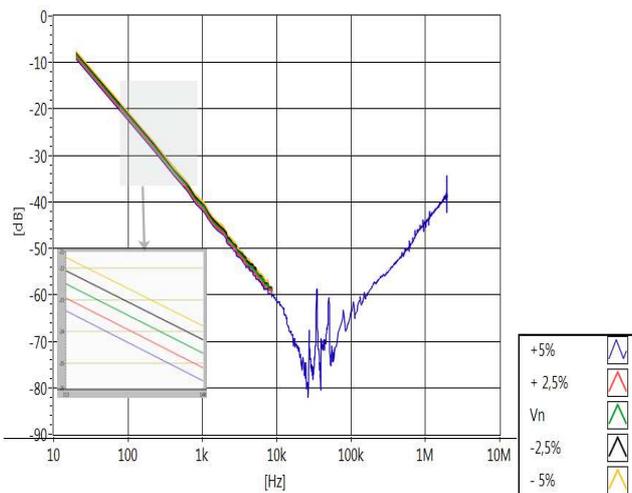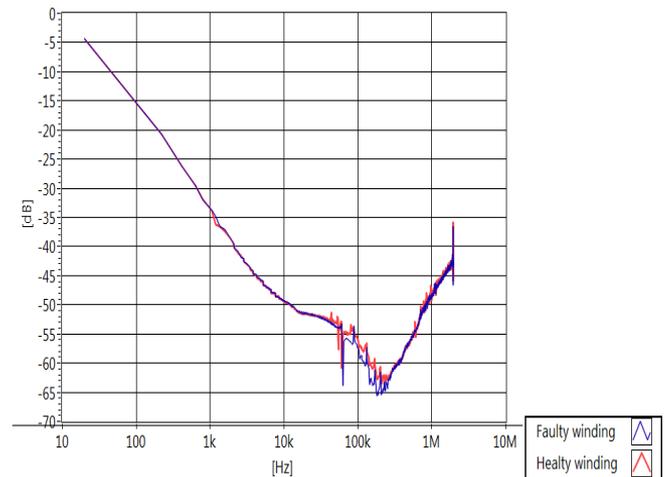

Fig. 10. Healthy winding Vs axial-decentralized non compliant winding.

Fig. 9. Measured TFs for different tap-changer connections (+5%, +2,5%, 0%, -2,5%, -5%) of a MV winding
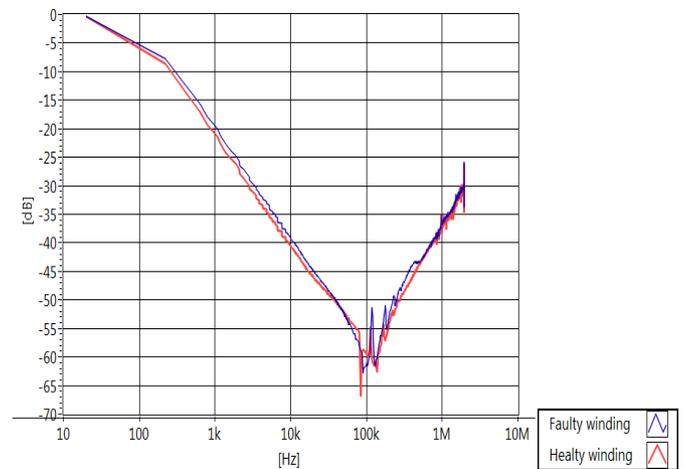

Fig. 11. Healthy winding Vs short-circuited twin winding

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The TF in Fig. 10 shows that the axial decentralization generates a variation in the band in which the capacity between turns is prevalent [11]. The results in Table 3 show that the SD is in range while the IC lowers because of the shape differences of TF in Fig. 9. It has been shown that both IC and SD parameters are useful for the fault detection in windings.

Table 3: Results obtained for the TF in Fig.10

Frequency interval	SD [dB]	IC
20 Hz – 20 kHz	0,12	0,99
20 kHz - 400 kHz	0,77	0,97
400 kHz - 700 kHz	0,22	0,98
700 khz - 1100 kHz	0,45	0,94
1100 kHz - 1.4 Mhz	0,31	0,31
1.4 MHz - 1.7 MHz	0,31	0,31
1.7 MHz - 2 MHz	0,33	0,33

Table 4: Results obtained for the TFs in Fig. 11

Frequency interval	SD [dB]	IC
20 Hz – 20 kHz	1,37	0,99
20 kHz - 400 kHz	1,25	0,94
400 kHz - 700 kHz	0,44	0,94
700 khz - 1100 kHz	0,37	0,97
1100 kHz - 1.4 Mhz	0,70	0,93
1.4 MHz - 1.7 MHz	0,70	0,93
1.7 MHz - 2 MHz	0,50	0,86

3. CONCLUSIONS

In this paper, an ad hoc instrument for the compliance control in the production process of cast resin transformer windings is proposed, based on the SFRA technique. Although it is characterized by low cost and compactness, it allows the SFRA characterization of unmounted windings in about 90s, by implementing a pass-fail test with an automatic update of windings reference TFs .
In the future some improvements will be considered, as the integrated management of measurement, the management of distributed clones of the instrument along the production line, the automatic switching of the tap changer connections for MV windings, the implementation of the correspondence between TFs variation and the non compliances. .by implementing a pass-fail test with an automatic update of windings reference TFs .
In the future some improvements will be considered, as the integrated management of measurement, the management of distributed clones of the instrument along the production line, the automatic switching of the tap changer connections

for MV windings, the implementation of the correspondence between TFs variation and the non compliances.

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