Transformer Inrush is Over: An Experience with a 100MVA, 230/138 kV Three-phase Transformer Controlled Energizing

H. S. Bronzeado, S. O. Pinto, Per Jonsson, J. C. de Oliveira and M. L. R. Chaves

•***Abstract*** **- Transformers are normally energized by closing arbitrarily the circuit breaker contacts, with the system voltage being applied on the transformer windings at random instants. In general, this switching introduces an asymmetrical magnetic flux in the windings, driving the transformer into saturation. As a result, high transient magnetizing inrush currents are produced in the transformer. One of the solutions for mitigating these currents is energizing the transformer by controlling the circuit breaker making instants in a way that the magnetic flux produced in the windings corresponds to the prospective flux in the core. This strategy was applied on a 100 MVA, 230/138 kV, three-phase three-limbed core type transformer, with the results showing that transformer inrush currents can be almost completely eliminated.**

Keywords: **controlled switching; inrush current; transformer energizing; transient mitigation; inrush mitigation;**

I. INTRODUCTION

THREE-phase power transformers are normally energized by closing erratically the poles of a circuit breaker, with the voltages being applied on the transformer windings at random instants. In this way, the magnetic flux produced in the windings, which are proportional to the integral over time of the voltage applied, will be, in general, asymmetrical. This flux asymmetry may cause an excessive flux density in the iron-core, driving the transformer into saturation, generating high magnetizing inrush currents. These inrush currents, which are characterized as being almost unidirectional, rise abruptly and reach their maximum peak in the first half cycle after the transformer being energized. Thenceforth, the currents begin to decay until the transformer reaches its normal magnetizing condition [1].

Depending on duration and imbalance levels, the high magnitudes inrush currents may cause serious disturbances in the system and in the transformer itself. Examples of these disturbances are temporary harmonic overvoltage, undesired operation of overcurrent and differential protection [2], momentary voltage dips and electromechanical stress on the transformer windings.

One of the solutions to mitigate such disturbances is to reduce the inrush current magnitude, which is traditionally done by using pre-insertion resistors in the circuit breakers. The voltage drop across the pre-insertion resistor produce by the inrush current will decrease the voltage on the transformer windings, which in turns decreases the magnetic over flux in the core. As a result, the magnitude of the transient magnetizing currents will be reduced as well.

Another way to reduce the magnitude of inrush currents is energizing a transformer by controlling the making instants (electric closing) of the circuit breaker poles. These instants should be those at which the magnetic flux in the iron-core coincides with that that would be produced by the voltage being applied on the transformer windings at that instant.

This controlling strategy was the aims of a R&D Project funding by the Companhia Hidro Elétrica do São Francisco – CHESF, Brazil. It development has the support by the Universidade Federal de Uberlândia – UFU, Brazil, and the Asea Brown Boveri – ABB (Sweden). Detailed models of circuit breakers and three-phase transformers were developed to investigating the transformer controlled switching. In addition, algorithms and devices for measuring the residual flux in each column of the transformer ferromagnetic core were also developed.

This paper presents an experience obtained from field tests carried out on a 100MVA, 230/138kV three-phase transformer, which was energized by controlling the making instants of a 245kV circuit breaker. The results have shown that transformer inrush currents can be almost completely eliminated or, at least, reduced to values of no consequence to the system.

II. TESTS SITE

The substation where the tests were carried out was that in which had occurred an undesired trip out of a transformer by a neutral over current protection during the energizing of another parallel transformers. This trip out was caused by a phenomenon between transformers called sympathetic interaction [3-5], which prolongs the transient inrush. Thus, a reduction of the magnitude of the transformer inrush currents would eliminate the risk of this nuisance trip and, also, the temporary overvoltages and momentary voltage dip, improving considerably the quality level of the voltage supply.

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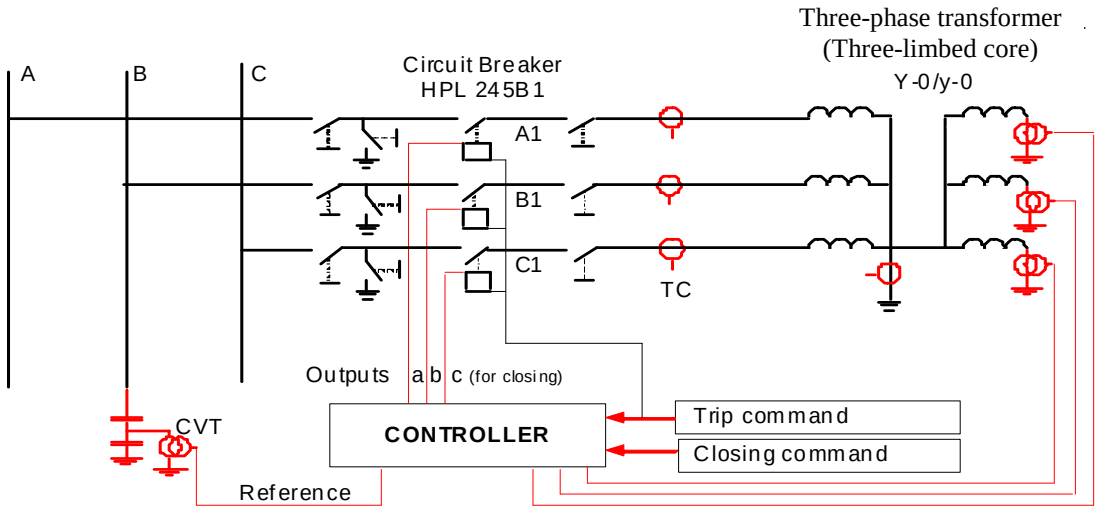

Fig. 1. Schematic of connections for the circuit breaker controller device. The de-energizing is not controlled but trip information is given to the controller.

III. Circuit Breaker Controller

During the development of the Chesf R&D Project, it was found that the controlled switching methodology used was similar to that used by ABB – Sweden. Then, it was agreed to test such a device (Switchsync T183™) as a part of the Project work. This provided a significant advancement in the Project as the device was ready prepared to apply in high voltage circuit breakers. Fig. 1 shows, schematically, the main connections of this device.

IV. Field Measurements

Fig. 2 shows the schematic diagram of the measurements carried out during the tests, which consisted basically of recording the voltages and currents waveforms in the transformers (04T2 and 04T3) during the energizing and de-energizing of the transformer 04T3 (100MVA, 230/138kV). Table 1 summarizes the field tests carried out.

The currents (230kV side) and the voltages (138kV side) in the transformer 04T2 were recorded with the objective to investigate the phenomenon of sympathetic interaction.

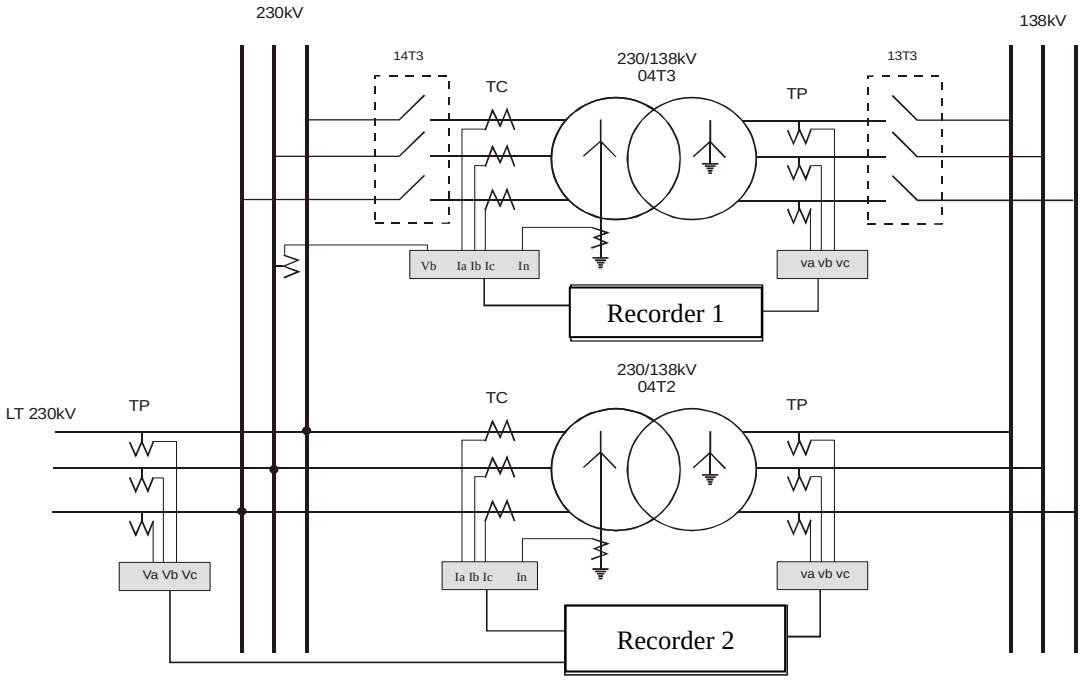

Fig. 2. Schematic diagram of the measurement points.

TABLE 1
FIELD TEST DESCRIPTION – TRANSFORMER SWITCHING

Test	Time	Test description
1	10:45	**Controlled** energizing of the transformer 04T3 **without information of residual flux** (considered zero)
2	11:07	De-energizing of the transformer 04T3
3	11:27	**Controlled** energizing of the transformer 04T3 **with information of residual flux** (measured)
4	11:50	De-energizing of the transformer 04T3
5	12:00	**Controlled** energizing of the transformer 04T3 **with information of residual flux** (measured)
6	14:08	De-energizing of the transformer 04T3
7	14:43	**Controlled** energizing of the transformer 04T3 **with information of residual flux** (measured)
8	15:19	De-energizing of the transformer 04T3
9	15:30	**Uncontrolled (random)** energizing of the transformer 04T3

V. ANALYSIS OF THE FIELD TEST RESULTS

Fig. 3 shows the inrush currents (230kV side) and voltages (138kV side) waveforms in the transformer 04T3. For comparison purpose, the waveforms are all shown in the same scale. The maximum peak of the inrush currents was 1,110A (Test 9). As can be observed from the voltage waveforms, the defined making instants of the circuit breaker in the Tests 3, 5 and 7 reduced successfully the inrush currents. In the Test 3, the magnitudes of the currents were so small that it was not possible to record their waveforms.

In the Test 1, the control device worked but the residual flux was not measured. Under this circumstance, the controller assumes the residual flux as being zero, making the first circuit breaker pole to close at voltage peak. In this case, the transformer was energized according to controller strategy but not at optimum instants. Even so, the peak of inrush current only reached about 600A, showing that this strategy still better than a random switching (Test 9).

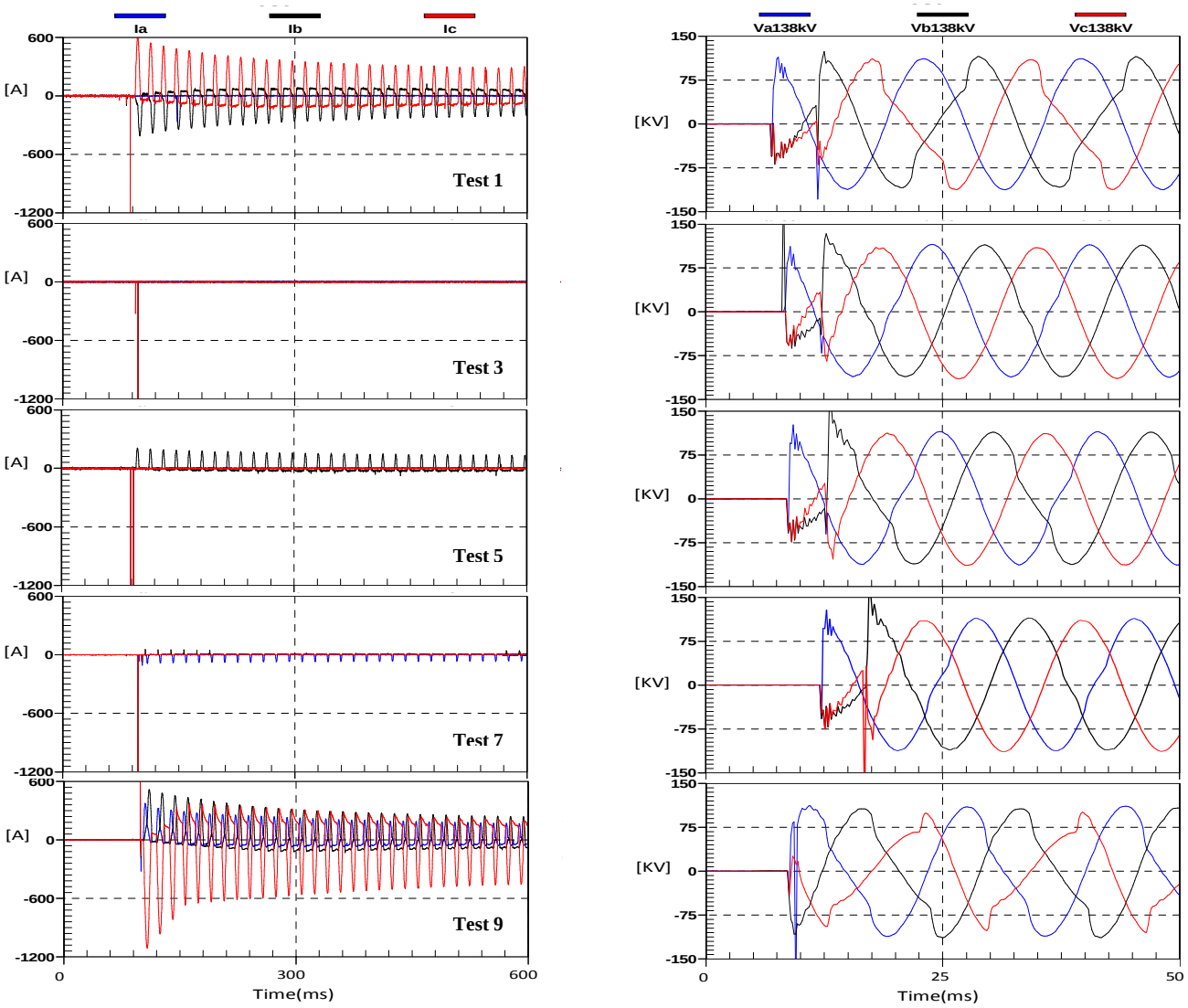

Fig. 3. The inrush currents (230kV side) and voltages (138 kV side) waveforms in the transformer 04T3 during field tests.

An analysis of the voltage waveforms in the Test 1 indicates that the first pole closed was that of phase A. In a sequential order, the other two poles were closed almost simultaneously, at approximately 4,2ms (¼ of cycle) after the first pole closing. The distortion presented on the voltages of the phases B and C indicates that the iron-core columns of those phases saturated. This can be confirmed by the magnitudes of the inrush currents of those phases. In addition, it can be noted that the voltage in phase A did not present a visible distortion, indicating that the corresponding iron-core column did not reach saturation.

In the Test 3, the transformer energizing was carried out according to the developed strategy, i.e., with the circuit breaker poles closed at instants that take into account the magnitude and polarity of the residual flux.

It can be observed that the transformer magnetizing inrush currents in the Test 3 were very low and could not be detected by the current measurement system used. This fact indicates that the transformer did not saturate, which can be validated by a very little voltage distortion presented on the transformer secondary (138kV). This fact shows clearly the success of the strategy utilized by the controller, reducing dramatically the inrush currents and, consequently, mitigating the system disturbances caused by this switching transient.

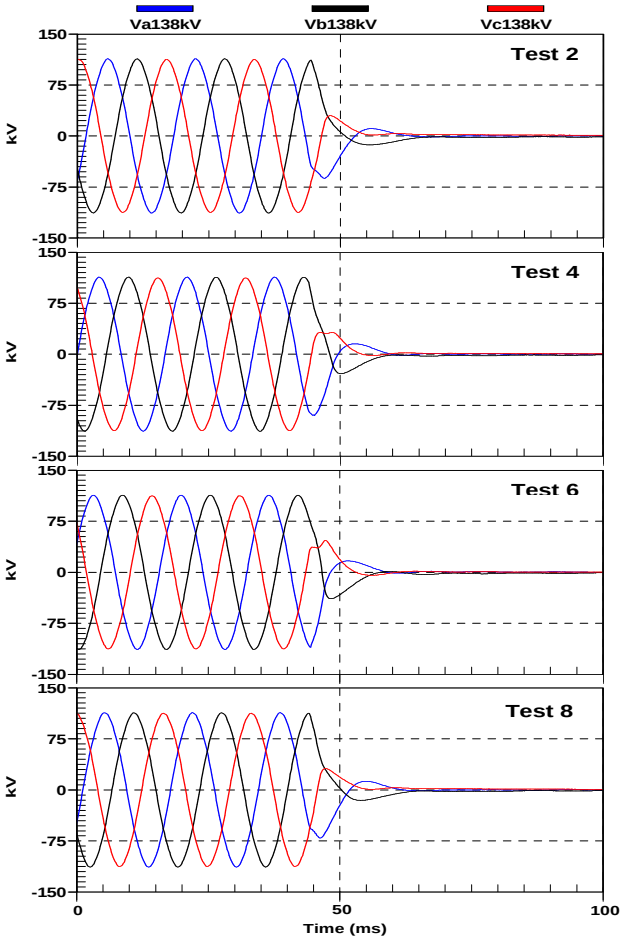

Fig. 4. Decaying voltages measured at the 138kV terminals of the transformer 04T3 during its de-energizing.

The further Test 5 and Test 7 were carried out to verify the robustness of the controlled switching strategy. In both tests, the making instants of the circuit breaker were controlled, taking into account the values of the residual flux "measured" during the previous transformer de-energizing, Test 4 and Test 6, respectively.

It is important to point out that the residual flux in each columns of the transformer iron-core is measured (calculated) based on the integral over time of the decaying voltages measured at the corresponding winding terminals during the transformer de-energizing (see Fig. 4). The value of the residual flux, together with the particular transformer design (electric and magnetic circuits), determines the exact making instant of the circuit breaker poles in the subsequent transformer energizing.

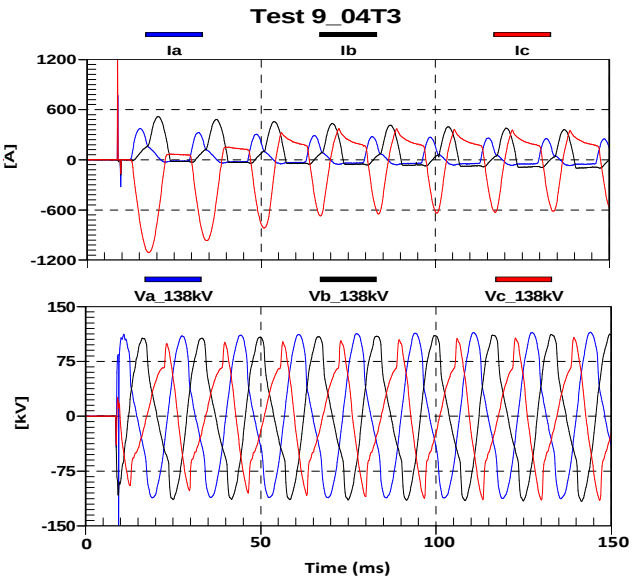

Fig. 5. Inrush currents (230kV side), and voltages (138kV side) waveforms measured in the transformer 04T3.

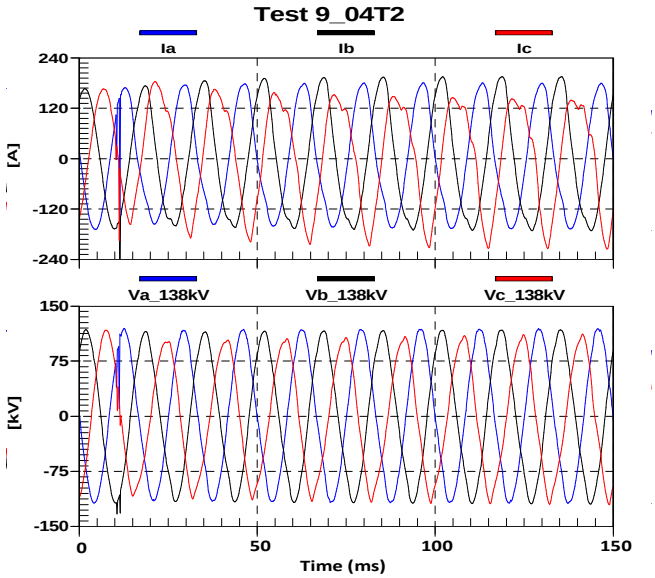

Fig. 6. Currents (230kV side) and voltages waveforms (138kV side) measured in the transformer 04T2 during the transformer 04T3 energizing.

In the Test 5 and Test 7, the peak of the inrush currents remained below 210A and 90A, respectively, which corresponds to less than 50% and 20% of the peak of the transformer nominal current ($251x\sqrt{2}=434A$). These results were considered satisfactory enough, as the inrush current magnitude has been far below the nominal current of the transformer.

In the Test 9, the transformer was energized without any control, with the circuit breaker poles being closed randomly. It can be observed that the inrush currents presented relatively high magnitudes, reaching a peak slight bigger than 1,100A in phase C. This value corresponds to approximately 250% of the nominal peak current of the transformer, demonstrating an occurrence of high levels of saturation in the transformer core.

An analysis of the corresponding voltage waveforms indicates that the circuit breaker poles were closed almost simultaneously. The voltage distortion in phases B and C reveals a significant level of saturation in the iron-core columns associated to those phases.

Fig. 6 shows the waveforms of the currents and voltages in the transformer 04T2, during the transformer 04T3 energizing (Test 9). It can be observed from the distortion presented in the currents in phases B and C of the transformer 04T2 that its core has saturated slightly. This indicates the occurrence of the phenomenon of sympathetic interaction between the transformers [3-5], which prolongs the transient inrush. The currents and voltages waveforms of the transformer 04T3 in Test 9 are shown in Fig. 5 at the same scale of the waveforms in Fig. 6 for comparison purpose.

It is important to note that the currents measured in the transformer 04T2 correspond to both load and magnetizing currents in that transformer. The distortions on the 138kV bus-bar voltages indicate some impact on the voltage quality on that bus-bar during the uncontrolled energizing of the transformer 04T3.

VI. CONCLUSIONS

The efficiency and robustness of the strategy used for controlled switching of three-phase transformer were verified by tests carried out on a 100MVA, 230/138kV, three-phase, three-limbed core type transformer. The test results showed the success of this control.

The controller used in the field tests, which, at that time, was under development by ABB was very similar (conception and methodology) to the controller that was being developed by the team of the Chesf Project of R&D. Other strategies for controlled switching of three-phase transformers still being investigated.

The transformer energizing without controlling the making instants of the circuit breaker may produce high levels of transient inrush currents. Besides high magnitudes peaks, these currents present significant asymmetries, harmonic components of all orders (including dc component) and a relatively slow damping due to the sympathetic interaction between the parallel transformers. With these characteristics, high magnetizing inrush currents may cause considerable impacts in power systems, such as temporary harmonic over-voltages, momentary voltage dips, stresses related with internal mechanical efforts on the transformer windings, undesired protection operation by high currents in capacitor banks and in transformers neutrals, etc, etc.

It has shown that the transformer controlled switching strategy developed is able to mitigate, or practically eliminate, the high magnitudes of the transformer transient inrush currents. In other words, **transformer inrush is over**.

It is essential to point out that the circuit breaker plays a crucial role in controlled switching, as it must work in a stable way, with a relatively small (close/open) time span.

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VIII. BIOGRAPHIES

Herivelto de Souza Bronzeado (M' 97) was born in Remígio, Paraiba, Brazil, on April 2, 1953. He was graduated by the Universidade Federal da Paraíba, Brazil, in July 1975, and since then, he works for the Companhia Hidro Elétrica do São Francisco – CHESF, being responsible for Power Quality area and R&D Projects. He received his MSc degree in Power System Engineering, in 1993, from the University of Aberdeen, Scotland (UK). He is also the chairman of the Study Committee C4 of Cigré-Brasil and the IEEE Joint Chapter PES/IAS/PELS, Northeast 1, Section Bahia, Brazil. His research interests include transformer modeling for transient studies and Power Quality issues.

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