

Controlled Energizing of Three-phase Transformer: Analysis of Test Results

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SUMMARY

Power transformers are generally energized by closing the contacts of a circuit breaker at random instants. Consequently, the voltage of the supply system is also applied on the transformer windings at random instants. This “uncontrolled” switching usually introduces an asymmetrical magnetic flux in the windings that can drive the transformer into saturation. As a result, transient magnetising inrush currents of high magnitude are generated in the transformer, which may cause serious system disturbances. One of the solutions for mitigating these high transformer inrush currents is controlling the making instants of the circuit breaker contacts so that the magnetic flux produced in the transformer windings corresponds, in magnitude and polarity, to the prospective flux in the transformer ferromagnetic core. This strategy makes the transformer energizing very “soft”, with no appreciably transient inrush currents being produced. This paper presents the results of fields test carried out on a 100 MVA, 230/138 kV, three-phase three-limb core type transformer, to validate the controlled switching strategy for this equipment.

KEYWORDS

Controlled Switching - Inrush Current - Transformer Energizing - Transient Mitigation.

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1. INTRODUCTION

The conventional way to energize a transformer is by closing randomly the poles of a circuit breaker, with the system voltages being applied on its windings at arbitrary instants. Thus, the magnetic flux initially produced in the transformer windings, which are proportional to the integral over time of the voltage applied, will be usually asymmetrical. This flux asymmetry causes an over-flux in the ferromagnetic core of the transformer, driving it into saturation, hence, generating high magnetising currents (inrush current).

Inrush currents of high magnitudes may cause serious disturbances in the supply system and in the transformer itself. Examples of these disturbances are temporary harmonic over voltage, unwanted operation of over current and differential protection [2], momentary voltage dips, and mechanical stress on transformer windings. One of the solutions to avoid such disturbances is to mitigate these high magnitude inrush currents.

Traditionally, transformer inrush currents have been mitigated by using pre-insertion resistors in circuit breakers. The voltage drop across these pre-insertion resistors reduces the voltage applied in the transformer windings, hence, the magnetic over-flux in the core. As a result, the magnitude of the magnetizing transient current is reduced.

Another way to reduce the transformer inrush current is using the controlled switching strategy, which consist of closing each pole of a circuit breaker at defined instants of time at which the magnetizing condition in the transformer iron-core coincides with that that would be produced by the voltage being applied on the transformer windings.

This strategy was developed in a Project of Research and Development by a Brazilian utility, with the technical support of a university. In this R&D Project, models for circuit breakers and three-phase transformers were developed. In addition, a mechanism to find out the residual flux in the columns of the transformer iron-core was proposed.

This paper shows the results of field tests of energizing a three-phase, three-limb 100 MVA, 230/138 kV transformers by controlling the making instants of the poles of a 230 kV circuit breaker.

2. CIRCUIT BREAKER CONTROLLER

During the development of the R&D Project, it was found that the methodology and the strategy that was being used for the switching control was similar to that used in one device being developed by a manufacturer at the same time. So, it was agreed to test the device of the manufacturer as part of the R&D Project. This provided a significant advancement in the Project, as the device was almost ready to apply in high voltage circuit breakers. Even that, it was necessary some adaptations in the control algorithm to match with the methodology/strategy proposed by the original Project. Fig. 1 shows the frontal view of the controller installed provisionally in one of the panels in the utility substation Eunápolis, and Fig. 2 shows the main connections of this device.



Fig. 1 – Frontal view of the controller installed in the utility substation.

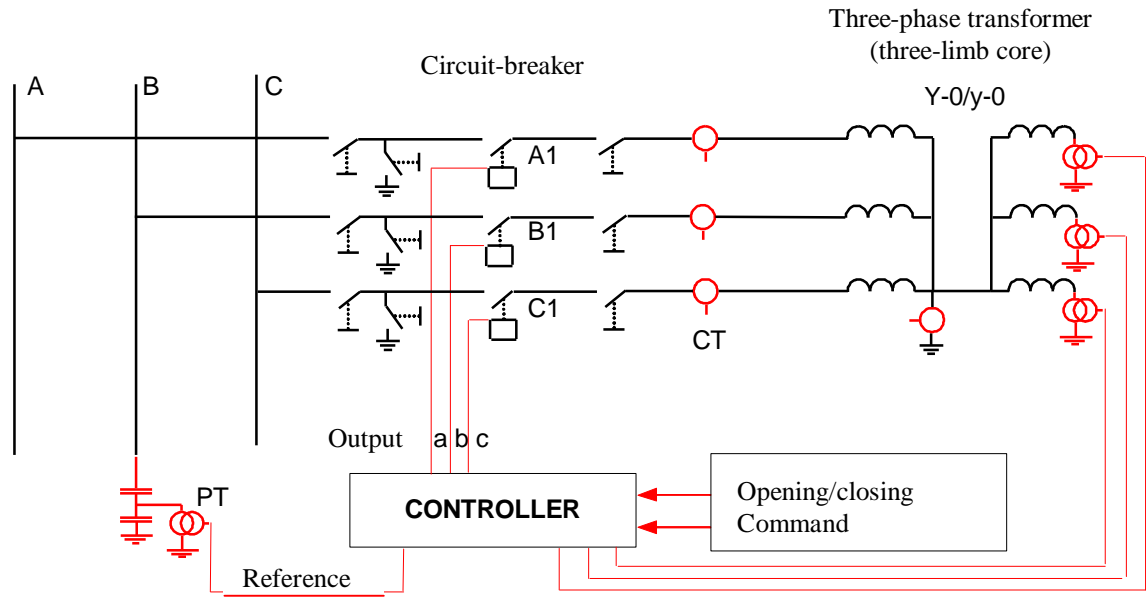


Fig. 2 - Main connections of the controller.

3. SITE MEASUREMENTS

The measurements carried out during the site tests consisted basically in recording the waveforms of the voltages and currents in the transformers named 04T2 and 04T3 of the utility substation (see Fig. 3), during the switching of the transformer 04T3 (100 MVA, 230/138 kV). The transformer 04T2 is identical to transformer 04T3).

Fig. 3 shows the schematic diagram of the measurement points (there was another identical transformer (04T1) in parallel that is not showed in the Fig. 3). The currents (230 kV side) and the voltages on the 138 kV terminals of the transformer 04T2 were recorded with the objective to investigate the phenomenon of sympathetic interaction between transformers.

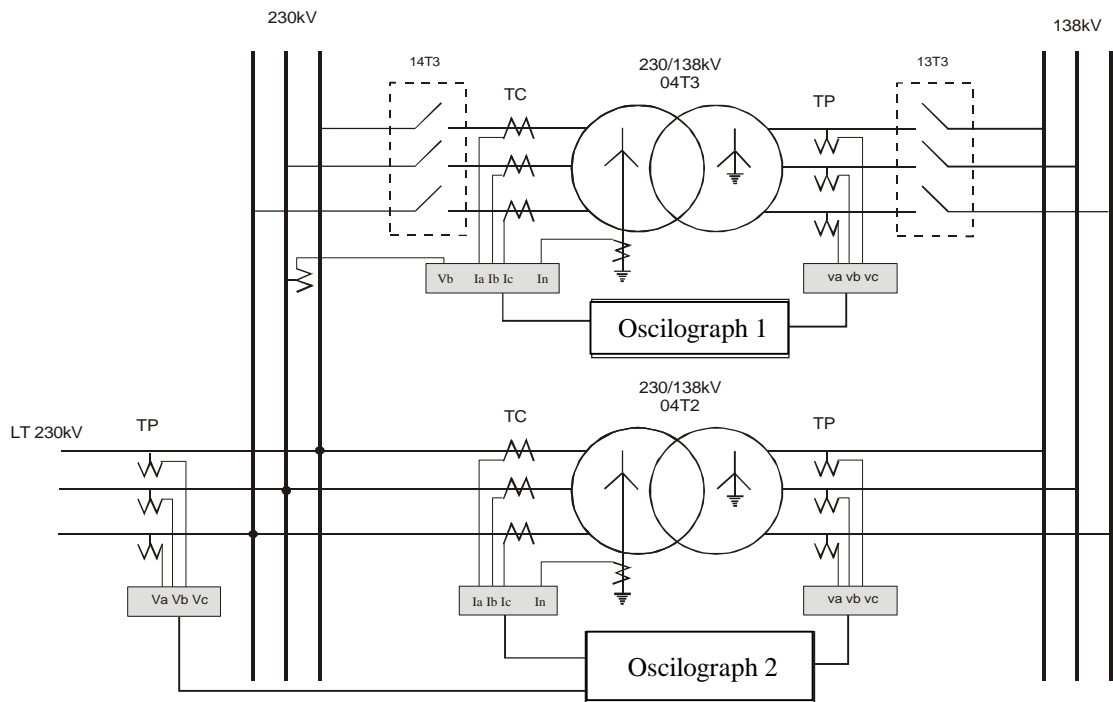


Fig. 3 – Schematic diagram of measurement points.

4. FIELD TEST RESULT ANALYSIS

The Table 1 shows a summary of the field tests carried out. Fig. 4 shows, in the same scale, the waveforms of the inrush currents in the transformer 04T3 during its energizing. The maximum peak of the inrush currents was 1110A (Test 9). As it can be observed, the control of the closing instants of the circuit breaker poles (Tests 3, 5 and 7) reduced significantly the magnitude of the inrush currents. In the Test 3, the magnitudes of the currents were so small that was not possible to record the waveforms.

TABLE 1 - FIELD TEST DESCRIPTION

Test	Time	Test description
1	10:45	<u>Controlled</u> energizing of transformer 04T3, <u>without</u> information of residual flux (assumed to be zero)
2	11:07	De-energizing transformer 04T3
3	11:27	<u>Controlled</u> energizing of transformer 04T3 <u>with</u> information of residual flux
4	11:50	De-energizing transformer 04T3
5	12:00	<u>Controlled</u> energizing of transformer 04T3 <u>with</u> information of residual flux
6	14:08	De-energizing of transformer 04T3
7	14:43	<u>Controlled</u> energizing of transformer 04T3 <u>with</u> information of residual flux
8	15:19	De-energizing of transformer 04T3
9	15:30	<u>Uncontrolled</u> energizing of transformer 04T3

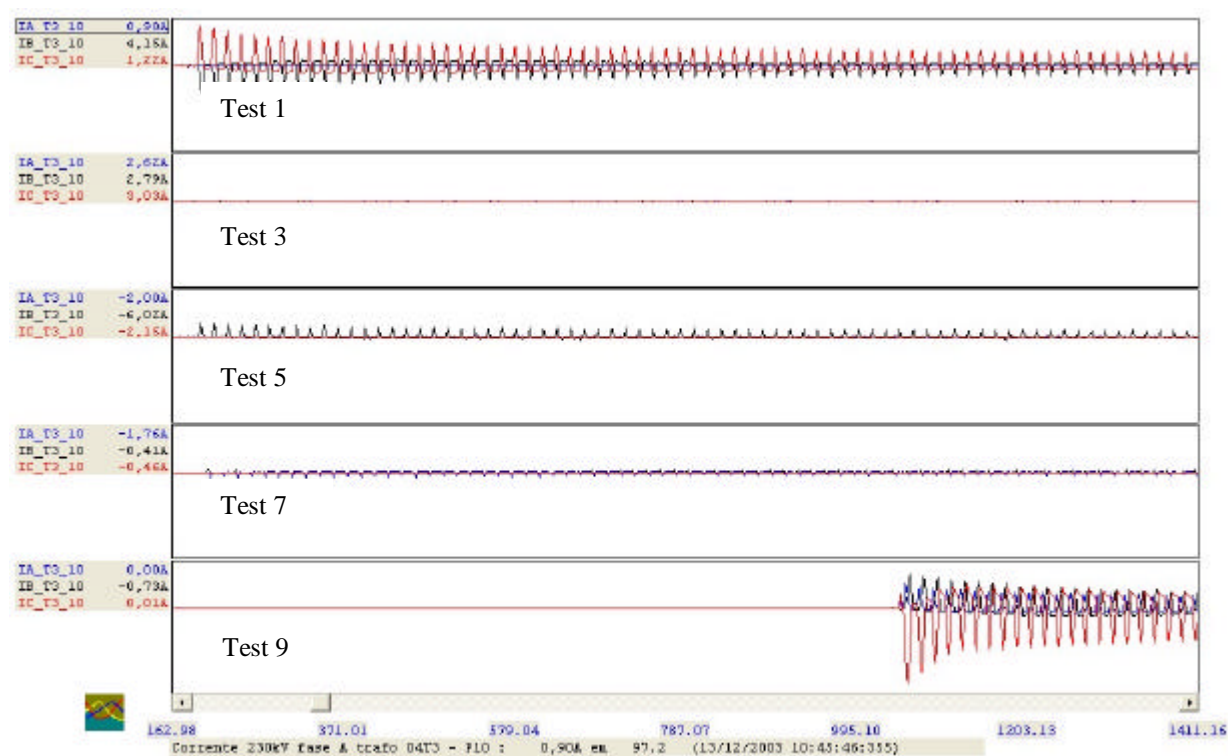


Fig. 4 – Inrush currents in the transformer 04T3 during the Tests 1, 3, 5, 7 and 9.

In the Test 1, the controller was activated, but the residual flux was not measured. Under this circumstance, the controller assumes the residual flux as being zero, with the first pole of the circuit breaker being closed at the voltage peak. In this case, the transformer was not energized according to control strategy developed, as the residual flux was not measured neither considered for the energizing. However, as the controller was on, the closing instants of the circuit breaker poles were controlled anyway by the device, assuming the residual flux was zero. It is interesting to observe that, in this case, the inrush current reached a peak of approximately 600 A, showing that even considering a fixed value for the residual flux (in this case, zero), a controlled switching is better than that without any control (Test 9).

In the Test 3, the energizing of transformer 04T3 was carried out according to the strategy developed, i.e., with the poles of the 230 kV circuit breaker being closed at defined instants based on the residual flux measured during the de-energizing of the transformer (Test 2). The residual flux was measured with base on the decaying voltage waveforms (see Fig. 7).

It can be observed in Test 3 that the magnetizing inrush currents in transformer 04T3 presented values so small that were not detected by the measurement system. This indicates that all three columns of the iron-core had not been saturated. This fact can also be confirmed by observing the small levels of distortion in the 138 kV voltage waveforms (Fig. 5).

The results of Test 3 show clearly the success of the strategy utilized for controlled switching, through which it is possible to energize a transformer without any transient inrush currents of high magnitude. This will, therefore, reduce the system disturbances customarily caused by transformer energizing.

The further Test 5 and 7 were carried out to confirm the robustness of the control strategy. In these tests, the instants of closing the circuit breaker poles were controlled, always taking into account the residual flux measured. As can be observed in Fig. 4, the controlled switching reduced the maximum peak values of the inrush currents to values less than 50% and 20% of the transformer nominal current peak ($251 \times \sqrt{2} = 434$ A), respectively. This validates the strategy proposed.

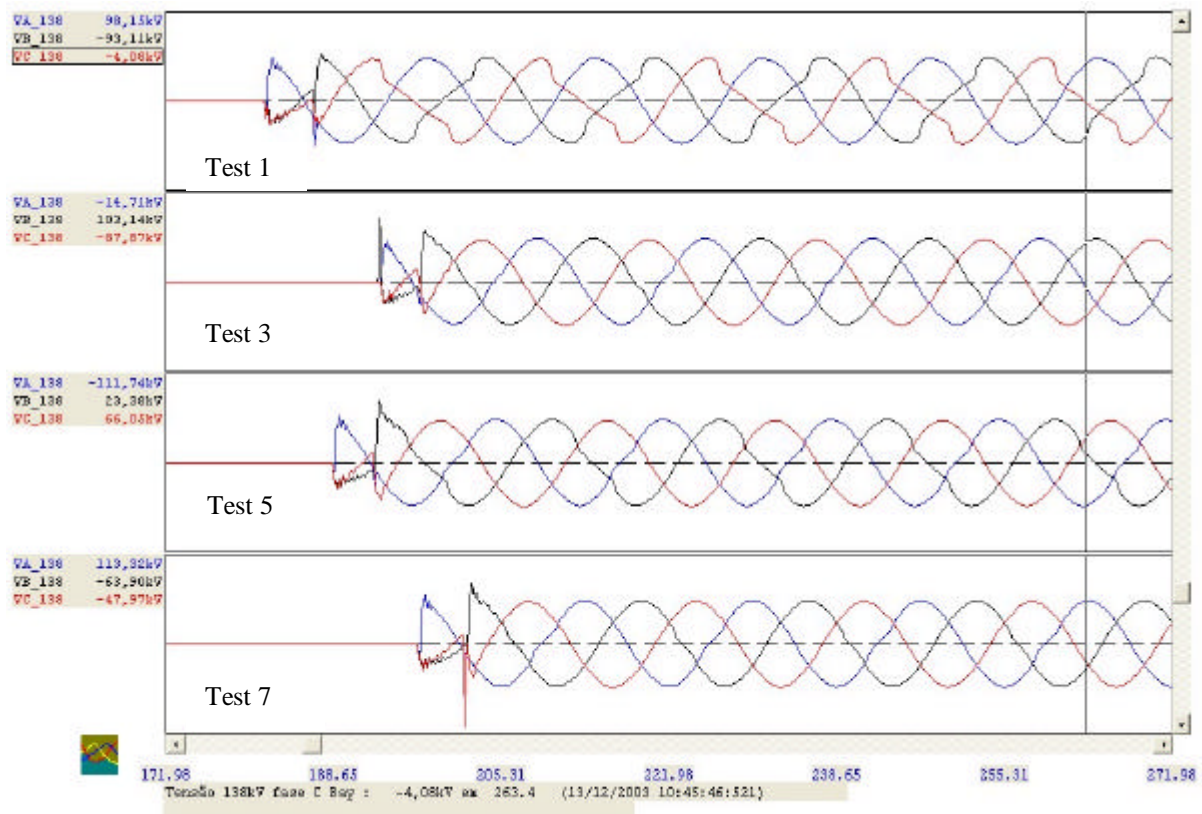


Fig. 5 – Voltages waveforms on the transformer 04T3 (138 kV terminals) measured during controlled switching (Tests 1, 3, 5 and 7).

The voltages waveforms showed in Fig. 5 are those on the 138 kV terminals of the transformer 04T3 during its energizing (Tests 1, 3, 5 and 7). An analysis of the waveforms in the Test 1 shows that the pole of phase A was the first pole closed. In the sequence, the other two poles were closed practically at the same instant, approximately 4.2 ms ($\frac{1}{4}$ of cycle) after the first closing (phase A). It can be observed that the distortions presented on the voltage waveforms of the phases B and C indicate that the core limbs corresponding to those phases have saturated. This can also be confirmed by analyzing the magnitudes of the inrush currents of those phases (Fig. 4, Test 1).

Fig. 6 shows the inrush current waveforms (230 kV side) and the voltages on the 138 kV terminals of the transformer 04T3 during its energizing without controlling of the closing instants of the circuit breaker poles (Test 9). In this case, the circuit breaker poles were closed randomly, with the inrush currents presenting high magnitudes. The first peak of the current in phase C reached a value bigger than 1.100A. This corresponds to approximately 250% of the peak of the transformer nominal current, indicating the occurrence of high levels of saturation in the transformer core. An analysis of the corresponding voltage waveforms suggests that the poles of the circuit breaker were closed practically at the same instant. The distortions presented on the voltages of phases B and C confirm the high level of saturation of the columns of the ferromagnetic core associated to those phases.

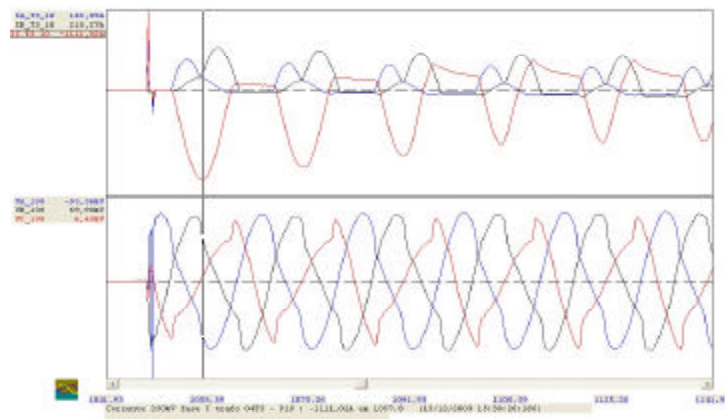


Fig. 6 – Inrush currents (230 kV side) and voltages waves measured in on the 138 kV terminals of transformer 04T3 (Test 9).

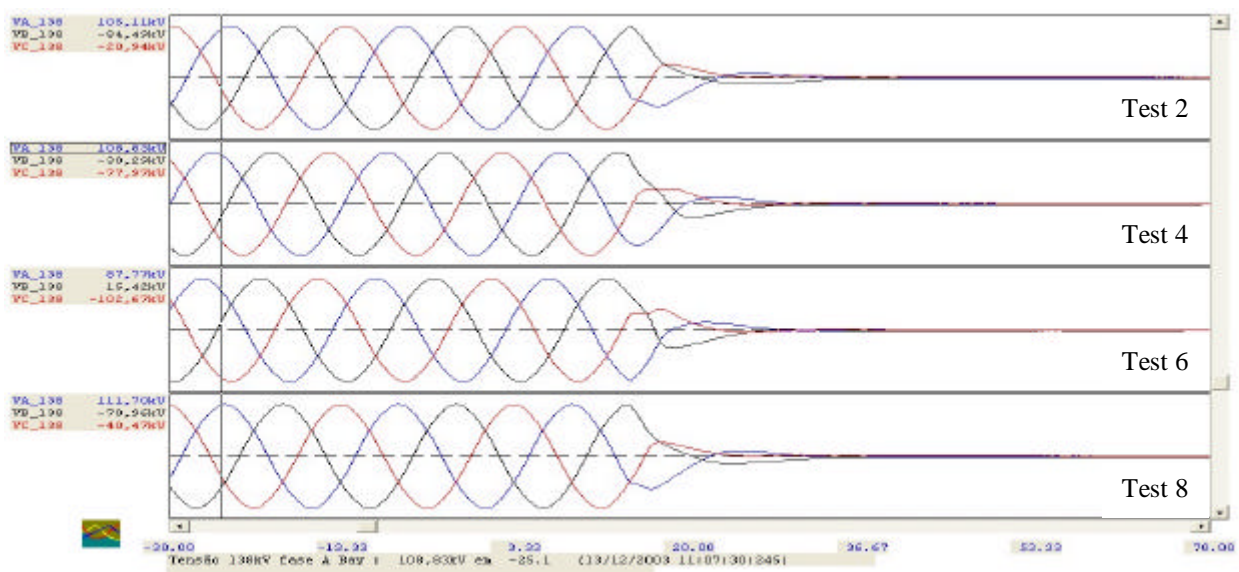


Fig. 7 – Voltages waveforms on the 138 kV terminals of the transformer 04T3 measured during its de-energizing (Tests 2, 4, 6 and 8).

It is important to emphasize that the residual flux in the transformer ferromagnetic core is calculated with base on the integral over time of the decaying voltages measured on the transformer terminals during its de-energizing (see Fig. 7). The value of the residual flux determines the exact instant of the circuit breaker poles closing in the subsequent transformer energizing.

Fig. 8 shows the current and voltage waveforms associated to the loaded transformer 04T2, during the energizing of the transformer 04T3 (Test 9) under test. The distortion presented in the currents of phases B and C indicates that the transformer 04T2 goes also into saturation, suggesting the occurrence of the sympathetic interaction phenomenon between the transformers [3-5].

It is important to note that the currents measured in the transformer 04T2 are the sum of the load and magnetizing currents in that transformer. The distortions in the voltages waveforms shown in Fig. 8 indicate a significant impact on the quality of the system voltage during the transformer (04T3) energizing when there is no control of the closing instants of the circuit breaker poles.

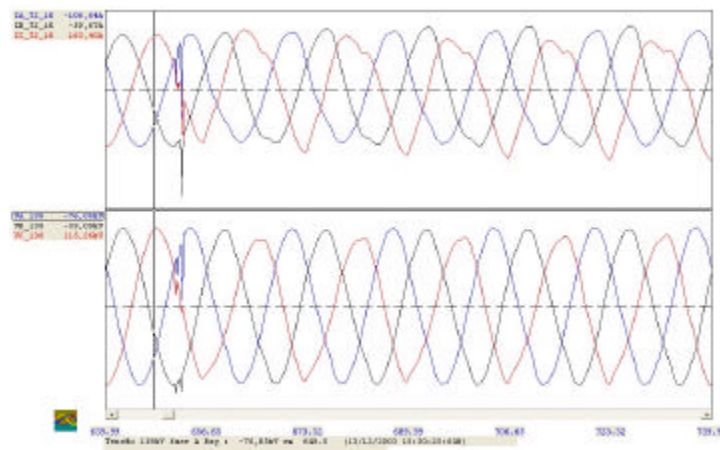


Fig. 8 – Currents (230 kV side) and voltages waveforms (138 kV) measured in the transformer 04T2 during the energizing of transformer 04T3 (Test 9) – Sympathetic interaction phenomenon [5].

5. CONCLUSIONS

The efficiency and robustness of the strategy for controlled switching of three-phase transformer developed were clearly demonstrated throughout several tests carried out on a 100 MVA, 230/138 kV, three-phase, three-limb transformer. The test results confirm the success of the procedures developed.

The test carried out without controlling the closing instants of the circuit breaker poles produced high levels of transformer transients magnetizing currents (inrush currents).. Besides peaks with high magnitudes, these currents present significant asymmetries, harmonic components of all orders (including the dc component) and a relatively slow damping due to the sympathetic interaction between the transformers. With these characteristics, these currents can cause considerable impacts in the supply systems, such as temporary harmonic overvoltages, momentary voltage dips, mechanical stresses on the transformer windings, capacitor banks and transformers protection operation, etc.

The controller used in the field tests proved to be able to mitigate the high magnitudes of transformer inrush currents, reducing all the disturbances caused by them. Other strategies for controlled switching of three-phase transformers still being investigated and will be presented in the near future.

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