IVTs Behavior Characterization in Switching Transients

Maria Carmen Falvo, Umberto Grasselli, Regina Lamedica, and Giuseppe Maranzano

***Abstract* — A power quality (PQ) and harmonics monitoring activity on the power systems in a metro-transit system has been performed by means of Instrument Voltage Transformers (IVTs) there installed. With the aim of identifying IVTs influence on the measurements, a wide laboratory survey has been carried out.**
The paper reports the present state of the work, in progress for many years, on the IVTs experimental analysis. In particular the paper deals with the main results obtained by the laboratory survey on two main types of IVTs: IVTs with equal constructive features and manufacture, IVTs with equal constructive features but different manufacture. The choice of these two types of IVTs is aimed at evaluating the impact of the production process and of the manufacture on IVTs behavior in switching transients.

***Keywords*: High Frequency, Instrument Voltage Transformers, Power Quality, Switching Transients.**

I. Introduction

Along power quality (PQ) and harmonics monitoring activity was performed on the power systems for supplying the electrified metro-transit system of Rome, by means of Instrument Voltage Transformers (IVTs) there installed. During the survey some significant voltage transients were recorded [1]-[4]. Even though it is well known that the best solution to correctly measure voltage transients is the employment of more suitable voltage transducers instead of traditional IVTs, some layout, security and safety constraints imposed to use the existing transducers and not others suitably chosen, as it can often happen in case of surveys on existing plants. By the post-processing of the recorded data, it was possible to identify the overvoltage transient origin in periodic switching operations, performed on the dedicated distribution network with the SF_6 switches. Otherwise the recorded surges were characterized by a front quite close to the standard one for very fast front over-voltages associated to the SF_6 switches, but a maximum value out of the typical range (7 - 8 p.u.) and a characteristic frequency about 100 kHz (found by a Fourier analysis) [5].

Since it is well known that IVT is a critical component for the accuracy of PQ event measurements, it became necessary to identify the IVT influence on these measurements, that could not be taken out of the data sheet specifications set by the manufacture makers. In fact the main parameters, defining the electrical equivalent circuit of an IVT, are usually tested and defined only for the fundamental frequency and not in a wide frequency range. So in order to know IVTs behavior and influence in wide frequency range phenomena, it is necessary to perform tests and to draw out different equivalent circuits for small frequency ranges. The usefulness of this type of analysis is not restricted to the authors' tasks considering that the IVTs are widespread components in many plants, where voltage transients measurements can make useful, and often they are linked to the use of existing IVTs, instead of more suitable voltage transducers. So investigating about the behavior of the traditional IVTs in voltage transients is worthy.

By light of that, in order to have some information on the IVT high frequency behavior trend, without referring to a specific equivalent circuit, a measurement laboratory survey was performed in frequency domain with a wide range (from 50 Hz to 100 kHz) and in time-domain by standard impulsive signals (step impulse, lightning impulse 1.2/50 μs, switching pulse 250/2500 μs) [6].

This survey had pointed out some characteristic frequency very close to the ones of the voltage switching transients, explaining their maximum value out of the typical range. In order to clarify if these resonance phenomena were characteristic of the single tested IVT or of its manufacture, the laboratory survey has been extended to various types of IVTs and in particular to:

- IVTs with equal constructive features and equal manufacture, with the aim of evaluating the impact of production process on their high frequency behavior;
- IVTs with equal constructive features and different manufacture, with the aim of evaluating the impact of manufacture on their high frequency behavior.

Considering the limited types and number of performed measurements, it has been possible only to verify the existence

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of an impact of the manufacture process (that influences the internal constructive characteristics) on the behavior in high frequency transient phenomena. Analytically it has been possible to define the resonance frequency values of the two types of IVTs, but it is not possible to find yet the analytical function that links these values to the electrical parameters of an equivalent circuit. In literature some mathematical models for IVTs at high frequencies are proposed, but sometimes they are very complex and it is not well clarified yet the influence that each constructive feature and the manufacture process can have on the single electrical parameter and its value [7]-[10]. Really some hypotheses have been just made by the authors on possible simplified equivalent circuit of IVT, useful for evaluating its influence on the PQ measurements, but work is in progress and the authors have got some partial results that prefer to show only when they are strongly validated.

For these reason the paper reports the first main results of the extended laboratory survey. In particular Section II reports the main figures of the different analyzed IVTs; Section III includes a description of the laboratory measurements layout; Section IV reports the main results obtained on the two types of IVT, and finally the Section V includes the conclusions.

II. Instrument Voltage Transformers

Instrument voltage transformers (IVTs) are measurement transformers whose primary winding is connected to the voltage that has to be monitored, whereas secondary winding supplies the measurement instruments, in order:

- to reach voltage values compatible to the instruments,
- to provide a galvanic insulation between the two windings,
- to reduce the energy consumption.

The ratio error and the phase displacement, related to the voltage drops on the windings, are the classical non-idealities considered for an IVT. The latter error is not relevant unless the IVT is used in wattmeter conditioning. It is important to stress that these parameters are tested and defined only for the fundamental frequency [11]-[13].

By the light of that, IVTs can be considered non-linear critical components for the PQ measurements, since they can give an inaccuracy in measurements at different frequencies from the rated one. Therefore, with the aim of understanding their effective influence on the measurement results accuracy, it is always necessary to try to characterize their behavior in specific conditions, that means to define their response with a laboratory analysis. This scope has been already reached for a specific type of IVT installed on the power systems for supplying the electrified metro-transit system of Rome (Met.Ro.), whose behavior to the high frequencies had influenced a PQ and harmonics survey, and in particular they had had a great impact on the overvoltages measurements [5]-[6]. In order to summarize the results of the above-said measurements Table I reports the main figures of the measured overvoltages, showing the high values of the switching over-voltage.

TABLE I
STATISTICAL DATA ON OVERVOLTAGES MEASURED AT THE SECONDARY WINDINGS OF IVTS

	Turn off Switching Overvoltage [p.u.]		Turn on Switching Overvoltage [p.u.]	
	Mean V_{rms}	Standard Deviation	Mean V_{rms}	Standard Deviation
Phase R	3.4	2.7	3.9	4.9
Phase S	4.7	4.9	7	5.6
Phase T	5.5	6.5	7.2	8.2

A preliminary laboratory survey and frequency domain analysis on the Met.Ro. IVTs had pointed out that IVTs gave a considerable contribution on the high frequencies events, because it demonstrated some characteristic frequencies about 75 kHz and 125 kHz (see Figure 1), that were very close in magnitude order to the characteristic frequencies of the measured overvoltages.

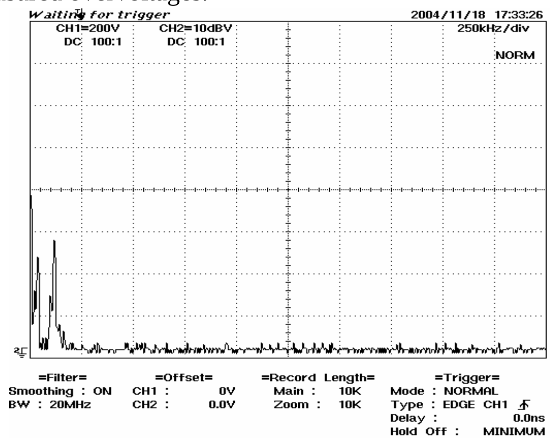

Fig. 1. DFT of the signal acquired at the IVT output when the primary circuit is fed by a very fast-front switching impulse.

In order to compare these IVTs behavior in switching transients and to get additional information on their behavior causes, a new laboratory survey has been performed considering:

- an other IVT of the same type of those ones installed in Met.Ro. power systems in the past time, at whose secondary windings the PQ survey had been performed (Type-A);
- another type of IVT installed in Met.Ro. power systems at the present, in substitution of the first type IVTs that, in the mean time, have been subject at faults (Type-B).

The characteristics of IVTs, subject to the analysis, are summarized in Table II and III.

TABLE II
MAIN CHARACTERISTICS OF TYPE-A IVTS

Model	TESAR VCB 11	
Insulation Level	24 / 50 / 125 kV	
Number of Windings	3	
Rated Transformation Ratio	20 / 0.1 / 0.1 kV	
Rated Frequency	50 Hz	
	First secondary winding	Second secondary winding
Rated Power	50 VA	50 VA
Accuracy Class	0.5	3P

TABLE III

MAIN CHARACTERISTICS OF TYPE-B IVTS

Model	MAGRINI GALILEO VRC 241A	
Insulation Level	24 / 50 / 125 kV	
Number Of Windings	3	
Rated Transformation Ratio	20 / 0.1 / 0.1 kV	
Rated Frequency	50 Hz	
	First secondary winding	Second secondary winding
Rated Power	30 VA	30 VA
Accuracy Class	0.5	0.5

Both the IVTs are fulfilling in according to the [11]. In this way it has been possible to compare the transient response of:

- IVTs with equal constructive features and equal manufacture (Type-A-1 and Type-A-2), by aim of evaluating the impact of production process on their high frequency behavior;
- IVTs with equal constructive features and different manufacture (Type-A and Type-B), by aim of evaluating the impact of manufacture on their high frequency behavior.

III. LABORATORY MEASUREMENT LAYOUT

Laboratory measurement layout has been defined after many tests on a laboratory IVT. A particular attention has been given to the surge generator in order to obtain a realistic reproduction of switching overvoltages and homogenous signals at each test. The final chosen configuration has been reported in Figure 2, where a simplified surge generator architecture and the values of electrical parameters have been reported:

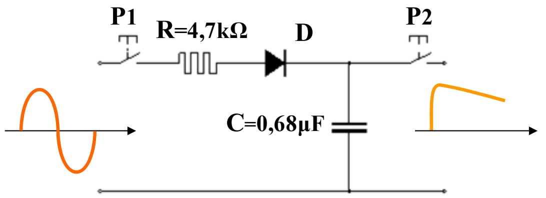

Fig. 2. Surge generator architecture.

The input voltage has been chosen in a range between 12 and 380 V for all the tests, in order to allow a direct output data acquisition by means of an Oscillograph and standard probes (10x and 100x).

The high resolution digital Oscillograph used for data acquisition has the main features summarized in Table IV:

TABLE IV

MAIN FEATURES OF THE OSCILLOGRAPH

Resolution	12 bits / BP 100 MHz
Sample Frequency	1 GS/s in real time 25GS/s with repeated signals
Record Length	2˙500

Fig. 3. Data Acquisition System

In order to estimate the high frequency behavior of the considered IVTs, several measurement set-ups have been implemented. They may be classified in the following configurations:

- tests with the supply on the primary winding and:
  - open-circuit in both secondary windings,
  - short-circuit in one of the secondary windings and open-circuit in the other of the secondary windings;
- tests with the supply on one of the secondary windings and:
  - open-circuit in the primary and in the other of the secondary windings,
  - short-circuit in the other of the secondary windings and open-circuit in the primary winding;
  - short-circuit in the primary winding and open-circuit in the other of the secondary windings.

For each test, repeated for many times, a frequency analysis has been performed by means of a Fast Fourier Transform (FFT) tool included in Oscillograph data software.

Besides a post-processing statistical analysis, on all the results of the same test type, has been carried out in order to evaluate the mean value and the deviation standard of the measured voltage profiles.

IV. EXPERIMENTAL RESULTS

A. *Type-A IVT: short-circuit and open-circuit tests*

Type-A IVTs are those ones installed in Met.Ro. power systems in the past time, at whose secondary windings the PQ survey had been performed.

By aim of evaluating the impact of production process on their high frequency behavior, two Type-A IVTs have been tested (Type-A-1 and Type-A-2), so that they have equal constructive features and equal manufacture.

For each test type (open-circuit and short-circuit), referring to the only ones with the supply on the primary winding, it has been reported as example one of the voltage profiles measured in the two Type-A IVTs input and output (Figures 4, 5 , 6 and 7):

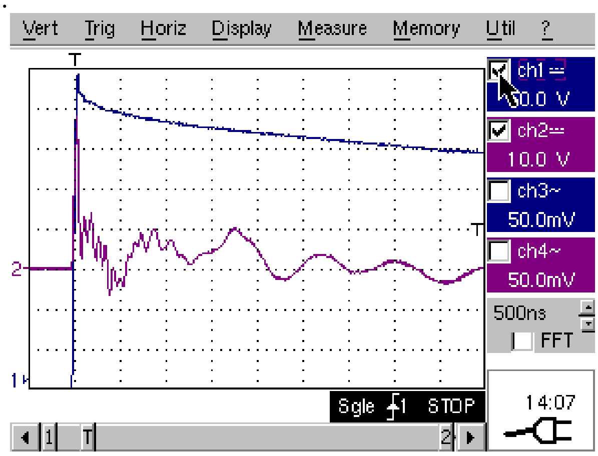

Fig. 4. Test on Type-A-1 IVT with the supply on the primary winding (CH1) and open-circuit in both secondary windings (CH2).

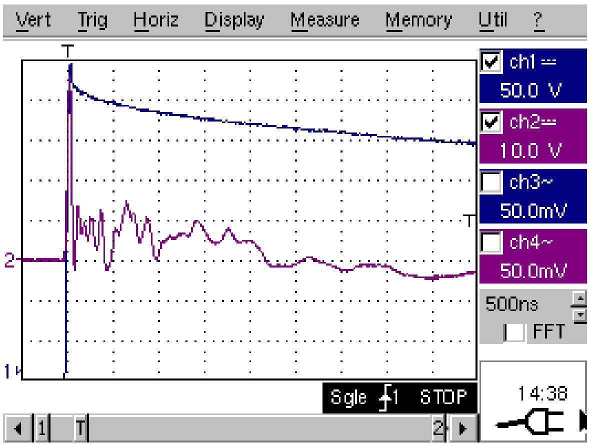

Fig. 5. Test on Type-A-2 IVT with the supply on the primary winding (CH1) and open-circuit in both secondary windings (CH2).

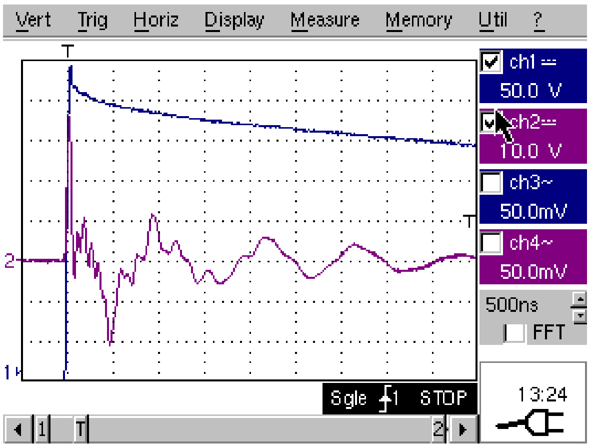

Fig. 6. Test on Type-A-1 IVT with the supply on the primary winding (CH1), short-circuit in one of the secondary windings and open-circuit in the other of the secondary windings (CH2).

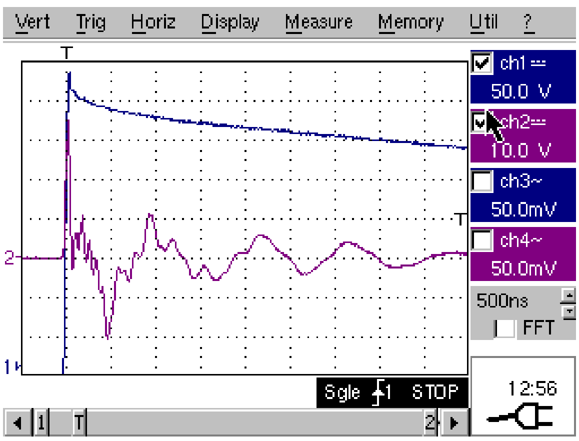

Fig. 7. Test on Type-A-2 IVT with the supply on the primary winding (CH1), short-circuit in one of the secondary windings and open-circuit in the other of the secondary windings (CH2).

As it is shown in the Figures 4, 5, 6 and 7, for all the tests (with open and short circuit), disregarding the highest frequency oscillations in the first instants, due to the surge generator architecture, damped oscillations are induced at the output of the IVT. These oscillations are very similar for the two IVTs. By means of a FFT analysis, it has been possible to verify that the two IVTs are characterized by the same values of characteristic frequencies.

Table V shows as example the characteristic frequencies of the voltage on the open-circuit secondary windings, during the test with supply on the other secondary one and the primary winding in short-circuit, for the two IVTs:

TABLE V
VOLTAGE CCHARACTERISTIC FREQUENCIES
ON THE SECONDARY WINDINGS DURING A TEST

Type-A-1 IVT		Type-A-2 IVT	
Frequency [kHz]	Voltage [V]	Frequency [kHz]	Voltage [V]
244,14	9,91	244,14	10,45
488,3	7,59	488,3	8,49
732,4	10,21	732,4	9,16
976,6	1,22	976,6	2,22
1220,7	2,05	1220,7	3,57
1464,8	2,25	1464,8	1,90

The same results have been found, but not reported, for all the tests.

So it is possible to conclude that equal constructive features and equal manufacture guarantee same behavior in switching transients that means the production process has not any impact on the IVTs high frequency behavior.

B. Type-B IVT: short-circuit and open-circuit tests

Type-B IVTs are another type of IVT installed in Met.Ro. power systems at the present, in substitution of the first type because all the Type-A IVTs, in the mean time, have been subject at faults [5]-[6].

They have been analyzed because they have equal constructive features and different manufacture in respect of Type-A, so it is possible to evaluate the impact of manufacture on IVTs high frequency behavior.

For each test type (open-circuit and short-circuit), referring to the ones with the supply on the primary winding, it has been reported as example one of the profiles of voltage measured in input and output at the Type-2 IVTs (see Figures 8, 9 , 10 and 11):

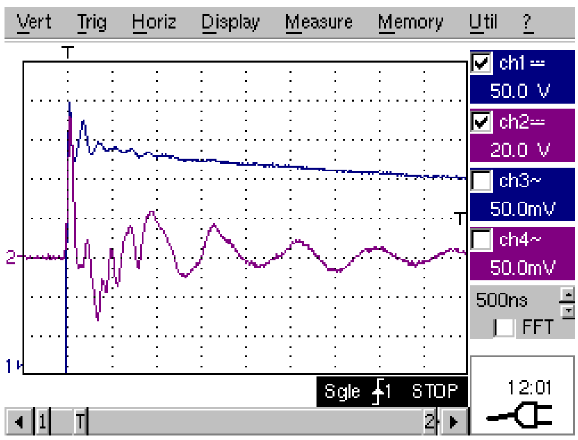

Fig. 8. Test on Type-B IVT with the supply on the primary winding (CH1) and open-circuit in both secondary windings (CH2 on the first secondary).

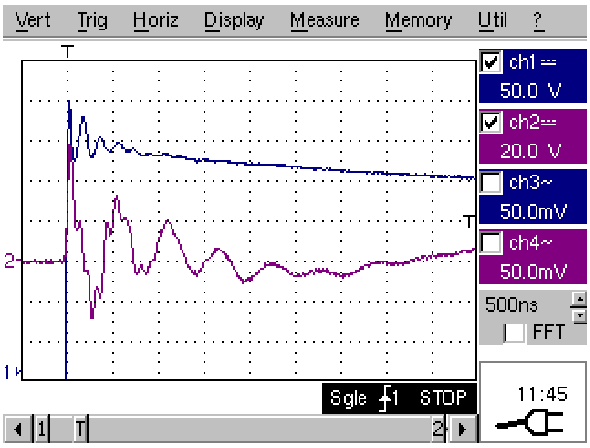

Fig. 9. Test on Type-B IVT with the supply on the primary winding (CH1) and open-circuit in both secondary windings (CH2 on the second secondary).

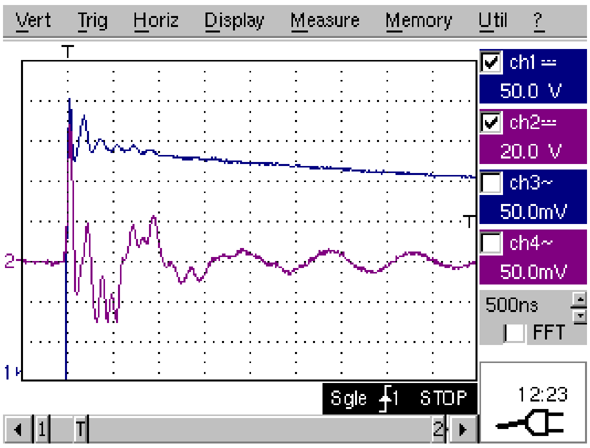

Fig. 10. Tests on Type-B IVT with the supply on the primary winding (CH1), short-circuit in the first secondary windings and open-circuit in the second secondary windings (CH2).

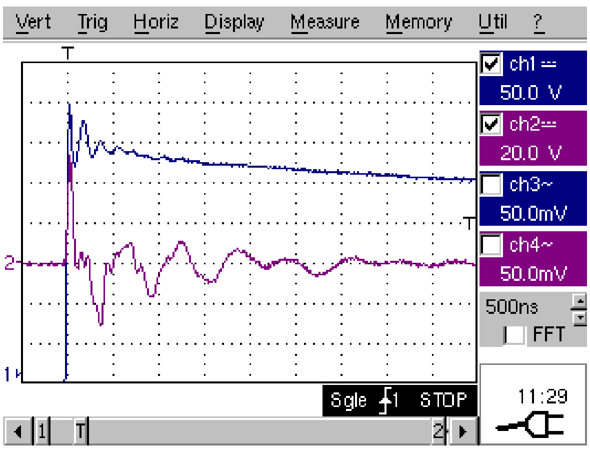

Fig. 11. Tests on Type-B IVT with the supply on the primary winding (CH1), short-circuit in the second secondary windings and open-circuit in the first secondary windings (CH2).

As it is shown in Figures 8, 9, 10 and 11, for all the tests (with open and short circuit), disregarding the highest frequency oscillations in the first instants, due to the surge generator architecture, anyway damped oscillations are induced at the output of the IVT. The same results have been found, but not reported, for all the tests.

These oscillations are clearly different in frequency from those measured on the Type-A IVTs. This statement has been confirmed by the FFT analysis of all the voltage profiles and their comparison.

Tables VI and VII show as example a comparison between the voltage characteristic frequencies of the Type-A and Type-B IVT, during the tests with supply on the primary winding and:

- both the secondary winding in open-circuit;
- one of the secondary windings in short-circuit and the other of the secondary windings in open-circuit.

TABLE VI
TEST WITH SUPPLY ON THE PRIMARY WINDING
AND BOTH THE SECONDARY WINDING IN OPEN-CIRCUIT

	Type-A IVT			Type-B IVT		
Frequenc y [kHz]	Primary Winding Voltage [V]	Secondary Winding Voltage [V]		Primary Winding Voltage [V]	Secondary Winding Voltage [V]	Frequency [kHz]
244,14	76,09	2,44		63,89	2,05	244,14
488,28	72,37	0,97		61,39	1,42	488,28
732,42	64,42	1,49		54,34	3,41	732,42
976,56	53,66	2,01		45,11	4,44	976,56
1220,70	41,20	3,42		34,97	9,19	1220,70
1464,84	27,86	1,68		23,28	1,95	1464,84
1708,98	15,00	1,31		12,51	2,84	1708,98
				3,45	4,41	1953,12

TABLE VII
TEST WITH SUPPLY ON THE PRIMARY WINDING
AND ONE OF THE SECONDARY WINDING IN SHORT –CIRCUIT AND THE OTHER ONE IN OPEN-CIRCUIT

	Type-A IVT			Type-B IVT		
Frequency [kHz]	Primary Winding Voltage [V]	Secondary Winding Voltage [V]		Primary Winding Voltage [V]	Secondary Winding Voltage [V]	Frequency [kHz]
244,14	75,11	0,90		64,42	0,33	244,14
488,28	71,53	0,75		61,92	0,45	488,28
732,42	63,60	2,30		54,84	2,31	732,42
976,56	53,12	5,17		45,46	8,11	976,56
1220,70	40,58	1,93		34,88	4,90	1220,70
1464,84	27,45	1,73		23,89	4,84	1464,84
1708,98	14,75	1,04		12,50	2,34	1708,98
				3,08	1,26	1953,12

The same results have been found, but not reported, for all the tests.

So it is possible to conclude that equal constructive features but different manufacture do not guarantee same behavior in switching transients, that means the manufacture can have impact on the IVTs high frequency behavior.

Taking into account that the two compared IVTs have the same data sheet and parameters set by their manufacturers, it can be deduced that the internal constructive characteristics, strictly depending on the manufacture process and that don't have any influence on the normative specifics, are those ones more impactive on the behavior in high frequency transient phenomena [11]-[13].

V. Conclusions

This work could be considered a good step towards the analysis and the characterization of the IVTs high-frequency behavior. An analysis of the performance of different types of IVTs in transient conditions, in particular in respect of overvoltages with a very fast front, has been carried out. This study has given some information about the IVTs influence on the high frequencies PQ events. In particular the frequency analysis has pointed out a behavior trend:

- equal constructive features and manufacture guarantee same high frequency behavior, that means that the production process does not have any impact on the IVTs high frequency performance,
- equal constructive features but different manufacture do not guarantee same high frequency behavior, that means the manufacture has an impact on the IVTs high frequency performance.

It can give a warning for IVT choice in dedicated applications where high frequency events are relevant (such as the metro-transit power systems): it seems to be crucial to provide to final users, that perform PQ measurements by means of IVTs, additional information about their high frequency behavior, therefore about the internal features depending on its manufacture.

The future activity will concern the analysis of a statistically significant sample of IVTs and the research of a simplified model of IVT in high frequency domain for the evaluation of their impact on PQ measurements performed by means of them.

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