Electrical Transient Interaction between Transformers and Power System – Brazilian Experience

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On behalf of Cigré-Brazil Joint Working Group – JWG – A2/C4-03
"Electrical Transient Interaction between Transformers and Power System"

Abstract – The paper goal is to present the work that has been carried out by the Cigré-Brazil Joint Working Group (JWG) A2/C4–03, called "Electrical Transient Interaction between Transformers and the Power System". A description of some Brazilian utilities experiences regarding transformer failures related to system transients is presented. It is also presented a proposed methodology for transient system studies, in order to evaluate a range of frequencies and waveforms that appear during circuit breaker or disconnector operations and short-circuits into the substation incoming lines, for different voltage levels and arrangements. A frequency spectrum (energy spectral density) comparison between standard impulse test curves and voltages curves, found in the electromagnetic transient simulations, is made. Finally, it presents a discussion on how to use the transient studies results to propose a revision of the specifications, design review practices, system planning and operation evaluations.

Keywords: Transformers, Switching transients, Reliability, Electrical system interaction.

I. INTRODUCTION

A significant number of transformers dielectric failures due to winding resonance has already been reported in the literature. The resonance overvoltages arise in transformers winding when an exciting oscillating voltage, generated by switching operations and faults, coincides with one of the fundamental natural frequencies of a winding or part of a winding. Depending on the magnitude and duration, these resonance overvoltages may cause damage to the transformer internal insulation structure [1]-[5].

Transformer dielectric failures due to system interaction have been reported in the Brazilian electrical system in recent years. In some cases, a clear diagnosis could not be achieved but the evidence led to switching operations being the most probable cause. These reports have motivated the engineering teams of utilities, transformer manufacturers, independent research centres and the national grid system operator to start the Cigré-Brazil Joint Working Group (JWG) A2/C4-03, called "Electrical Transient Interaction between Transformers and Power System" to analyse this problem [6]-[10].

The main focus of this JWG is to gain a better understanding of the oscillatory phenomena resulting from the interaction between the transformer and its surrounding electrical environment after a transient event. In addition, a better knowledge of this phenomenon will allow the group to recommend special procedures to improve system reliability regarding its effects on the transformer.

The report of the members' experiences and the electromagnetic transient studies of several substation arrangements for different voltage levels, commonly used in Brazil, provided the basis for the coming discussions. The electromagnetic transient studies performed by the group were focused on quantifying the magnitude and typical frequency ranges of the high-frequency transient voltages in the transformer terminals, produced by the circuit breaker or disconnector operations and short-circuits close to the substation.

A comparison of the frequency spectrum of the simulated transformer terminal voltage with the spectrum of standard impulse waves were carried out with the aim of checking how representative the standard dielectric tests, which validate the transformer design, are [9], [10].

Also, the JWG A2/C4-03 has been discussing and analyzing alternatives to insert in the processes of planning, specification and design some requirements concerning the high frequency transient voltages. The main idea is to find ways to have more representative transformer models to allow utilities to have more realistic simulation results. Hence, both utilities and manufacturers will have at the design stage a better knowledge of the stresses imposed by the system on the transformer.

The objective of this paper is to present the work that has been carried out so far by the group, including the main discussions and the conclusions reached up to now [6]-[10]. It is important to emphasize that this paper complements the reference [10] with a summary of all simulation results achieved by the group, including transformer energization,

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short-circuit and switching operations.

II. Utility Experiences: Transformers and Power System Interaction

Some important transformer failures have occurred in the Brazilian transmission system in the last ten years. Unfortunately, for different reasons, a clear diagnosis could not be achieved but the evidence led to possible interaction with some system event [6]-[10].

The experience of some Brazilian utilities (CEMIG, CHESF, CTEEP, ELETRONORTE, ELETROSUL and FURNAS) with occurrences involving interaction between transformers and power system is described below:

Case 1: Unexplained dielectric failures of two 500/345/13.8 kV – 400 MVA autotransformers, a few days from each other, in February 1995, led the utility to review its traditional approach regarding transformer reliability. After exhaustive analyses, a common cause suggested for these failures, was the occurrence of internal overvoltage due to frequent switching operations in the substation.

Case 2: During a no-load 230/138/13.8 kV – 55 MVA transformer switching, through the 230 kV bus tie breaker, a flashover occurred in the 13.8 kV bushings leading to a short-circuit to earth. The 13.8 kV transformer terminals were operating in an open condition and not protected by lightning arresters. Failure analysis showed that the dominant frequency of the transient voltages calculated in the 230 kV terminals is very close to one of the winding resonant frequencies, which corresponds to the highest amplification factor in the 13.8 kV terminals.

Case 3: Dielectric failures have been registered in single-phase units of different manufacturers, since the 16/16/500 kV – 555 MVA step-up transformer banks started their operation in 1988. Short-circuits between turns in the HV winding, between HV and LV windings, and LV winding to ground were observed. Digital simulations of no-load breakers and disconnectors switching in the 500 kV terminals and frequency response measurements showed that the transient voltage dominant frequencies were very close to the windings resonant frequencies for some units, leading to the highest amplification factors in the 16 kV terminals.

Case 4: In a group of twelve 765/345/20 kV – 500 MVA single-phase autotransformers of different ages and manufacturers, four units have failed within six months in 2005, leading the utility to a detailed investigation to determine possible causes. During this investigation, a new failure occurred in April 2006. This substation has 9 shunt capacitor banks of 200 Mvar each that were gradually included in the 345 kV sector due to the necessity of voltage control in this system area. The failures occurred after the last 4 shunt capacitors banks were installed. Site measurements and digital analysis have not shown any relationship between the failures and the switching of these capacitive units. Two more units have been damaged after this date.

Case 5: In 1994 there was a failure in a 13.8/550 kV – 378 MVA step-up transformer due to very fast transients associated with disconnect switching operation in the 550 kV GIS. The analysis performed by a team composed of utility, manufacturer and research centre engineers, helped by digital simulation, field measurements and analysis of the transformer internal insulation withstanding, confirmed that the very fast transients were the fundamental cause of the failure.

Case 6: In 1988 some minutes after a phase to ground fault in a 460 kV transmission system followed by automatic reclosure, there was a dielectric failure in one phase of a 550/460/13.8 kV – 300 MVA transformer bank. The internal inspection concluded that there had been an electric discharge between contacts of the tap changer. The frequency response measurement carried out on the regulation winding showed significant resonance in the range of 4 to 6 kHz, which is typical of switching surges.

III. Digital Simulations

The analysis of these occurrences motivated the development of large-scale electromagnetic transient simulations with the objective of investigating the transient voltages in the transformer terminals that arise during circuit breaker closing (transformer energization), disconnector operations and short-circuits close to the substations. The objective was to quantify not only the magnitude but also the typical frequency ranges of the high frequency transient voltages in the transformer terminals. These studies were carried out for several voltage levels and for typical layouts of high voltage substations in Brazilian system.

In order to verify how this frequency range was taken into account in the standard dielectric tests, an analysis of their frequency spectrum was performed and afterwards compared with the spectrum of the simulated curves. The aim was to check if some voltage stress determined by the case studies were well reproduced in the standard tests and consequently in the transformer designs [9], [10].

The following section will present a brief description of the modeling guidelines considered in digital simulations [6], [7], the simulation results and analysis for circuit breaker closing, disconnector operations and short-circuits close to the substation.

A. *Modeling Guidelines*

An accurate simulation requires a valid representation of network components for a specific frequency range that usually corresponds to some particular transient phenomenon. An acceptable representation of each component in a wide frequency range is very difficult, and even practically impossible for some components [6], [7]. Due to the frequency spectrum considered, the frequency dependence of the parameters should be taken into account, when possible, in models for transmission lines, substation buses and power apparatus. For this to be done, modeling guidelines based on reference [11] are applied. The present section describes the adopted approach. In all transient studies, digital simulations were carried out using the Alternative Transients Program (ATP) [12].

1) Power transformer modeling:

In this work three different power transformer models were considered:

a) Simple lumped capacitance to ground: This model is traditionally applied in insulation coordination studies;

b) Network of lumped capacitances: A more accurate model supported by the manufacturer, considering capacitances between windings, windings to core and windings to ground as well as bushing capacitances;

c) Frequency-dependent equivalent model (black box): An equivalent RLC network obtained from field measurements (admittance curve in the frequency-domain). This model is adequate when frequency responses are available. The black box model was obtained using a recent implementation of the Vector Fitting routine [13], [14] called Matrix Fitting [15] or with the software Sintnet [16].

As far as the transformer modeling is concerned, application of frequency-dependent equivalent models (black box) [13], based on system identification routines, were expected to give more accurate results with transient voltages having relatively greater attenuation and smaller amplitudes due to the presence of resistances in the equivalent transformer circuit. It was also observed that the simple lumped capacitance model representation may lead to similar results if the equivalent capacitance is obtained from the frequency response model for the dominant frequency because, in this case, this dominant component will be well reproduced. The other frequency components, as a consequence of the model simplification, might not be so well reproduced [9], [10].

2) Substation and transmission lines modeling:

The substation apparatus, such as circuit breakers, disconnectors and instrument transformers were represented by their stray capacitances to ground, as proposed in [11]. All of the equipment locations were derived from the substation layout drawings. Mostly, frequency-dependence of transmission lines parameters were taken into account using ATP JMarti setup [12]. Substation buses and conductors between discontinuity points inside the substation, and connections between substation apparatus were represented by line sections, modeled as three-phase untransposed distributed parameter, taking frequency-dependence into account, if they were long enough. Otherwise, a lumped impedance was used.

B. Digital simulations Results

The electromagnetic transient simulations results are presented for several case studies that evaluate the high frequency transient voltages in the transformer terminals generated by circuit breaker closing, disconnectors operations and short-circuits close to the substations.

Initiated with circuit breaker closing operations (transformer energization), the transient voltages values at the transformer terminals were below the typical surge arrester protective level and the transformer insulation levels. The dominant frequency of the transient voltages was in the 60/200 kHz range, regardless the voltage level and for typical layout of high voltage substation. Only in the cases for uncommon substation ring arrangement or with a short distance between the transformer and the circuit breaker, the dominant frequency was above 200 kHz. These results were presented and deeply discussed in [6], [7].

Afterwards, electromagnetic transient simulations were performed to investigate the high frequency transient voltages in the transformer terminals generated by disconnector operations. The critical frequency of the transient voltages was in the 200/800 kHz range.

The same was performed for short-circuits close to the substations and the critical frequency of the transient voltages was in the 20/970 kHz range.

The frequency spectrum analysis (unit *Vs*) for the standard dielectric tests waves and for the simulated curves, were also compared for each transient and several cases resulted in stresses.

Based on this analysis, the group devised a new parameter, Frequency Domain Severity Factor (FDSF), defined as the ratio of the *Vs* calculated from the transient analysis to the *Vs* associated with the standard impulse test waves. To assure that the system event will be properly represented by the standard impulse waves, the FDSF should be less than 1 considering their maximum Vs values of these waves. These values give rise to a Vs envelope curve, which represents the limit to be considered for the tests to be applied in the transformer. This envelope considers the variation of the chopping time from 2 µs to 6 µs of the chopped wave. Fig. 1 shows the spectrum of these test waves considering different time to chopping from 2 µs to 6 µs [9], [10].

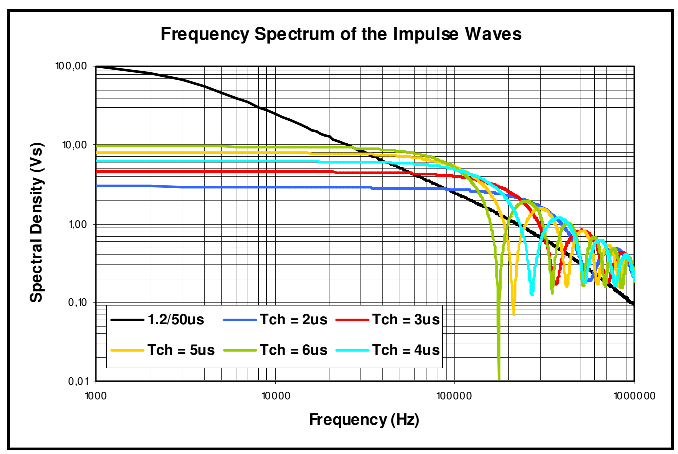

Fig. 1 Spectrum of lightning impulse waves

The FDSF values are presented in Tables 1, 2 and 3 for circuit breaker closing, disconnectors operations and short circuits analysis, respectively. In Table 1, for several case studies, the FDSF values are greater than one, which means that the spectrum of the transformer terminal voltages exceed the spectrum of the dielectric standard waves.

TABLE I
SIMULATION RESULTS FOR CIRCUIT BREAKER CLOSING

Study	Voltage level (kV)	Station layout	Switched equipment	Breaker distance (m)	Critical frequencies (kHz)	FDSF			Transformer Model
						1.2/50us	CW (3us)	Envelope	
1	345	Breaker-and-a-half	Autotransformer 500/345/13.8 kV – 400 MVA	123	190	1.62	0.75	0.75	RLC
2	230	Main and auxiliary bus	Transformer 230/138/13.8 kV – 55 MVA	20	350	3.90	7.31	1.57	CAP
				128	210	2.95	1.30	1.29	
3	500	Breaker-and-a-half	Transformers 500/16/16 kV – 555 MVA	540	70	1.43	1.19	0.76	CAP
					160	1.20	0.55	0.54	
4	345	Breaker-and-a-half	Autotransformer 765/345/20 kV – 500 MVA Manufacturer A	190	90	1.87	1.37	0.87	CAP
				190	90	1.29	0.94	0.60	RLC
			Autotransformer 765/345/20 kV – 500 MVA Manufacturer B	190	70	1.60	1.46	0.79	CAP
				190	70	1.19	1.08	0.59	RLC
5	230	Double bus, single breaker	Autotransformer 345/230/13.8 kV – 225 MVA	60	190	3.62	1.52	1.52	CAP
				180	120	2.21	1.13	0.96	
					320	1.20	1.16	0.47	
6	500	Breaker-and-a-half	Autotransformer 525/230/13.8 kV – 672 MVA	186	120	1.86	1.00	0.85	CAP
					420	5.0	3.87	1.97	
					460	3.42	1.66	1.27	
					510	3.04	1.12	1.12	
				186	130	1.98	1.01	0.90	RLC
					410	2.06	1.91	0.80	
					510	2.08	0.77	0.77	
7	500	Breaker-and-a-half	Transformer bank 525/230/13.8 kV – 450 MVA	170	90	1.63	1.04	0.73	CAP
					130	2.15	1.05	0.94	
					280	2.30	1.34	0.92	
					810	3.96	1.33	1.10	
					980	3.75	1.45	1.09	

TABLE II
SIMULATION RESULTS FOR DISCONNECTOR OPERATIONS

Study	Voltage level (kV)	Station layout	Switched Disconnector	Critical frequencies (kHz)	FDSF			Transformer Model
					1.2/50us	CW (3us)	Envelope	
1	500	Breaker-and-a-half	Breaker Disconnector	340	0.53	0.84	0.22	RLC
				410	1.08	1.00	0.42	
				500	1.38	0.53	0.53	
2	500	Breaker-and-a-half	Breaker Disconnector	467	1.99	0.92	0.75	CAP
				840	4.12	1.25	1.19	
3	230	Double bus	Breaker Disconnector	790	1.86	0.67	0.57	CAP
				720	0.07	0.05	0.02	RLC
4	345	Breaker-and-a-half	Transformer Disconnector	215	0.98	0.44	0.43	RLC
				304	0.93	0.73	0.38	
5	345	Breaker-and-a-half Man. A	Breaker Disconnector	760	0.37	0.23	0.11	CAP
				730	0.85	0.77	0.26	RLC
		Breaker-and-a-half Man. B	Breaker Disconnector	750	0.18	0.12	0.05	CAP
				730	0.87	0.79	0.27	RLC
6	230	Double bus	Breaker Disconnector	820	2.12	0.61	0.61	CAP

CAP: Lumped capacitance transformer model
RLC: Frequency dependence equivalent transformer model

TABLE III
SIMULATION RESULTS FOR SHORT-CIRCUITS

Study	Voltage level (kV)	Station layout	Distance from the SS (km)	Critical frequencies (kHz)	FDSF			Transformer Model
					1.2/50us	CW (3us)	Envelope	
1	500	Breaker- and-a-half	1	110	1.09	0.62	0.50	RLC
				140	0.84	0.41	0.38	
				190	0.51	0.22	0.22	
			5	30	0.42	0.79	0.39	
				80	0.39	0.29	0.19	
				130	0.57	0.29	0.26	
				210	0.50	0.22	0.22	
2	500	Breaker- and-a-half	0.5	20	0.28	0.76	0.28	CAP
				90	1.26	0.23	0.16	
				210	0.40	0.18	0.18	
				970	0.64	0.24	0.20	
3	230	Double bus	0.50	370	0.36	0.88	0.15	CAP
			3	370	0.30	0.72	0.12	
4	345	Breaker- and-a-half	3.75	153	0.18	0.08	0.08	RLC
				213	0.23	0.10	0.10	
				242	0.22	0.10	0.09	
				274	0.27	0.15	0.11	
				359	0.26	0.75	0.11	
5	345	Breaker- and-a-half Manufacturer A	1	140	0.25	0.13	0.11	CAP
				140	0.17	0.09	0.08	RLC
				560	0.40	0.15	0.14	
		Breaker- and-a-half Manufacturer B	1	100	0.21	0.14	0.10	CAP
				100	0.13	0.09	0.06	RLC
				560	0.29	0.11	0.10	
6	230	Double bus	4.0	150	0.05	0.16	0.04	CAP

CAP: Lumped capacitance transformer model
RLC: Frequency dependence equivalent transformer model

Nevertheless, in the case studies for disconnector operations showed in Table 2, the FDSF value is greater than one in just one case. For short-circuit analysis, showed in Table 3, there is no case study with FDSF values greater than one.

It is necessary to emphasize that FDSF values, presented in Tables 1, 2 and 3, considered critical frequencies up to 1 MHz in accordance with the range of frequency responses measurements for most transformers under analyses that did not exceed this frequency. Hence, up to 1 MHz, it is possible to assure that the frequency dependent equivalent models, considered for the transformers, are representative of the equipment behavior. Transformer measurement and modeling guidelines for frequencies above 1 MHz are still under analysis.

An example of the spectrum of the transformer terminal voltages compared with the spectrum of the dielectric standard test waves for each type of transient are presented in the Figs. 2b, 3b and 4b. These Vs curves correspond to the case studies from Tables 1, 2 and 3, which presented the greatest FDSF values.

Figs. 2a and 2b present the transformer terminal voltages for circuit-breaker closing and its frequency spectrum from the case study 6 of the Table 1. In this case, the FDSF value reaches 1.97 at the critical frequency of 420 kHz, considering the transformer modelling as a lumped capacitance to ground. This result indicates that this event is not properly represented by the standard impulses. Still on Fig. 2b, the Vs curve, for the frequency dependent equivalent model (RLC) of the transformer, at 130 and 410 kHz the FDSF, is greater than one considering the 3 µs chopped wave but less than one for the 6 µs chopped wave. This result shows the importance of considering in the transformer insulation design chopped waves with time varying from 2 µs to 6 µs and the adequate transformer modelling.

Figs. 3a and 3b present the transformer terminal voltages for disconnector operations and its frequency spectrum from the case study 2 of the Table 2, whose FDSF value reaches 1.19 at 840 kHz.

Figs. 4a and 4b present the transformer terminal voltages and its frequency spectrum for short circuit analysis. For these cases, as shown in Table 3, there was no FDSF value greater than one.

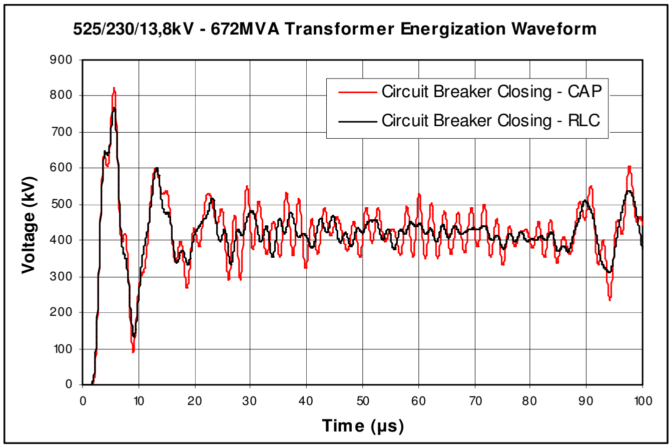

Fig. 2a Transformer terminal voltage waveform for transformer energization.

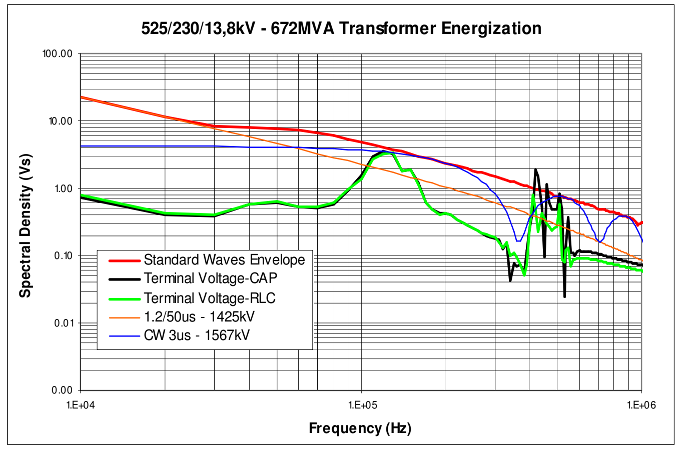

Fig. 2b Spectrum of transformer terminal voltage for transformer energization.

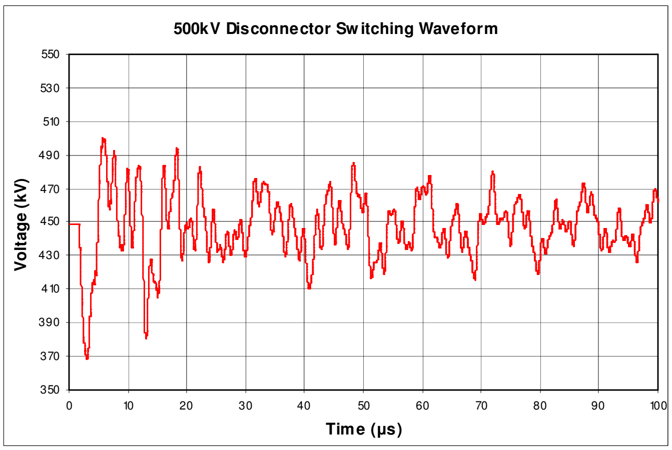

Fig. 3a Transformer terminal voltage waveform for disconector switching.

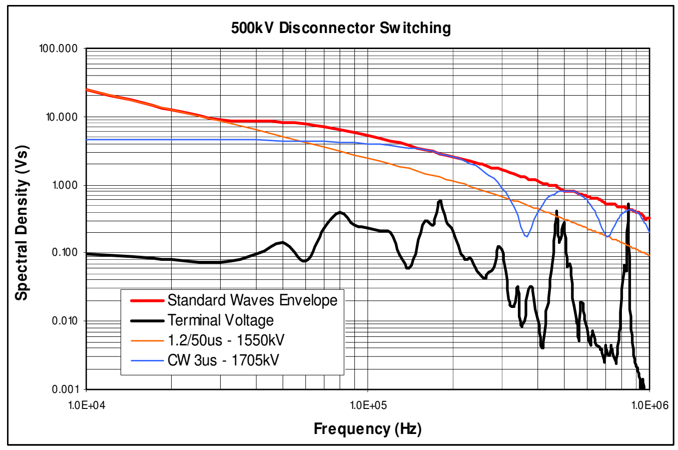

Fig. 3b Spectrum of transformer terminal voltage for disconnector switching.

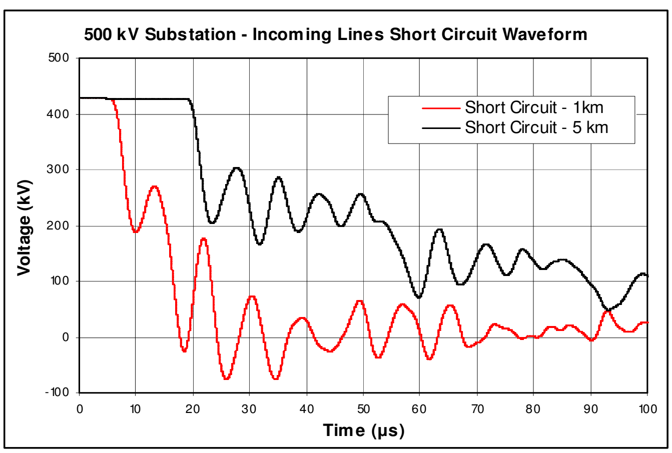

Fig. 4a Transformer terminal voltage waveform for short-circuits

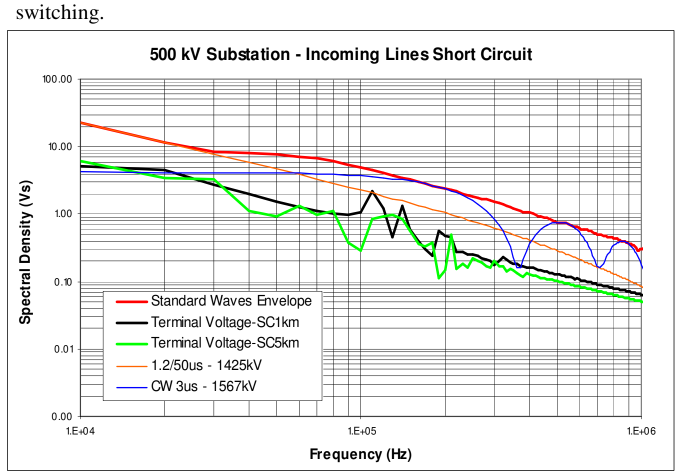

Fig. 4b Spectrum of transformer terminal voltage for short-circuits

According to the Brazilian standards, chopped waves are required for every impulse test sequence in the mentioned range. Therefore, it is possible to consider that a new transformer designed according to the Brazilian standards is able to withstand, at least once, dielectric stress with the frequency spectrum below the upper contour of the Fig. 1 [9], [10].

One important conclusion that could be drawn by the analysis presented was the importance of the chopped wave standard test as in most cases considered it was the one that better represents the stresses imposed by the system [9], [10].

In general, the historical high reliability and low rate of failure of the transformers show that most of this equipment is expected, in some frequency range, to withstand operational stresses higher than the standardized ones. A critical situation, for example, is when one or more frequencies of the terminal voltage coincide with some transformer internal resonance. In this case the resulting voltage amplification may lead to the transformer failure. This coincidence must be avoided or mitigated and early stage analyses may be an efficient alternative [9], [10].

One possible alternative is the usage of the spectral density diagram of Figs. 2b, 3b and 4b in the substation design stage or during the expansion planning. Transformers are well designed to withstand all dielectric tests and consequently, stresses up to the limit of the standard waves envelope. Therefore, a similar principle of the traditional insulation coordination may be used in frequency spectrum. Both, the adoption of an adequate transformer insulation level or the use of mitigation techniques to reduce the stresses across the transformer [9], [10] are alternatives to adjust and select the desired safety margin of the equipment.

This safety margin to be applied to the envelope of the dielectric standard test waves must take into account the maintenance and operation conditions, the statistical dispersion of the insulation withstand voltage and the number of applications expected through the equipment service life.

The application of pre-insertion resistors is one of the conventional solutions to reduce the overvoltage magnitudes at the transformer terminals and to increase the voltage attenuation. Controlled closing switching could also be applied to provoke a reduction of the overvoltages but should be analyzed with care, as it will cause an increase in the inrush current during transformer energization [9], [10].

IV. Transformer Specification

The results of the transient electromagnetic simulations together with the analysis of the transformer failures in the field, pointed out the necessity of a better knowledge of the transformer dielectric response. Important voltages in frequencies up to 1MHz may not be well represented by the standards and, consequently not considered during the design. This fact may explain some transformer failures and their influence in system reliability [9], [10].

Based on these facts, the JWG A2/C4-03 has been discussing and analyzing alternatives to insert in the processes of planning, specifications and design some requirements concerning the high frequency transient voltages. Fig. 5 presents a flow diagram that proposes some steps to be followed by utilities and manufacturers and includes a close interaction between the parts during the design process of the transformer. The main idea is to find ways to have more representative transformer models to allow utilities to have more realistic simulation results.

On the other hand, the manufacturers will have a better knowledge of the stresses the system will impose on the transformer, in order to take these into consideration at the design stage [9], [10].

The feasibility of putting into practice the steps proposed by the flow diagram above was thoroughly discussed by the group with important contributions from the manufacturers concerning the impact on the transformer design cost and delivery time. To start with, the main difficulty recognized was the lack of knowledge of the transformer characteristics, necessary for the utility to perform the initial transient studies, especially for new equipment. On the other hand, the manufacturers pointed out some difficulties in devising a representative white box model of the transformer considering the loss variation with the frequency.

To tackle these points, the group agreed on some recommendations that are presented below [9], [10]:

A. Insulation Coordination Studies

In insulation coordination studies, which are usually performed at the planning stage and substation design, the definition of the insulation levels should take into account not only the maximum value of the transient voltages but also their frequency spectra, comparing them with the spectrum of standard impulse waves (FDSF calculation). In case of FDSF greater than one, an increase of the insulation levels, changes in substation arrangement and/or overvoltage mitigation techniques should be considered.

B. Transformer model for initial studies.

For new transformers, a typical impedance versus frequency curve measured from a similar transformer can be used in two ways:

1) *Calculation of a black box model using the Vector Fitting routine [13] or similar.*

2) *Simple lumped capacitance model representation:* An equivalent capacitance can be obtained for the dominant frequency range of each event considered, based on the impedance x frequency curve. If no typical curve is available, simple lumped capacitance may be used [11].

For transformers already in operation, it is suggested having the impedance versus frequency curve measured if it is not already available and to use it to calculate a black box model, as discussed above.

The manufacturer can also provide a more detailed model of the transformer with at least some representative capacitances to earth and among the windings.

C. Manufacturer transformer model

During a more advanced stage of the design, it is highly recommended that the manufacturer provide the client with a more accurate model of the transformers to allow a revaluation of the transient studies. This can be done by providing a lumped RLC circuit representing as many elements as possible of the winding parts. This model would be valid for a given specific frequency range.

Another possibility is to provide a theoretical impedance versus frequency curve that can be used as an input for the calculation of a black box model, already discussed.

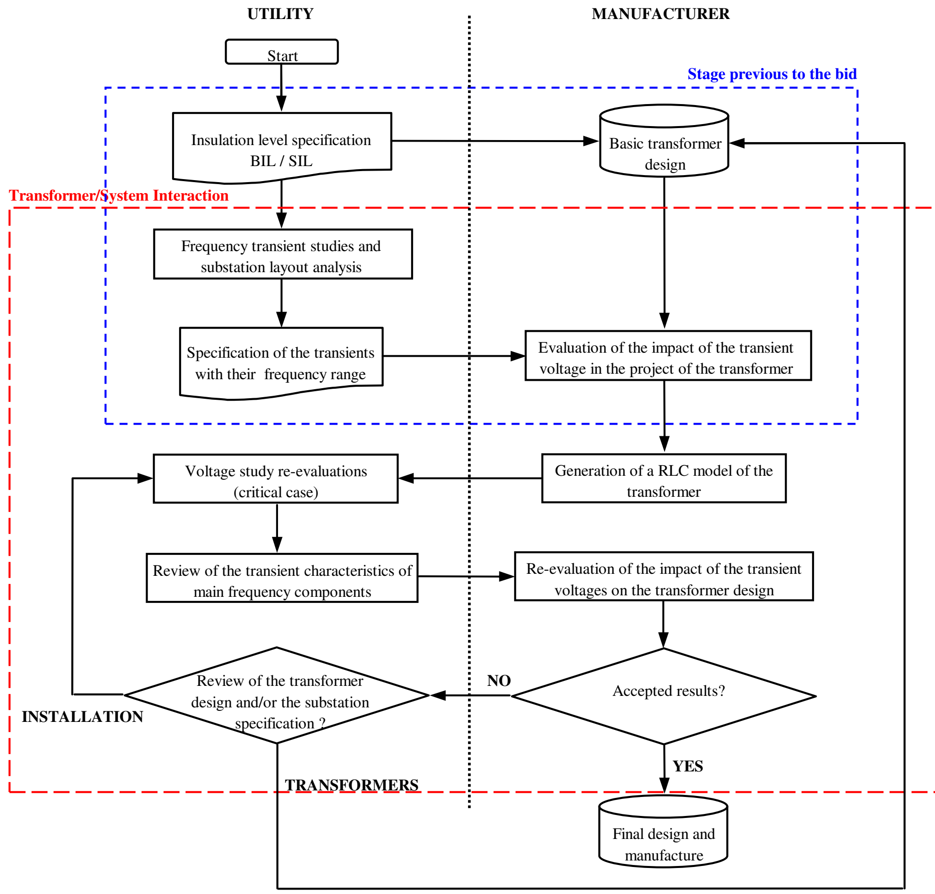

Fig. 5 Proposed Flow diagram

V. Conclusion

Although very reliable, some transformers have failed in conditions where the cause of failure could not be identified. In some cases, the evidence led to system interaction as the most probable cause. Digital simulations have shown that the voltage stresses at the transformer terminals may be not well covered by specified standardized waves. These voltage stresses may exceed the transformer withstand design capability.

As far as the transformer design is concerned, the group agrees that an improvement in reliability may be achieved by an upgrade of transformer specifications, the implementation of design review practices or even the improvement of standard dielectric tests to make them cover a wider range of system condition.

Alternatively, system analyses may consider economical aspects of using controlled switching or introducing pre-insertion resistors in circuit breakers or even a resistor-capacitor snubber to reduce the stress amplitude and increase the damping at higher frequencies.

The group next main task will be to find a reasonable way to use the transient study results to identify risk factors that may increase the probability of transformer failures due to transients and help evaluate the necessity of a case-by-case analysis. In critical cases, during the design stage, the transient analyses may be made in a more accurate way by the utility's and the manufacturer's engineers in order to have the results of the interaction considered in the substation design. One way to achieve this interaction was described by the flow diagram.

VI. Credits

The Cigré-Brazil Joint Working Group (JWG) A2/C4-03 is composed by A.C. O. Rocha (Convener), A. B. Fernandes, A. Portillo, A. R. F. Freire, C. Machado Jr., C. O. Kajikawa, D. S. Arentz, F. R. Alves, F. Salgado, G. M. Bastos, G. S. Luz, J. C. Mendes, J. F. L. Oliveira, J. R. Torrens, J. T. Honda, M. V. Godoi, R. Antunes, R. Asano Jr., R. Vaisman, R. G. Tompson, R. M. Azevedo, S. O. Moreira, U. R. R. Massaro.

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