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Electrical Transient Interaction between Transformers and the Power System

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"Electrical Transient Interaction between Transformers and Power System"
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SUMMARY

Transformer dielectric failures in the Brazilian transmission system, with unexplained causes, motivated the formation of a Cigré Joint Working Group JWG A2/C4–03 called "Electrical Transient Interaction between Transformers and the Power System". The group's main goal is to acquire a better knowledge of this phenomenon, discuss new actions to prevent failures and thus contribute to the improvement of system reliability.

With this objective, the JWG intends to propose some recommendations, regarding the electrical transient interaction between transformers and the power system, that will emphasize the necessity of detailed transient studies to promote an upgrade of technical specification, an improvement in system planning and operation criteria.

The working group started its activities in May 2005 and is composed of around 30 members, representing utilities, research center, manufacturers, universities and the national grid system operator.

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 already reached. The following topics will be presented: a methodology for transient system studies, the first results related to transformer energization, disconnector switching, design review practices, system planning and operation improvement. The future activities of the JWG will also be commented.

KEYWORDS

Transformers - Switching transient – Reliability - Electrical System Interaction

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1. INTRODUCTION

In recent years some transformer dielectric failures due to system interaction have been reported in the Brazilian electrical system. In some cases, a clear diagnosis could not be achieved but the evidence led to switching operations being the most probable cause [1]. These reports have motivated the engineering teams of utilities, transformer manufacturers and independent research centers to start a Joint Working Group A2/C4-03 – Electrical Transient Interaction between Transformers and Power System to analyse this problem.

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 enable the group to recommend special procedures to improve system reliability regarding its effects on the transformer.

Digital programs for electromagnetic transient simulation in time-domain have been used for years to calculate system overvoltages and to provide the necessary data for an optimized insulation coordination based on the peak voltage. With the current experience, it is possible to conclude that, peak values, although very important, are not the only risk factor for the transformer. Also the oscillatory excitation involving the specific interaction of each piece of equipment with the system, due to transient events, should be taken into account.

Some oscillatory excitation, even of low amplitude, may occur in frequencies that may excite a part-winding resonance resulting in a local amplification. As the transformers are constantly exposed to transient events such as lightning, switching operations, short-circuits, etc. the resonance at singular points in the winding may continuously stress its insulation leading to a failure, sometimes hours after the events.

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 already reached. The main topics are summarized below:

- Brazilian utility experiences regarding transformer failures related to system transients;

- Transient system studies in order to evaluate the range of frequencies that appears during switching operations in substations of different voltage levels and arrangements;

- Presentation of the first results related to circuit breaker and disconnector switching and short-circuits close to substations of different utilities up to 500 kV;

- Proposal for an upgrade of present transformer specifications.

The report of the members' experiences and the simulation of several substation arrangements for different voltage levels, commonly used in Brazil, provided the basis for the coming discussions. Transformer standards and specifications are to be reconsidered in order to establish an adequate compromise between the equipment operational reliability and the necessary clarity and impartiality to evaluate designs of different manufacturers.

2. 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.

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

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 center engineers, with the help of 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 on the regulation winding showed significant resonance in the range of 4 to 6 kHz, which is typical of switching surges.

3. DIGITAL SIMULATIONS

The analysis of these occurrences motivated the development of large-scale electromagnetic transient simulations with the objective of quantifying not only the magnitude but also the typical frequency ranges of the transient voltages in the transformer terminals. These voltages were generated by the switching-on operations considering different configurations and voltage levels. Three different transformer models were considered [1,2]: Frequency-dependent equivalent model (black box); equivalent capacitance obtained from the transformer frequency response for the dominant frequency;

network of lumped capacitances provided by the manufacturer. The methodology of these simulations, the description of the cases studied and the results were presented and deeply discussed in [1, 2].

The overvoltage values 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 in the Brazilian system. 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.

As far as the transformer modelling is concerned, application of frequency-dependent equivalent models (black box) [3], 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.

Figures 1 and 2 below present the transformer voltage related to two different energization case studies described in the previous item.

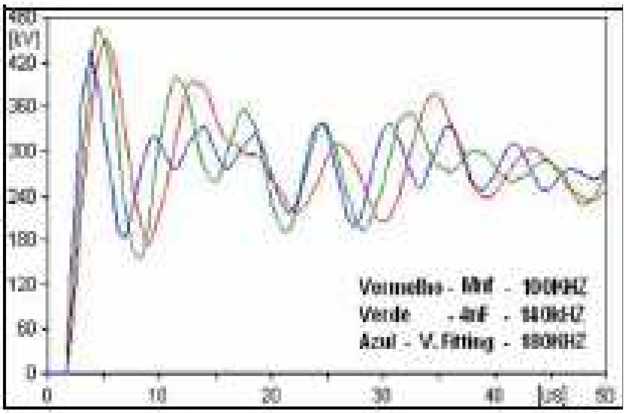

Figure 1 – Case 1
Dominant frequencies: 100 (red), 140 (green), 180 (blue) kHz according to the transformer model

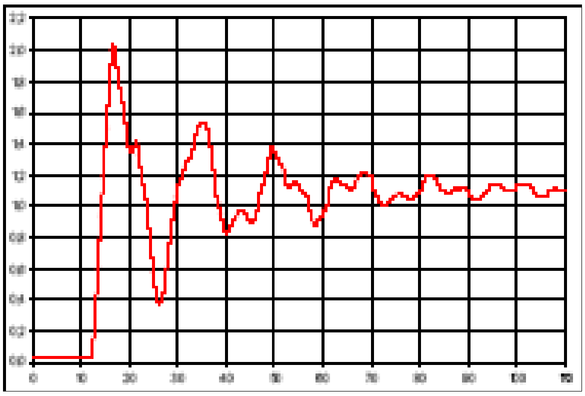

Figure 2 – Case 2
Dominant frequencies: 60, 70, 140, 170 kHz

As it is shown above, the simulation results show voltage oscillations with predominant frequencies in a range from 60 to 200 kHz. 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.

The frequency spectrum of the standard lightning impulse full and chopped wave, represented as a double exponential wave shapes were calculated with their corresponding crest levels. Figure 4 shows the spectrum of these test waves considering different time to chopping from 2 µs to 6 µs.

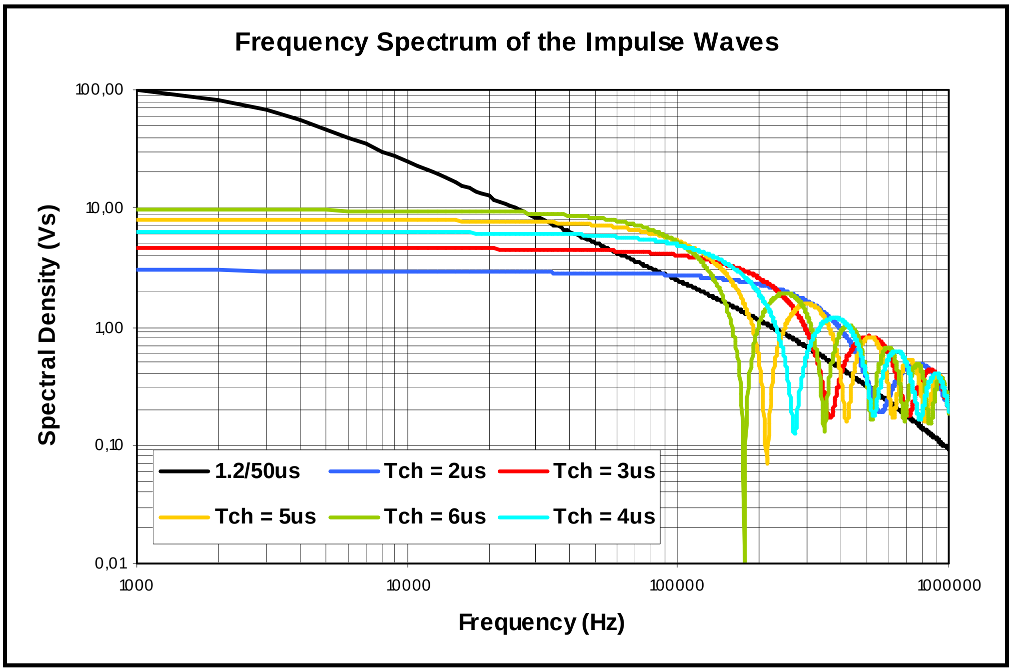

Figure 4: Spectrum of the lightning impulse waves

For several cases calculated in this study, the spectrum of the transformer terminal voltage resulted in stresses, considered proportional to the energy of the voltage frequency components (unit *Vs*) that exceeded the standardized ones. 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 be sure 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. This envelope considers the variation of the chopping time from 2 µs to 6 µs of the chopped wave.

The most important transients for the transformer, according to the electrical point where it is connected, should be considered in the FDFS determination. Table 1 presents the result of the studied cases for circuit-breaker closing.

Study	***Voltage level (kV)***	***Station layout***	***Switched equipment***	***Breaker distance (m)***	***Critical frequencies (kHz)***	***Severity Factor (FDSF)***			***Transformer Model***
						1.2/50 µs	***CW (3 µs)***	***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	80	1.74	1.39	0.83	RLC
					1460	5.46	1.46	1.17	
					1470	4.50	1.14	0.97	
					1820	5.90	1.24	1.13	
			Autotransformer 765/345/20 kV – 500 MVA Manufacturer B	190	110	1.79	1.02	0.83	RLC
					120	1.95	1.05	0.90	
					1460	4.23	1.13	0.91	
					1820	5.78	1.20	1.10	
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 (BCB)	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 (BCB)	130	1.98	1.01	0.90	RLC
					410	2.06	1.91	0.80	
					510	2.08	0.77	0.77	
				186 (CCB)	90	2.04	1.36	0.95	CAP
				186 (CCB)	90	1.72	1.15	0.80	RLC
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 1 – Simulation results
🟨 FDSF greater than 1
CAP: Lumped capacitance model
RLC: Frequency dependence equivalent model

Figure 5 presents, as an example, the result of one of the case studied (case 2 system) where the Frequency Domain Severity Factor (FDSF) is disconnector switching and circuit-breaker closing. The FDSF for disconnector switching is greater than one at 840 kHz. This result indicates that this event is not properly represented by the standard impulses. It is interesting to observe that at 66 kHz the FDSF, for circuit-breaker closing, 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.

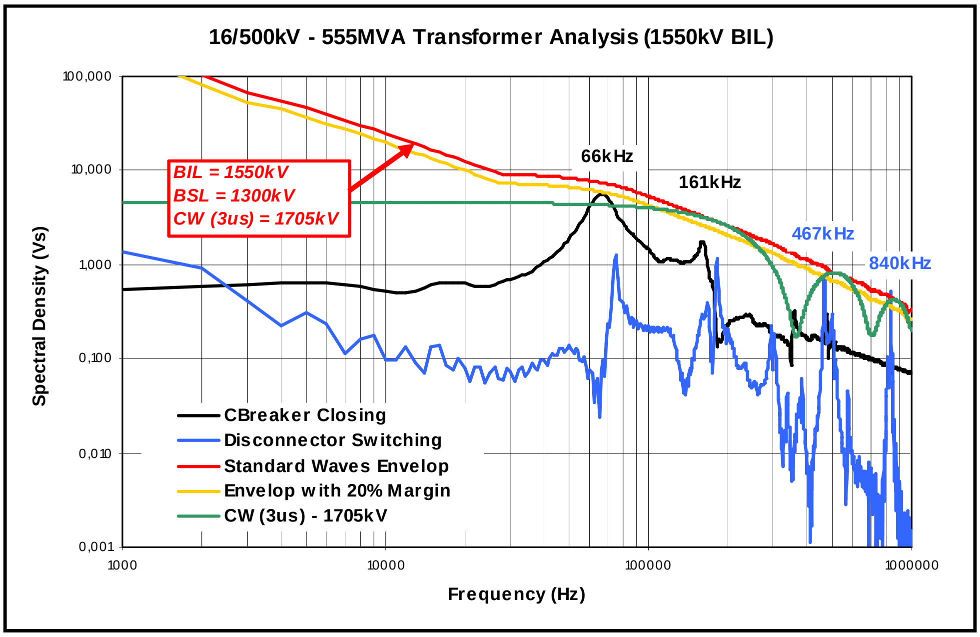

Figure 5: System transient Vs curves compared with the standard impulse wave envelope.

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 figure 4.

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.

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.

One possible alternative is the use of the spectral density diagram of Figure 5 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 (red curve - adapted to each individual equipment insulation level). Therefore, a similar principle of the traditional insulation coordination may be used in frequency spectrum. Both, the adoption of the transformer insulation level with adequate safety margin (severity factor < 0,8) or the use of mitigation techniques to reduce the stresses across the transformer to a level below the 20% safety margin envelope (yellow line) are good options to assure the reliable operation of the equipment subject to the studied transient conditions.

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 energization.

Some previous results have already been obtained for disconnector switching in the substation. It has been observed for higher frequencies, reaching some MHz, in the transformer voltages compared to the results for circuit-breaker energization. The consideration of reignition phenomena in the disconnector switching simulation explains that tendency and is in compliance with what is expected to happen in the field. The effect of short-circuits close to the substation will also be analyzed by the group in future studies.

4. 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 for a specific frequency range from 60 to 200 kHz. Important voltages in this frequency range may not be well represented by the standards and, consequently not considered during the design. This fact may explain some transformer failure and influence in system reliability.

4.1 Process Representative Flow Diagram

Based on these facts, the JWG A2/C4 has been discussing and analyzing alternatives to insert in the processes of planning, specifications and design some requirements concerning the high frequency transient voltages. Figure 6 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 and to take these into consideration at the design stage.

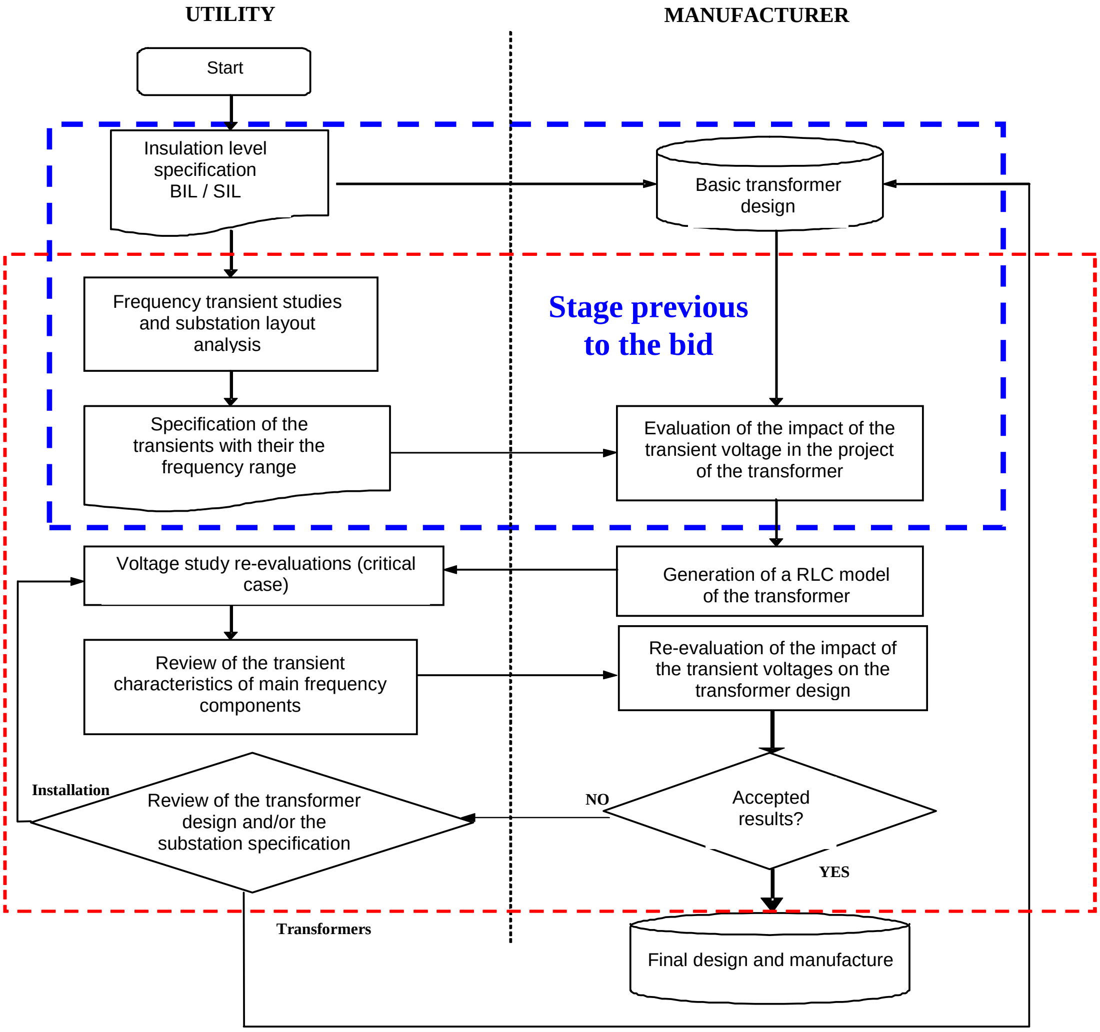

Figure 6 - Proposed Flow diagram

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:

a) Coordination insulation studies

In coordination insulation 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 (FDSD 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 x frequency curve measured from a similar transformer can be used in two ways:

- Calculation of a black box model using the Vector Fitting routine [3] or similar.

- 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 [4].

For transformers already in operation, it is suggested having the impedance x 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 x frequency curve that can be used as an input for the calculation of a black box model, already discussed.

5. 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 over the transformer terminals are usually restricted to frequencies below 200 kHz. However, when these stresses are compared with the specified standardized waves, they 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. Some proposals were presented throughout the paper regarding these items.

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 proposed in the paper.

JWG-A2/C4 is composed of the following:

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