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Discussion on the Interaction between Transformers and the Power Systems

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Cigré-Brazil Joint Working Group
JWG – A2/C4-03 – Electrical Transient Interaction between
Transformers and Power Systems
Brazil

SUMMARY

A general increase in transformer dielectric failures in the Brazilian transmission system, some of them with no specific causes, motivated the start up of a Cigré Joint Working Group JWG A2/C4–03 Electrical Transient Interaction between Transformers and the Power System. This group has been gathered to assess and discuss the different types of electrical transient interaction between transformers and other components of the T&D power system that could explain some of these failures.

The main focus of the JWG is to pursue an improvement of the system reliability based on recommendations regarding the electrical transient interaction between transformers and the power system. This takes into account the necessity of detailed transient studies looking for an upgrade in equipment specifications, 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 JWG including the main discussions and the conclusions already reached.

KEYWORDS

Transformers – Switching transient – Reliability – Electrical System Interaction

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1. INTRODUCTION

In recent years some transformer failures due to system interaction have been reported from members of the Brazilian Study Committees A2 and C4. These reports have motivated the engineering teams of utilities, transformer manufacturers and independent research centers to start a Joint Working Group to study this problem named JWG – A2/C4-03 - Electrical Transient Interaction between Transformers and Power Systems.

The main focus of this JWG is to improve the system reliability by suggesting additional recommendations after a better understanding of the oscillatory phenomena resulting from the interaction between the transformer and its surrounding electrical environment after a transient event.

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 a range of frequencies that appears during switching in substations of different voltage level and arrangements;
- Presentation of the first results related to circuit breaker switching in substations of different utilities up to 500 kV.

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 interact with a transformer winding part resulting in a local amplification due to resonance. As the transformers are constantly exposed to transient events such as lightning, switching operations, short-circuits, etc. the resonances at singular points in the winding may continuously stress its insulation leading to a failure, sometimes hours after the events.

The report of the members' experiences and the simulation of several substation arrangements for different voltage levels frequently used in Brazil provided the basis for the coming discussions. Transformer standards and specifications are asked 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. In some cases, a clear diagnosis could not be achieved but the evidences led to switching operations as the most probable cause. The analysis of these occurrences motivated the development of large scale electromagnetic transient simulations with the objective of quantifying not only the magnitude but mainly typical frequency ranges of the high frequency transient voltages in the transformer terminals. These voltages were generated by the switching-on operations, in substations of different configurations and voltage levels. The results of these evaluations were a valuable contribution to the CIGRÉ Brazilian JWG-A2/C4-03 and will be discussed in the next items.

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 the transformer reliability. After exhaustive analyses, a common cause suggested for these failures, although not proved, was the occurrence of internal overvoltage due to frequent switching in the substation. This fact showed the necessity to improve discussions with the manufacturer about the electrical system environment and design based on a better understanding of the interaction of the power system and transformers. Some actions have been taken with this aim, including switching transient simulations studies with more realistic transformer models and field measurements to subsidise new transformer specifications and reproduce system disturbances [1].

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 were not protected by lightning arresters. Failure analysis showed that the dominant frequency of the transient voltages calculated in the 230kV terminals is very close to one of the winding resonant frequencies, which corresponds to the highest amplification factor in the 13.8 kV terminals. The resonant frequencies related to the 230/13.8 kV voltage ratio were determined by field measurements of the frequency response.

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. Simulations and field measurements of the transient voltages presented very close frequency ranges.

Case 4: In a group of twelve 765/345/20 kV – 500 MVA single-phase autotransformers of different ages and manufacturers, four units failed within six months in 2005, leading the utility to conduct 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 high number of switching of these capacitive units was considered as a possible cause of such failures. However, site measurements and digital analysis have not shown any relation between the failures and these operations so far.

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 disconnecting 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. The failure involved mainly turn to turn, disk to disk close to the HV terminal and main duct insulation between HV and LV windings.

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. So the transformer failure was considered a direct consequence of the system disturbance mentioned above.

3. DIGITAL SIMULATIONS

In accordance with the scope of the Brazilian JWG-A2/C4-03, this item presents the investigations carried out by the Brazilian utilities and research center members of the group, concerning transformers energization at different voltage levels and substation arrangements. A brief description of the modelling guidelines, the studies performed and the results achieved are presented below.

3.1 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 [2]. In this work, the objective of electromagnetic transient studies is to quantify the magnitude and typical frequencies range of the high frequency transient voltages in the transformer terminals produced by the switching-on operations. According to reference [3], these studies can be classified as fast transients and the associated frequencies can vary from 10.0 kHz up to 3.0 MHz. Due to the involved frequency spectrum, the frequency dependence of the parameters should be taken into account, when possible, in models for transmission lines, substation buses and power apparatus. To do this, modeling guidelines based on reference [2] are applied. The present section describes the adopted approach. In all transient studies, digital simulations were carried out using the Alternative Transients Program (ATP) [4].

a) Power transformer modeling:

In this work three different power transformer models were considered:

I) Simple lumped capacitance to ground: This model is traditionally applied in insulation coordination studies;
II) 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;
III) Frequency-dependent equivalent model (black box): An equivalent RLC network obtained from field measurements (admittance curve in the frequency-domain). This model is usefully when frequency responses are available. The black box model was obtained using a recent implementation of the Vector Fitting routine [5, 6], called Matrix Fitting [7] or with the software Sintnet [8].

b) 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 [2]. All 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 [4]. 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 are long enough. Otherwise, a lumped impedance was used.

3.2 Case studies – description and results

The purpose of these studies was to determinate the amplitudes of the high frequency voltages and their frequency range that appear during transformer energization. A brief description of the substation arrangement, the studies performed and the results achieved are presented below:

3.2.1 Description

Study 1 – CEMIG: Ouro Preto II substation has an arrangement of breaker-and-a-half with three 345kV line transmission bays. The 500/345/13.8 kV – 400 MVA autotransformers are connected directly to the bus and are switched by either one of the transmission line circuit breakers. The distance between the breakers and the autotransformers varies from 60 to 120 m. In this study, the circuit breaker by which the transformers were energized was varied, considering or not the presence of a 345 kV reactor bank installed at one of the transmission line bays for voltage control. This reactor is around 200 m away from the closest transformer. Circuit beakers has no pre-insertion resistor.

Study 2 – CHESF: Campina Grande II 230 kV substation has a main and auxiliary bus arrangement, with ten transmission lines and six transformers. Simulations were performed for the no-load switching-on of a 230/138/13.8 kV – 55 MVA transformer, through the transformer breaker (20 m away) and through the transfer breaker of the substation (128 m away).

Study 3 – CHESF: Luiz Gonzaga 500 kV substation has a breaker-and-a-half bus arrangement, with six transmission lines and three links of about 400 m for interconnection with the Luiz Gonzaga hydroelectric power plant. In the power plant there are three step-up transformer banks of 16/16/500 kV – 555 MVA. Simulations were performed for the no-load switching-on of a transformer bank with respective link (400 m away).

Study 4 – FURNAS: The 345 kV sector of Tijuco Preto substation has a breaker-and-a-half bus arrangement of 700 m length, ten transmission line bays, four autotransformer banks and four islands of capacitor shunt banks. Each 765/345/20 kV – 500 MVA autotransformer is around 190 m away from two possible breakers for its switching. Simulations were performed for the no-load switching-on of transformer banks of two different manufacturers with and without pre-insertion resistor (R) represented. Autotransformer bank for each manufacturer were represented by two different models.

Study 5 – CEPEL: The 230 kV substation studied was a typical double bus, single breaker arrangement, with six lines and one 345/230/13.8 kV – 225 MVA autotransformer bank. The transformer was energized, from the 230 kV side, considering two basic substation configurations: first, switching the breaker that connects the autotransformer directly to the two main buses (i.e., the transformer circuit breaker); second, switching the bus tie breaker, which is located within a longer distance from the switched transformer. Both circuit breakers were not provided with closing resistors. Separating distances between switched breaker and the transformer being energized are, approximately, 60 and 180 m, respectively.

Study 6 – ELETROSUL: Campos Novos 525 kV substation has a breaker-and-a-half arrangement with six bays, four transmission lines and two 525/230/13.8 kV – 672 MVA single-phase autotransformer banks. The simulations took into account the autotransformer being switched by the bus circuit breaker (BCB), and by the tie circuit breaker (CCB) with and without the 800 Ω pre-insertion resistors (R). The autotransformer bank was modeled by a 3 nF capacitance which represents its impedance for 150 kHz.

Study 7 – CTEEP: Aparecida 230 kV substation has a ring bus, two transmission bays and three 230/88 kV – 60 MVA transformer banks. An analysis of the energization of the third bank from the 230 kV side, 72 m away from the circuit breaker was made. Measurement during its energization and simulation using the ATP program with the transformers modelled as concentrated 2 nF, 3 nF and 4 nF capacitances were performed.

Study 8 – ELETRONORTE: Tucurui I 500 kV substation has a breaker-and-a-half bus arrangement, with three transmission lines and six links of about 1000 m for interconnection with twelve generators of the hydroelectric power plant. Simulations were performed for the no-load switching-on of a 550/230/13.8 kV – 450 MVA transformer bank with respective link (170 m).

3.2.2 Results

Figures 1 to 10 typify the results (voltage in the terminal of the corresponding transformer) and Table I sumarizes the main parameters and values obtained in the studies.

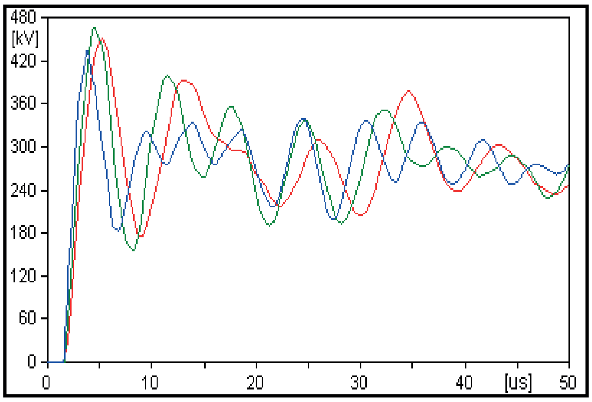

Figure 1: Study 1 – Model I (green);
Model II (red) and Model III (blue)

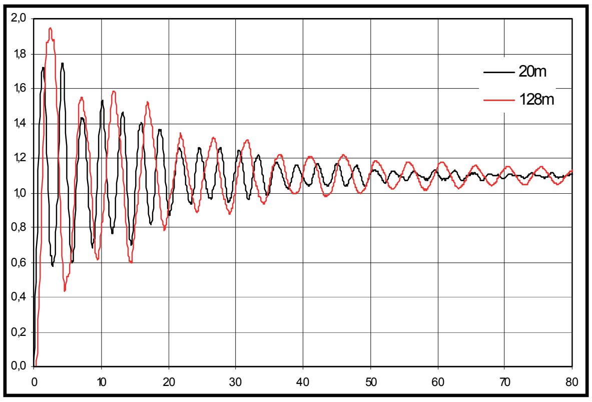

Figure 2: Study 2 – Breaker distance
20 m (black) and 128 m (red)

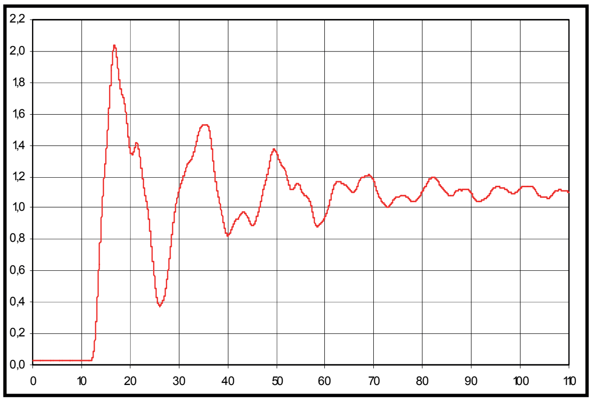

Figure 3: Study 3 – Breaker distance 400 m

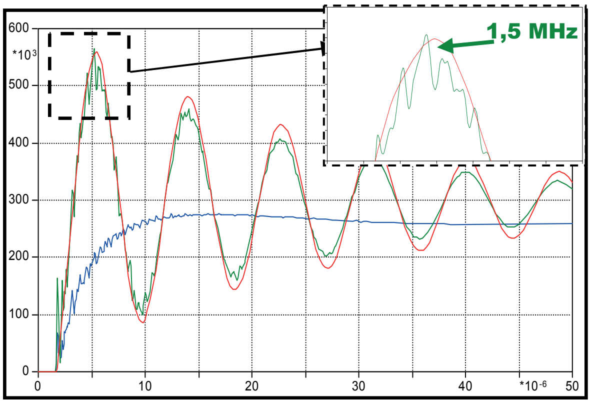

Figure 4: Study 4 – Manufacturer A - Models:
I-without R(red); III-without R(green); III-with R(blue)

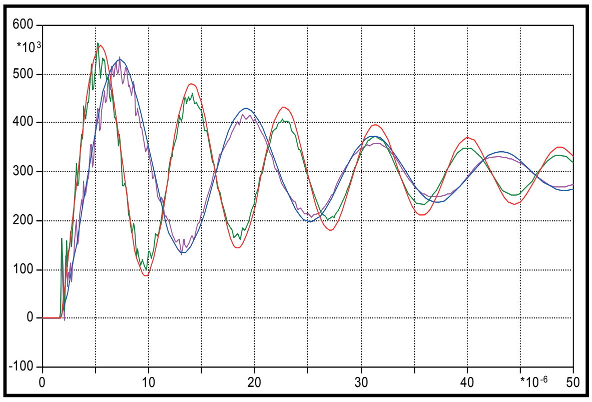

Figure 5: Manufacturer A Models I (red); III (green) (Study 4) Manufacturer B Models I (blue); III (violet)

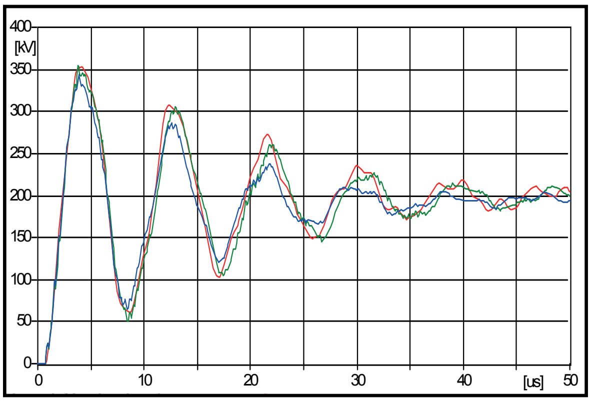

Figure 6: Study 5 – Breaker distance 180 m
Models: I (blue); II (green) and III (red)

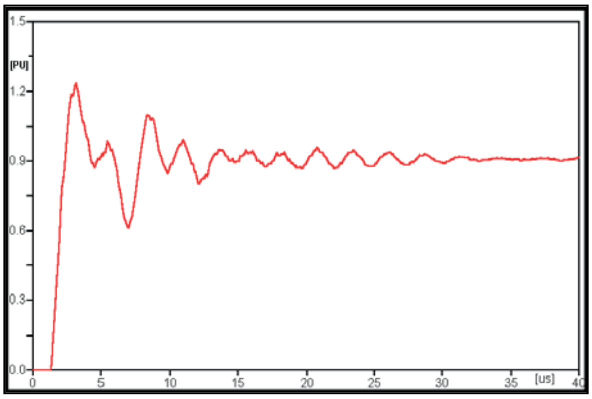

Figure 7: Study 7 – Breaker dist. 170 m (simulation)

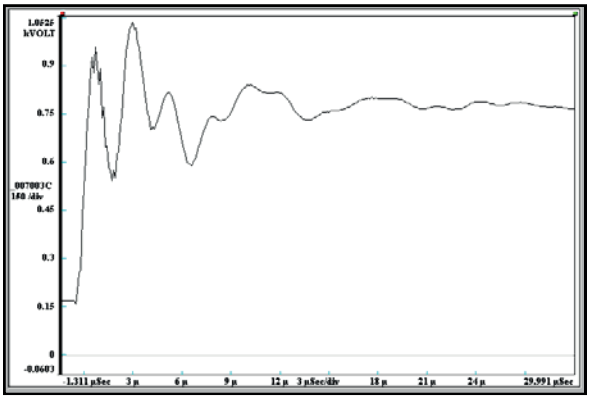

Figure 8: Study 7 – Breaker dist 170 m (measurement)

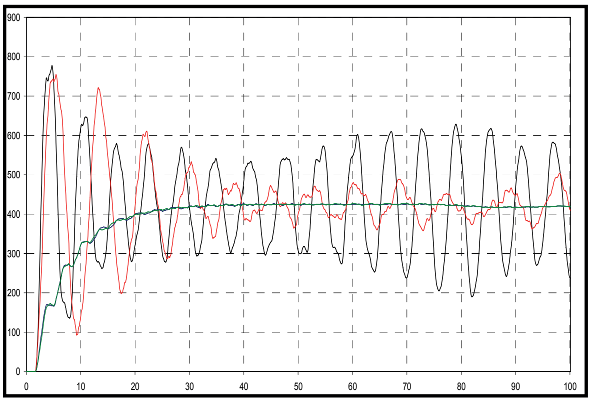

Figure 9: Study 6 – BCB without R (black); with R (blue); CCB without R (red); with R (green)

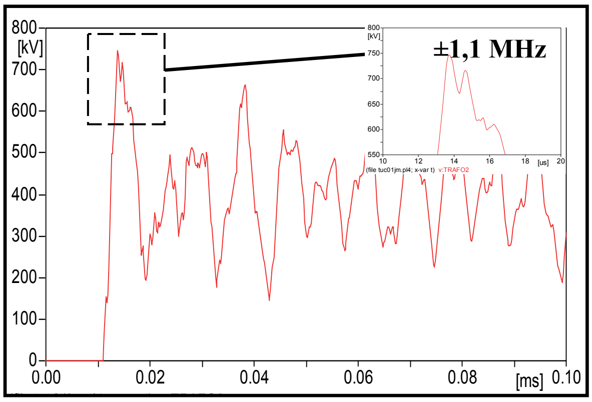

Figure 10: Study 8 – Breaker distance 170 m

Table I – Summary of simulations results

Study	*Voltage level (kV)*	*Station layout*	*Switched equipment*	*Breaker distance (m)*	*Maximum overvoltage (pu)*	*Dominant frequency (kHz)*	*Model (item 3.1a)*
1	345	Breaker-and-a-half	Autotransformer 500/345/13.8 kV – 400 MVA	123	1.60	100	I
					1.65	140	II
					1.54	180	III [1]
2	230	Main and auxiliary bus	Transformer 230/138/13.8 kV – 55 MVA	20	1.75	340	I
				128	1.95	210	I
3	500	Breaker-and-a-half	Transformers 500/16/16 kV – 555 MVA	540	2.04	60 -70 140 -170	I
4	345	Breaker-and-a-half	Autotransformer 765/345/20 kV – 500 MVA Manufacturer A	190	1.98	117	I [3]
				190	2.00	117	III [2]
			Autotransformer 765/345/20 kV – 500 MVA Manufacturer B	190	1.89	85	I [3]
				190	1.90	85	III [2]
5	230	Double bus, single breaker	Autotransformer 345/230/13.8 kV – 225 MVA	60	1.94	194	I [3]
				60	1.93	194	II
				60	1.93	193	III [2]
				180	1.88	117	I [3]
				180	1.88	117	II
				180	1.87	118	III [2]
6	500	Breaker-and-a-half	Autotransformer 525/230/13.8 kV – 672 MVA	186	1.81	157	I
				186	1.76	122	I
7	230	Ring bus	Transformer bank 230/88 kV – 60 MVA	72	1.24	180 380	I
8	500	Breaker-and-a-half	Transformer bank 525/230/13.8 kV – 450 MVA	170	1.84	100	I

[1] Using Vector Fitting

[2] Using SINTNET

[3] Equivalent capacitance obtained from the frequency response model for the dominant frequency

4. CONCLUSIONS

The paper presented the investigation carried out up to now by the Brazilian JWG–A2/C4-03 to study the electrical transient interaction between transformers and the power system. ATP simulations of transformer energization were performed, considering different voltage levels and substation arrangements, and the results pointed out the importance of a better knowledge of transformer behaviour in the range of 40 kHz to 200 kHz. Significant voltage stresses in these frequencies may not be very well represented by the standard dielectric tests or taken into account during the project which can contribute to equipment failures.

Cases where frequencies greater than 200 kHz were observed –were those corresponding to the ring substation arrangement or with very small distance between the transformer and the circuit-breaker. For larger distances between the transformer and the circuit-breaker, the oscillation frequencies presented lower spectrum, considering the same transformer modeling.

As far as the transformer modeling is concerned, application of Vector Fitting and SINTNET routines seemed to give more accurate results with the voltage transients having relatively greater attenuation and smaller amplitudes caused by the resistances of the equivalent RLC circuit provided.

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 components, as a consequence of the model simplification, might not be well reproduced.

The application of pre-insertion resistors is one of the conventional solutions to reduce the overvoltage magnitudes on the transformer terminals and to increase the voltage attenuation.

5. JWG-A2/C4-03 NEXT STEPS

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 and propose an upgrade of the transformer specifications design review practices and an improvement of standard dielectric tests to make them more representative.

It is relevant to point out the advantages of joint evaluations involving different experiences such as utilities, research center, manufacturers, universities and the national grid system operator, as the work being done by the JWG-A2/C4-03 of Cigré-Brazil, especially when the solution depends not only on the power system but also on the characteristics of the equipment.

JWG-A2/C4 is composed by the following members:

Angélica da Costa O. Rocha (CEMIG) – Convener; Alecio Barreto Fernandes (ONS); Álvaro Portillo (TRAFO-Consultant); Antonio Carlos S. de Lima (UFRJ); Antonio Roseval F. Freire (CHESF); Camilo Machado Jr. (ELETRONORTE); Carlos Ossamu Kajikawa (ELETROPAULO); Davi Sixel Arentz (FURNAS); Fernando Rodrigues Alves (CHESF); Francisco Salgado Carvalho (CEPEL); Gilson Machado Bastos (FURNAS); Guilherme Sarcinelli Luz (FURNAS); João Maria Fontoura Júnior (COPEL); José Carlos Mendes (ABB); José Francisco Lofrano de Oliveira (TRAFO); José Renato Torrens (WEG); José Toshiyuki Honda (ELETRONORTE); Luiz Henrique S. Duarte (CEMIG); Methodio Varejão de Godoi (CHESF); Roberto Asano Junior (SIEMENS); Roberto Vaisman (CEPEL); Rogério Lima Tompson (CTEEP); Rogério Magalhães de Azevedo (CEPEL); Sebastião Otávio Moreira (CEMIG); Ulisses R. R. Massaro (ELETROSUL); Walter Carvalho Pereira (VONCKEL/DOBLE)

BIBLIOGRAPHY

[1] Rocha, A.C.O. et al., “Análise das falhas dos autotransformadores da SE São Gotardo 2 - Enfoque na ressonância parcial de enrolamento”, GSI – XV SNPTEE, 17 a 22 de Outubro de 1999, Foz do Iguaçu – Paraná – Brasil (in portuguese).

[2] IEEE WORKING GROUP 15.08.09, “Modeling and Analysis of System Transients Using Digital Programs”, Piscataway: IEEE PES Special Publication, 1998.

[3] Working Group SC 33-02 CIGRÉ, “Guidelines for Representation of Network Elements when Calculating Transients”, Technical Brochure CE/SC GT/WG 02, 1990.

[4] LEUVEN EMTP CENTER, “ATP – Alternative Transient Program – Rule Book”, Herverlee, Belgium, July 1987.

[5] Gustavsen, B., Semlyen, A., “Rational Approximation of Frequency Domain Responses by Vector Fitting”, IEEE Trans. on Power Delivery, Vol. 14, Iss.3, pp. 1052-1061, July 1999.

[6] Gustavsen, B., “Application of Vector Fitting to High Frequency Transformer Modeling”, IPST 2003, New Orleans, USA, 2003.

[7] Online available: http://www.energy.sintef.no/produkt/VECTFIT/index.asp.

[8] Azevedo, R. M., Junqueira, A. J. S., “Programa Sintnet – Síntese de redes para modelagem de equivalentes em freqüência – método de Cauer”, Relatório CEPEL 851/95 – DPP/TEC, 1995.