Impact of Transformer Modeling in Assessing Dielectric Failure Analysis

Angélica C. O. Rocha, Antonio Lima, Adinã M. Pena and Sebastião O. Moreira

***Abstract*—In this paper we analyze the possible causes of two dielectric failures that occurred in a hydropower substation. To investigate the possible causes, the substation was modeled in detail and distinct transformer models were considered: a simple RLC circuit given by the manufacturer and fitted rational modeling of the transformer admittance matrix. The rational modeling was implemented as a multi-phase RLC circuit and a companion network in ATP. Accuracies issues regarding the realization of the rational modeling in ATP are also presented. The obtained waveforms were further analyzed using a detailed winding model of the transformer. The results indicated that higher overvoltages occurred across some parts of the winding.**

***Keywords*: overvoltage, transformer modeling, dielectric failure, switching transients, high frequency transients.**

I. Introduction

TRANSFORMERS failures have increased considerably in the last couple of years. Several utilities have reported transformer failures in an increasing rate over the years. One important phenomenon that can contribute to these failures is when there is a resonance between the transformer and the network that feeds them. Depending on the magnitude and duration, these resonance overvoltages may cause damages to the transformer internal insulation structure [1]-[6].

In Brazil, some important transformer dielectric failures have been reported in the recent years. The analysis of these failures indicated that a dielectric failure in the transformer winding was the main cause and it seems that the interaction between transformer and power plant was responsible for the overvoltages that caused the failures. These reports led to a creation of a CIGRE Joint Woking Group (JWG A2/C4-03) involving utilities, transformer manufacturers, independent research centers and the Independent System Operator (Brazilian ISO) to analyze these issues[7][8]. One important focus of this JWG is to study the effect of very fast transients (VFT) in transformers generated by disconnector switchings in Extra High Voltage (EHV) air substations. Although this effect is more critical in Gas-Insulated-Substation (GIS), there are some field experiences showing that VFT overvoltages occurring during disconnector switchings are the main cause of the transformer failures [7][9][10].

Typically power equipments are submitted to different levels of dielectric stresses depending on the cause of the overvoltages: switching, lightning strikes or short-circuit. These phenomena demand a wideband modeling of all the components involved. A global/unique transformer model for most of the frequency band of power system transients remains a goal for the future. A transformer model must be adapted as a function of the phenomenon being analyzed. For instance, despite its use in several references, a model using short circuits data with external capacitances fails to give an accurate assessment of the overvoltages for a ground fault when the cable that feeds the transformer is represented in more detail [9]. As a matter of fact, the actual network involved in the transient should also be considered as it may affect the transient waveforms [10]-[12].

Dielectric failures in power transformers are most likely to be caused by high frequency phenomena leading to an uneven voltage distribution along the transformer winding. In this work we report the analyses carried out for the investigation of two step-up transformers dielectric failures belonging to A CEMIG, a power utility in Brazil. The failures occurred over a period of slightly a year and both transformers presented inter-turn short-circuits at the top (beginning) of the winding, i.e. in the first disks. Conventional maintenance procedures were not able to determine the actual cause of the failure. One possible cause considered was the interaction between the power transformers and the electrical network that feeds them. Therefore, this study demands a detailed of all components involved. A representation of the complete substation lay-out was implemented in electromagnetic transients (EMT) type of program. The power substation was represented in detail: frequency-dependent models were used to represent all the power equipment possibly involved in any electromagnetic transients of the transformer.

In the case of transformer modeling, there are several models in the technical literature to be considered. The simplest one is a capacitor to ground to represent a parallel of winding equivalent capacitance to ground and stray capacitances [13][14]. The second one is a single-phase RLC to represent the winding at a resonant frequency that is supposed to be dominant during the transients. More recently there has been some proposals of either black box modeling based on transformer terminal measurements [15][16][17] or a detailed winding modeling [13][18] also called white box model. The latter has the drawback that one has to have access to the actual transformer dimensions and design details thus being more suitable for manufacturers. On the other hand this so-called white box model allows the analysis of internal overvoltages in the transformer so dielectric stresses in the transformer windings can be evaluated. In this work we have used both models. The black box model was used together

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with a detailed representation of the substation in order to obtain the terminal overvoltages the transformers must withstand. These results were later used to obtain the voltage profile along the transformer winding. The black box model was obtained using the matrix fitting toolbox of the vector-fitting (VF) algorithm [19][20][21] implemented in MATLAB. The results from the black-box model, i.e, the transformer terminal voltages served as an input to a detailed winding model aiming at identifying possible points of stresses.

II. Description of the Transformer Failures

A simplified single-line diagram for the studied system is presented in Fig. 1, it consists of 6 generators of 66MW with four transformers banks, namely, T1, T2, T3 and T5. As shown in Fig. 1, the transformers banks T1 and T2 are the only ones directly to a generator. Each unit in these two banks is a 25 MVA transformer with three windings. The voltage ratio of the transformer banks is 289:13.8:13.8 kV. Short transmission lines of 600 m length connect the transformers to the 300 kV bus in substation. In this work we opted to present the investigation regarding the failure in T1 as it was the first one and it seems that T1 failure may have had some impact in the failure of T2.

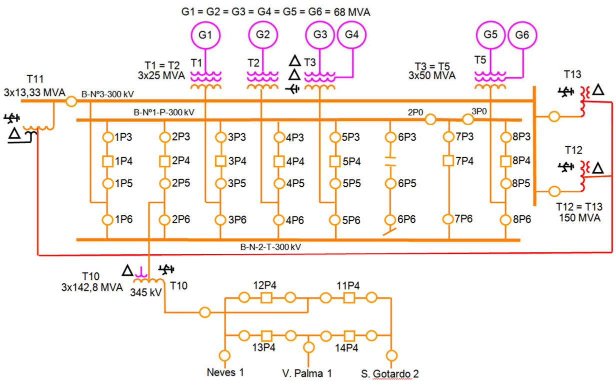

Fig. 1. Single line diagram for the analyzed substation

Transformers T1 and T2 have been in operation for over 30 years. The maintenance of these transformers has not indicated any abnormalities in the analysis of dissolved gases throughout the years. In addition to that, samples of the paper in the transformer coils were analyzed to assess the remaining life span of the transformer. The results indicated that the windings are well within the normal parameters and no compromises were found in terms of the transformers' life span. Fig 2 shows a schematic of the transformer winding distribution and an indication of the winding failure. The analysis of the faulted winding after the failure indicated that there has been a compromised of the isolation throughout the years that led to a dielectric fault between successive turns that created a short-circuit and the total failure of the transformer. Fig. 3 depicts the internal part of the high voltage winding where we can clearly see the failure.

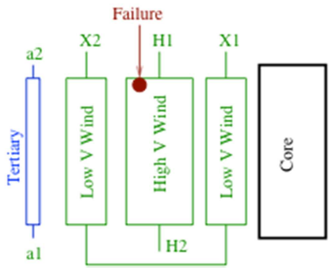

Fig. 2. Transformer winding distribution and dielectric failure location

Fig. 3. Internal part of the high voltage winding indicating the failure

A possible cause was the high number of switching during a large-scale refurbishment of the hydroelectric power plant. In this period of time there has been several maneuvers, Table 1 shows the number of disconnector switching operation in the last four years and from 2005 and before. It is known that sequence of maneuvers in a short period of time may cause cumulative stresses in the winding internal points. In addition to that, the withstand of the insulation could be decreased due to other effects, such as presence of humidity, which is possible considering the age of the transformers.

TABLE I Number of Manuever in the Disconnector Switching in Três Marias Substation

Gen. Unit	Id	2005 and before	2006	2007	2008	2009	Total
G1	3P5	8	6	2	22	5	43
	3P3	3	2	1	7	2	15
G2	4P5	19	9	4	8	8	48
	4P3	6	3	1	3	3	16
G3/G4	5P5	1	2	4	5	5	17
	5P3	1	1	1	1	2	6
G5/G6	8P5	1	10	12	7	1	31
	8P3	1	3	4	2	1	11

III. System Modeling

To investigate whether or not the sequence of switching was the main reason for the failure, the complete substation was implemented in ATP/EMTP using ATPDRAW. Transmission lines were represented as untransposed and using the JMARTI model in ATP. Bus bars were also represented using frequency dependent line models considering the actual geometrical distribution. Switches and circuit breakers were represented using their equivalent capacitance. Fig. 4 shows the simulated system represented using ATPDRAW.

A. Transformer Modeling

Three different models were considered to represent the transformer: a capacitance to ground, a simple RLC provided by the manufacturer, see Fig. 5, and a rational model of the measured admittance.

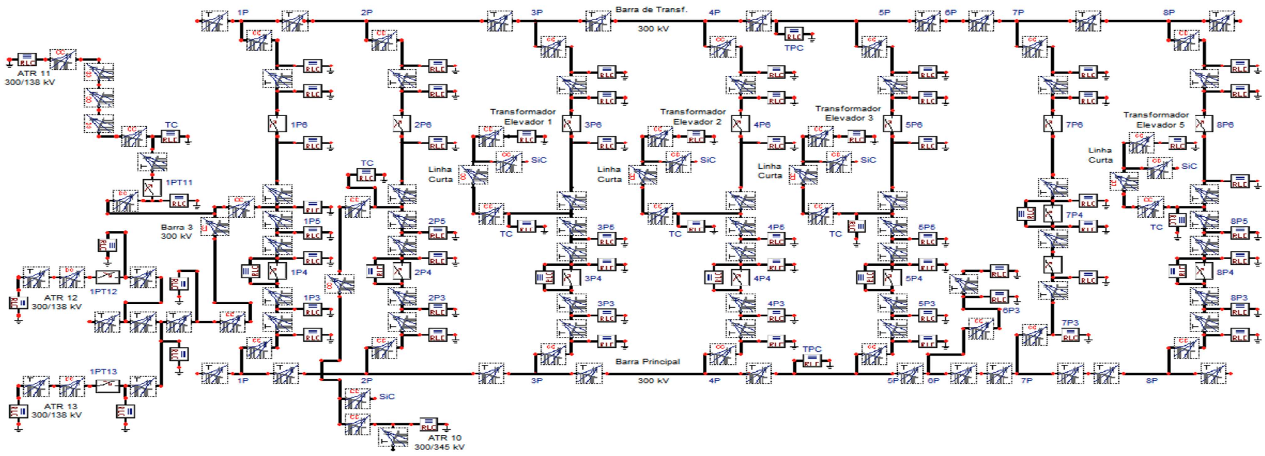

Fig. 4. Substation represented in ATP/EMTP using ATPDRAW

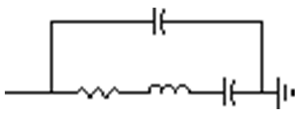

Fig. 5. RLC circuit to represent the transformer – data for the RLC was provided by the manufacturer

Some tests of the substation without the transformer indicated that there was a dominant frequency around 150 kHz This information was passed to the manufacturer that in turn provided the data for the RLC circuit. As mentioned before, for the rational model we used the VF where the measured admittance matrix is approximated using (1).

$$\mathbf{Y}(s) \approx \sum_{n=1}^{N} \frac{\mathbf{R}}{s-a_n} + \mathbf{D} + s\mathbf{E} \quad (1)$$

In the matrix fitting toolbox, the elements of the upper (or lower) triangle of **Y** are stacked in a vector. Using a common set of poles, the problem of determination of **R**, **D**, and **E** can be solved using a two-stage procedure, see [19][20][21] for details. A direct application of VF to **Y** typically produces a model that is more suitable for impressed voltages. To minimize this problem the elements in **Y** are fitted assuming an inverse magnitude weighting function. As the transformer is a single-phase unit with tertiary winding, we have a 5x5 admittance matrix to fit.

To ensure that the fitted network can be implement in EMT type of programs, the **Y** must be passive or otherwise numerical instability may occur. Usually a non-passive model can be made passive in a post-processing stage where the model parameters are perturbed [22][23][24]. These approaches require a frequency sweep of the eigenvalues of the terminal conductance matrix.

Although this can be easily done in the frequency domain, these approaches have the drawback that passivity violations can be missed since a violation can occur between two frequency samples. An alternative to this procedure is to use a Hamiltonian matrix calculated directly from the rational model [25][26]. The main disadvantage of a Hamiltonian approach is its computational burden. A solution to this problem is presented in [27] and it is implemented in the matrix fitting toolbox.

After obtaining an accurate and stable rational model we have two distinct possibilities to implement it in an EMT-type of program: synthesize an equivalent RLCG network that can be implemented as branch cards in ATP or use a convolution based model.

As it was shown in [28] there are some concerns about the usage of an equivalent circuit. The finite precision of branch card may cause the truncation of some pole-residue terms. This truncation results in a deviation at the points of minima in **Y** leading to a system that is not accurate for open voltage configurations. In the same reference a wider format, 16.8e (MATLAB notation) for the branch card is proposed. Unfortunately, we have found that there are cases even when this format does not provide an accurate representation.

Fig 6 shows the comparison of the frequency response for the element (1,1) in the transformer admittance matrix considering distinct RLCs approaches. In this figure *conventional RLCs* stands for the results using branch cards with 14.6e, *improved RLCs* are for branch cards using 16.8e and *simple RLC model* is the one with data provided by the transformer manufacturer. The procedure to convert a rational model in an equivalent electric circuit is summarized in Appendix A.

It is interesting to note that the simple RLC circuit was able to represent the transformer response from 50 kHz up to almost 300 kHz. The improved RLCs were able to represent the both minima in the admittance as well as the local maxima. An examination of the fitted poles indicated that there were poles very close to the real axis that were not accurately represented in the RLCG branch. This shift in the response also occurs for the conventional RLCs.

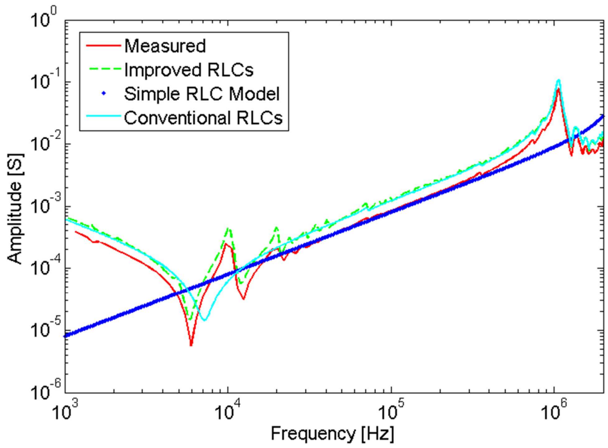

Fig. 6. Comparison of the transformer frequency response using distinct RLC circuits

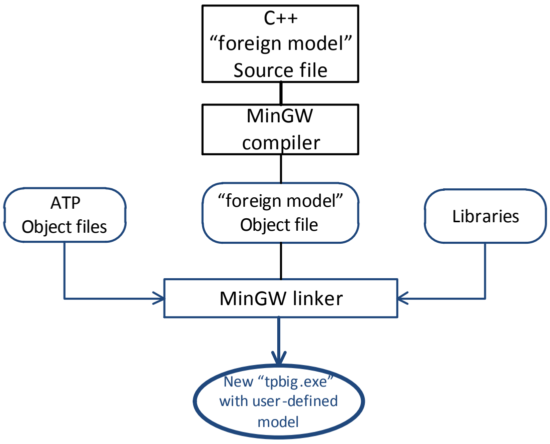

Fig. 7. Overview of the linking process for creating a user defined model in ATP with MinGW32

These results indicate that a convolution based approach is preferred [30]. However, the development of a user defined convolution based model in ATP is not as straightforward as in other EMT-type of programs. For instance the methodology used in [29] is not directly applicable. In ATP either the foreign function or the so-called type-94 in MODELS must be used.

A C++ program was created for the realization of the state-space equation. Using the Minimalist GNU for windows compiler (MinGW) [31] an executable containing the state space model is s linked with the ATP object files creating a new executable file for ATP (*tpbig.exe*). Fig. 7 depicts an overview of this process.

As shown in Appendix B, a state-space realization of (1) can be obtained using trapezoidal integration or recursive convolution. In both cases the expressions are identical but with distinct coefficients. In this work we preferred to use the recursive convolution as some tests indicated it to be a slightly less prone to Gibbs oscillations in the time domain responses. Further investigations is still needed to investigate the cause for such differences.

As the frequency response represented is finite, some spurious oscillations appear in the time-domain responses. For instance consider a chopped current test. In this case the input current is given by a Heidler type-15 source as shown in (2) with T_f =1.2μs, τ=50μs and n=2.

$$1000\left({}^{t}\!/_{Tf} \right)^{n} \left[1+\left({}^{t}\!/_{Tf} \right)^{n} \right]^{-1} \exp(-t)^{\tau} \tag{2}$$

To create the chopped current the source is only active until 2μs. This current source is injected at the high voltage side of the transformer. Fig. 8 shows the voltage at all the windings for this test using recursive convolutions for the state-space representation of the transformer, while Fig. 9 depicts the same voltages using trapezoidal rule integration, it is clearly noticeable the occurrence of numerical oscillations. Therefore, we opted to use only recursive convolutions for the time-domain realization of the fitted function.

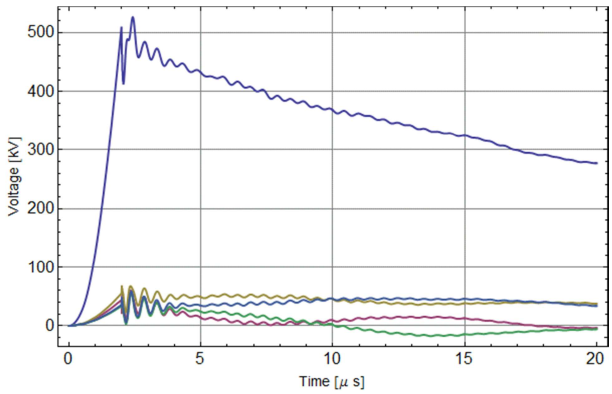

Fig. 8. Voltage output for the chopped current test using recursive convolutions

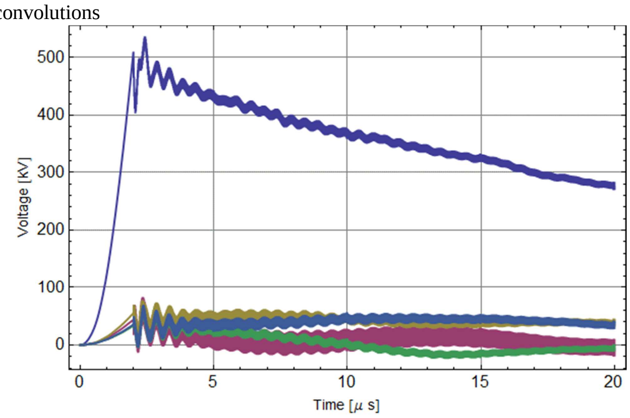

Fig. 9. Voltage output for the chopped current test using trapezoidal rule integration

IV. Test Cases

For the analysis of the transformer overvoltage we considered a disconnector switching maneuver depicted in Fig. 10. In this figure 3P3, 4P3, 3P5, 4P5 are switches and 3P4, 4P4 are breakers. The two breakers have an equalizing capacitor, 3P4 is open, switches 4P6 and 3P6 are also open, 3P5 is a switch that closes at the beginning of the simulation and remains closed. Transformer T1 was unloaded during the simulation, while T2 was in operation. Fig. 11 shows the voltage at the transformer high voltage side during the transient considering a RLC circuit obtained using the network synthesis of rational function, (see Appendix A) and using recursive convolution (see Appendix B). The results indicated that both formulations lead to very close results in the beginning of the simulation up to 5 µs. In terms of maximum overvoltages the results were very close, as expected the highest voltages appeared at the first instants of the simulation.

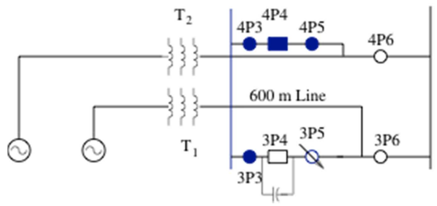

Fig. 10. Detail of the switching scenario considered for the test case.

The Fourier analysis of both waveforms indicated that there are components with considerable amplitude at frequencies around 180 kHz. The components of highest frequency were very close regardless of the transformer model considered. The Fourier analysis also indicated the presence of high frequency components above 1 MHz. Although not shown here we have considered other possible maneuver swicthings with similar results, i.e., the presence of non-negligible frequency components above 1 MHz.

The frequency domain components also indicate that there are points in the range of a few kHz where the curve is higher that the envelope of standardized dielectric impulses. This results points to a dielectric stress caused by the maneuver.

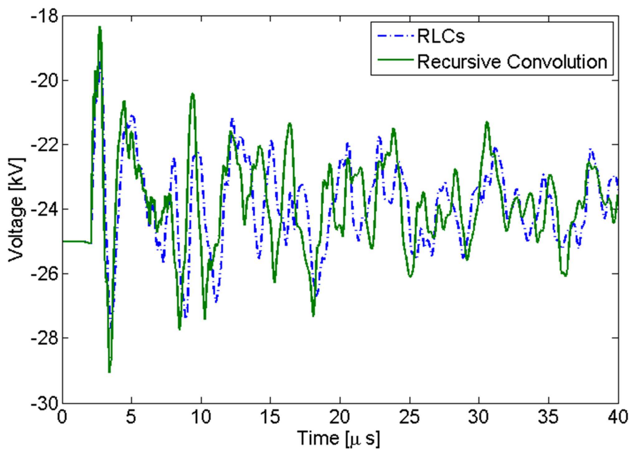

Fig. 11. Transformer Voltages with different representations

C. Voltage Profile Analysis

The voltage waveforms were provided to the manufacturer which in turn using a detailed modeling for the winding identified the voltage amplitude distribution along the winding. This analysis pointed out that the voltage amplitude where found in the first disc of the high voltage winding which is the point where the dielectric failure occurred.

V. Conclusions

In this work we have investigated the impact of distinct high frequency transformer model for the analysis of dielectric failure. For the correct assessment of the dielectric stress a coherent model for the transformer and network. With a detailed transformer and network representations we were able to obtain voltage waveforms indicating that internal resonances may occur in the transformer due to the switching leading to the dielectric failure. There are other factors, not so easily accountable, that may have influenced the coil-to-coil insulation. Most likely, it was the sum of all these factors led to the transformer failures. The results indicate that a wideband representation of the network is needed to obtain waveforms as close as possible to those found in the field. Cooperation between manufacturer and utilities are needed as a detailed winding model may be needed to assess the voltage distribution along the coils.

A simple RLC circuit if correctly fitted can provide some useful information regarding maxima and some information regarding the first instants of a high frequency component. The usage of finite precision branch for the realization of frequency dependent network should be avoided as even with the highest possible representation truncation can occurs leading to inaccuracies in the frequency domain response. Although some authors may regard recursive convolution as obsolete, this paper has shown that there are cases where the recursive convolution is a better approach than the usage of trapezoidal integration of the state equation.

VI. Appendix A

In this appendix we present the derivation of the electric circuit from a rational approximation. Consider a single-phase admittance given by (3).

$$y=\frac{r}{s-a}+\frac{r'-jr''}{s-(a'-ja'')}+\frac{r'+jr''}{s-(a'+ja'')}+d+s\,e \qquad (3)$$

To synthesize (3) we need a RLC circuit shown in Fig. 8 where

$$R_0=\frac{1}{d}\ ;\ C_0=e\ ;\ \mathrm{L_r}=\frac{1}{r}\ ;\ R_r=-\frac{a}{r} \qquad (4)$$

and the complex conjugate pair is given by RLCG where

$$\begin{aligned} L_c&=\frac{1}{2r'}\\ R_c&=2L_c\left(L_c\left(r'a'+r''a''\right)-a'\right)\\ C_c&=\frac{1}{L_c\left(a'^2+a''^2+2R_c\left(r'a'+r''a''\right)\right)}\\ G_c&=-2L_c\left(r'a'+r''a''\right) \end{aligned} \qquad (5)$$

Note that G_c is a conductance, so truncation errors appears as branch cards in ATP due to the inversion of G_c. This leads to an equivalent circuit shown in Fig. 12.

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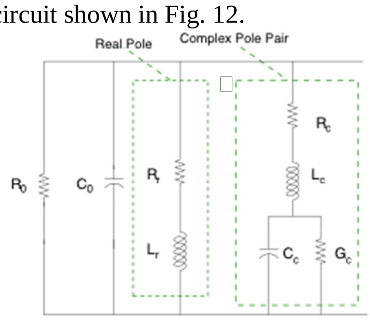

Fig. 12. Equivalent network for the synthesis of frequency dependent admittance in ATP

VII. Appendix B

The coefficients for the state-space model can be calculated directly from the integration of the state-space equation. For instance, consider a first order model with real poles and residue with input *u* (voltage) and output *y* (current)

$$y = \frac{r}{s-a} u \tag{6}$$

In the time domain (2) can be written as shown in (3).

$$\dot{x} = ax + u \tag{7}$$

$$y = rx$$

Either applying trapezoidal rule integration or recursive convolution leads after some manipulation to (3).

$$x(n) = \alpha \; x(n-1) + u(n-1) \tag{8}$$

$$y(n) = c \; x(n) + g \; u(n)$$

With recursive convolution we have the following coefficients

$$\alpha = \exp(a \; \Delta t) \quad \lambda = -\frac{1}{a}\left(1 + \frac{1-\alpha}{a \; \Delta t}\right) \quad \mu = \frac{1}{a}\left(\alpha + \frac{1-\alpha}{a \; \Delta t}\right) \tag{9}$$

$$g = r \; \lambda \quad c = r \; (\alpha \; \lambda + \mu)$$

and if trapezoidal rule is used we have

$$\alpha = \frac{1 + a \; \Delta t / 2}{1 - a \; \Delta t / 2} \quad \lambda = \mu = \left(\frac{\Delta t / 2}{1 - a \; \Delta t / 2}\right) \tag{10}$$

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IX. References

[1] R. J. Musil, G. Preininger, E. Schopper and S. Wenger, " The Resonance Effect of Oscillating System Overvoltages on Transformer Windings", in IEEE *Trans. on Power Apparatus and Systems*, vol. 10, pp 3703-3711, Oct. 1982.

[2] A.S.Morched, L.Marti, R.H.Brierley and J.G.Lackey, "*Analysis of Internal Winding stress in EHV generator step-up transformer failures*", IEEE Trans. on Power Delivery, vol. 11, No.2, April 1996.

[3] Study Committee 12 (Transformers) – WG 12-07, "Resonance Behavior of High-Voltage Transformers", *in Proc. CIGRÉ Large High Voltage Electric Systems Int. Conf.*, Paris, France, 1984

[4] Study Committee A2/B3/A3, JWG 21 "Electrical Environment of transformers", *Electra* No.219, Feb 2005.

[5] M.Hori, M. Nishioka, Y. Ikeda, K .Noguchi, K. Kajimura, H. Motoyama and T. Kawamara, "Internal winding failure due to resonance overvoltage in distribution transformer caused by winter lightning". *IEEE Trans. on Power Delivery*, vol. 21, No.3, July 2006.

[6] R. R. Massaro, on behalf of Cigré-Brazil Joint Working Group – JWG – A2/C4-03, Electrical Transient Interaction between Transformers and Power System", International Conference on Power Systems Transients (IPST2009) in Kyoto, Japan June 3-6, 2009

[7] A. Rocha, "Eletrical Transient Interaction between Transformers and the Power System", In Proc. of *CIGRÉ Bienal Session*, Paper C4-104, Paris, France, August 2008

[8] CIGRÉ Working Group 33.02, "*Guidelines for representation of network elements when calculating transients*" Technical Brochure, CE/SC, GT/WG 02, 1990

[9] B. Gustavsen, "Simulation of resonant overvoltages on a generator step-up transformer using a black-box modeling approach, "in *Proc. VI International Workshop on Power Transformers, VI WORKSPOT*, Foz do Iguaçú, April 2010.

[10] B. Gustavsen, B,"Study of Transformer resonant overvoltages caused by cable-transformer high-frequency interaction," *IEEE Transactions on Power Delivery*, vol. 25, no.2, pp. 770 -779, Apr. 2010.

[11] M. Popov, R. Smeets, L. van der Sluis, H. Herdt and J. Declercq, "Experimental and theoretical analysis of vacuum breaker prestrike effect on a transformer", *IEEE Trans. Power Delivery*, vol. 24, no. 3, pp. 1266-1274, Jul. 2009

[12] M. Popov, L. van der Sluis and R. Smeets, "Evaluation of surge transferred overvoltages," *Electric Power Systems Research*, vol. 78, no. 3, pp. 441-449,2008

[13] J. A. Martinex-Velasco (ed.), *"Power System Transients: Parameter Determination,"* CRC Press, 2009.

[14] N. R. Watson and J. Arrilaga, *"Power Systems Electromagnetic Transients Simulation,"* IET, Dec. 2002

[15] A. Morched, L. Marti and J. Ottevangers, "A high frequency transformer model for the EMTP," IEEE Trans. Power Delivery, vol. 8, no. 3, pp.1615-1626, Jul. 1993

[16] B. Gustavsen, B., "Wide band modeling of power transformers, *IEEE Trans. Power Delivery*, vol.19, no. 1, pp. 414-422, Jan. 2004

[17] B. Gustavsen, Frequency-dependent modeling of power transformers with ungrounded windings," *IEEE Trans. Power Delivery*, vol. *19*, no. 3, pp.1328 – 1334, Jul. 2004

[18] S. Kulkarni and S. Khaparde, *"Transformer Engineering,"* CRC Press, 2004

[19] B. Gustavsen and A. Semlyen, "Rational approximation of frequency domain responses by Vector Fitting", *IEEE Trans. Power Delivery*, vol. 14, no. 3, pp. 1052-1061, July 1999.

[20] B. Gustavsen, "Improving the pole relocating properties of vector fitting", *IEEE Trans. Power Delivery*, vol. 21, no. 3, pp. 1587-1592, July 2006.

[21] D. Deschrijver, M. Mrozowski, T. Dhaene and D. De Zutter, "Macromodeling of Multiport Systems Using a Fast Implementation of the Vector Fitting Method", *IEEE Microwave and Wireless Components Letters*, vol. 18, no. 6, pp. 383-385, June 2008.

[22] B. Gustavsen and A. Semlyen, "Enforcing passivity for admittance matrices approximated by rational functions," *IEEE Trans. Power Syst.*, vol. 16, no. 1, pp. 97–104, Feb. 2001.

[23] B. Gustavsen, "Fast passivity enforcement for pole-residue models by perturbation of residue matrix eigenvalues," *IEEE Trans. Power Del.*, vol. 23, no. 4, pp. 2278–2285, Oct. 2008.

[24] D. Saraswat, R. Achar and M. Nakhla, "A fast algorithm and practical considerations for passive macromodeling of measured/simulated data," *IEEE Trans. Adv. Packag.*, vol. 27, no. 1, pp. 57–70, Feb. 2004.

[25] S. Grivet-Talocia, "Passivity enforcement via perturbation of Hamil-tonian matrices," *IEEE Trans. Circuits Syst. I*, vol. 51, no. 9, pp. 1755–1769, Sep. 2004.

[26] B.Gustavsen, "Fast passivity enforcement of rational macromodels by perturbation of residue matrix eigenvalues," in *Proc. 11th IEEE Work-shop Signal Propagation on Interconnects*, Genova, Italy, May 13–16, 2007, pp. 71–74.

[27] A. Semlyen and B. Gustavsen, "A half-size singularity test matrix for fast and reliable passivity assessment of rational models," *IEEE Trans. Power Del.*, vol. 24, no. 1, pp. 345–351, Jan. 2009.

[28] A. Lima, B. Gustavsen and A. Fernandes, "Inaccuracies in network realization of rational models due to finite precision of RLC branches," Proc. of IPST'07 International Power System Transients Conference, Lyon, France, 2007, available at http://www.ipst.org

[29] B. Gustavsen and O. Mo, "Interfacing convolution based linear models to an electromagnetic transients program," Proc. of IPST'07 International Power System Transients Conference, Lyon, France, 2007, available at http://www.ipst.org

[30] A. Semlyen and A. Dabuleanu, "Fast and accurate switching transient calculations on transmission lines with ground return using recursive convolutions," *IEEE Trans. on PAS*, vol. PAS-94, no.2, pp.561-571, Mar. 1975

[31] MinGW User Group, "*Introduction to MinGW*," available at http://www.mingw.org

[32] S. Moreira, A. Rocha, G. Fabris, A. Martins, "Failures analysis of step-up transformers at Três Marias Power Plant – Technical and econonimcal aspects"(in Portuguese**)** in *Proc. VI International Workshop on Power Transformers, VI WORKSPOT*, Foz do Iguaçú, April 2010.