Harmonic Domain Modeling of Transformer Nonlinear Characteristic with Piece-Wise Approximation

Aleksandar Damnjanovic, Arif Islam, Alex Domijan, Jr.
Power Center for Utility Explorations -PCUE,
Department of Electrical Engineering
University of South Florida,
4202 E Fowler Ave, Tampa , FL 33620

***Abstract*—Power system devices such as transformers, generators, and reactors have nonlinear characteristics because of the magnetic material used for their construction. Hence, understanding how the harmonics affect the power system requires explorations of the harmonic characteristics of each nonlinear component including the transformers. Thus, particular models need to be developed for the power system and machines design, and harmonic power flow analysis. Regarding the modeling of transformer nonlinearity, including hysteresis, there are many numerical methods that have been applied and many models have been developed. The nonlinearity of these devices cannot be correctly represented unless the hysteresis is included. Although the developed model can be used for other devices such as reactors, generators and motors, we are primarily focused on modeling of the transformers. There are many models developed for nonlinear transformer characteristics from various aspects, but none address the influences of the actual mechanical stresses on the magnetic materials. Mechanical stress modifies the nonlinear characteristics of the transformer and consequentially influences the operation of the transformers generating higher level of harmonics, increasing both losses and transformer noise. Our goal was to develop an accurate model and expressive formulas that can be used for practical engineering applications in transformer design and power system analysis based on minimal measured data requirements. The excitation characteristics of the transformer are presented with two piecewise approximated functions. The Harmonic Balance Method – Describing Function is used to obtain the harmonic magnitude and phase angles of the excitation current. The proposed model has been verified with experimentally obtained results for the transformer excitation current.**

***Index Terms*— Excitation curve, Harmonics, Harmonic Balance-Describing Function Transformers, Hysteresis,**

Aleksandar Damnjanovic is with the Department of Electrical Engineering, University of South Florida, Tampa, FL 33620 USA (e-mail: adamnjan@usf.edu).

Arif Islam is with the Department of Electrical Engineering, University of South Florida, Tampa, FL 33620 USA (e-mail:arifi@eng.usf.edu)

Alex Domijan is with the Department of Electrical Engineering, University of South Florida, Tampa, FL 33620 USA (e-mail: alexd@eng.usf.edu).

I. Introduction

Harmonics are generated in power systems mainly due to the nonlinear characteristics of the load. It is also known that harmonics are generated due to the nonlinear characteristics of the power system devices such as, power transformers, saturable reactors, and power electronic devices. Generated harmonics can cause a malfunctioning in relay protection, interfere with the operation of telecommunications equipment, increase power system losses, or cause overloading of such apparatuses as power transformers and cables [1].

Transformer generated harmonics, called no load current harmonics, are mainly due to the nonlinear relationship between the flux density, and the magnetic field strength in a transformer core. This relationship depends on several factors such as the stacking method, core material, maximum allowable flux density and mechanical stress.

In regard to the modeling of transformer nonlinearity, including hysteresis, there are many numerical methods that have been applied and many models have been developed. There are three approaches in the modeling of transformer nonlinearity that includes hysteresis [2].

The first models are developed by physicists. They primarily look at the physical properties of the material, i.e. domain alignments, wall movements, spin rotations, etc. The Second group are those working on machine designs based on electromagnetic fields. They prefer a macroscopic description of hysteresis using mathematical models to predict the *B-H,* curve but without completely neglecting the physics of the material. The third group are power system engineers. They need the equivalent circuit to be modeled in existing computer programs. Their basis for modeling is the *B-H* curve which is obtained by tests. The model we developed is primarily intended for the application in power system analysis and machine design.

From a large number of modeling approaches, very few are in the frequency domain [3,4,5]. All models, including frequency domain ones are created for regular shapes of the hysteresis curve. Irregular shapes of hysteresis are very difficult to model. There are very few attempts to simulate the effect of mechanical stresses and magnetostriction. Usually for simulations of irregular shapes of the hysteresis, the most used are Preisach and Jiles – Atherton models. The Preisach model requires very complex mathematical operations and

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intensive measured data while the Jiles – Atherton model does not recover the hysteresis curve accurately [6].

The goal of this research was to develop practical harmonic domain models that can include irregular or special shapes of transformer nonlinear excitation characteristic curves. The goal is achieved using a combination of the Harmonic Balance Method – Describing Function piece-wise approximations, and a representation of the hysteresis curve with two functions. All these methods were applied [7,8], before in separate occasion. These models are lacking, either accuracy, flexibility or applicability. To overcome these obstacles, we combine these three methods and the result was an accurate and flexible model that can be applied for various shapes of the hysteresis.

The advantage of using the Harmonic Balance Method-Describing Function is that the generated formulae can efficiently and accurately estimate amplitudes and phase angles of harmonic components without a direct application of the Fourier series algorithm, thereby reducing calculation time.

The compressive stresses and magnetostriction are important in the design of the transformers and the study of their operation. The magnetostriction harmonics were important because of their contribution to the audible noise output of electromagnetic devices such as power transformers. It was obviously important to know to what extent the nominal loss and other magnetic properties are degraded when the material becomes stressed, particularly the material with the best nominal loss had the lowest stress sensitivity. Mechanical stress could also be produced by encapsulating the magnetic material in resin, such as in small power or instrument transformers. Setting the resin induced compressive stress on the material had a considerable effect on the permeability, hysteresis shape and losses.

II. Describing Function – Harmonic Balance Method

The method of the Harmonic Balance - Describing function has been used to determine the limit cycle and dynamic behavior of a nonlinear system [9,10,11,12,13]. The describing function can also be viewed as harmonic balance. It allows us to interpret the transformers nonlinearity and derive a mathematical expression for the excitation current. With the Fourier series, the equations of various order harmonic magnitudes and harmonic angles can be obtained.

Let's assume that for a given sinusoidal excitation there exists a steady-state solution that can be approximated, to a satisfactory degree of accuracy, by means of a finite Fourier series. The input function to the nonlinear element, Fig.1, and Fig.2 is given by a sinusoidal signal:

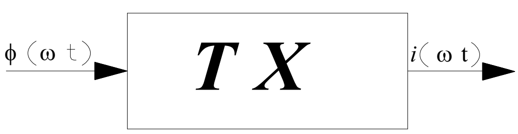

Fig.1 Nonlinear System

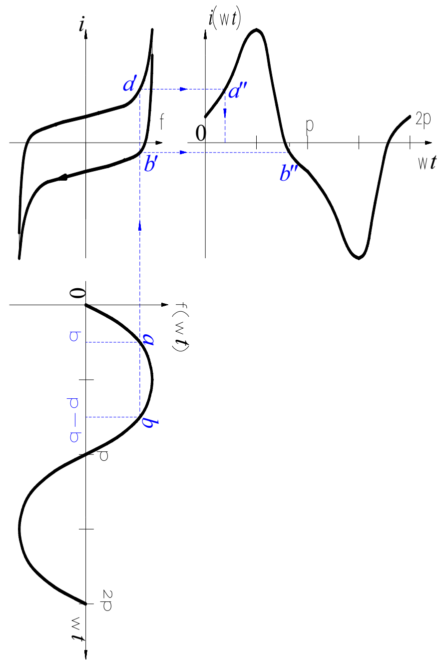

Fig. 2. Excitation Current Waveform for Sinusoidal Input Function

$$\varphi(\omega,t)=\varphi_m \sin(\omega t) \quad (1)$$

Where Φ_m is the maximum of the magnetic flux. The output current is a periodic function that can be expressed as a Fourier series:

$$i(\omega t)=\frac{A_0}{2}+\sum_{k=1}^{k=q} A_k \cos(k\omega t)+\sum_{k=1}^{k=q} B_k \sin(k\omega t)\,, \quad (2)$$

Assuming that $\frac{A_0}{2}=0$, A_k and B_k can be obtained:

$$A_k=\frac{2}{T}\int_0^T i(\omega t)\cos(k\omega t)d(\omega t)\,,\ k=1,2,3...q \quad (3)$$

$$B_k=\frac{2}{T}\int_0^T i(\omega t)\sin(k\omega t)d(\omega t)\,,\ k=1,2,3...q \quad (4)$$

Equation (2) can be rewritten in the complex domain, using trigonometric identities:

$$I_k=\sum_{k=1}^{k=q}(B_k+jA_k) \quad (5)$$

The Describing Function of the nonlinear system can be expressed as a complex number:

$$TX_k(\varphi_m,\omega)=\frac{B_k+jA_k}{\Phi_m}\,,\ k=1,2,3...q \quad (6)$$

III. MODELING PROCEDURE AND DEVELOPMENT OF THE MODEL

The excitation curve that includes hysteresis is defined as the sum of two continuous functions [14], it is presented in Fig.3 with reversed axes:

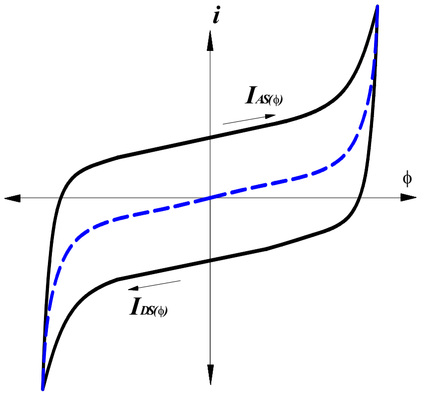

Fig.3. Excitation Curve with Hysteresis and Reversed Axes: abscissa - Magnetic Flux, ordinate - Excitation Current

Excitation current $I_E(\varphi)$ is equal to $I_{AS}(\varphi)$ for increasing of $\varphi(\omega t)$, and $I_E(\varphi)$ is equal to $I_{DS}(\varphi)$ for decreasing of $\phi(\omega t)$, where: $\varphi = \varphi_m \sin(\omega t)$.

The two new defined piece –wise approximated functions are illustrated in Fig.4. They are defined as follows:

$$I_N(\varphi) = \frac{1}{2}\left[I_{AS}(\varphi) + I_{DS}(\varphi)\right] \qquad (7)$$

$$I_{CF}(\varphi) = \frac{1}{2}\left[I_{AS}(\varphi) - I_{DS}(\varphi)\right] \qquad (8)$$

The excitation current $I_E(\omega t)$ is:

$$I_E(\omega t) = I_N(\omega t) + I_{CF}(\omega t) \qquad 0 < \omega t \le \frac{\pi}{2}$$

$$I_E(\omega t) = I_N(\omega t) - I_{CF}(\omega t) \qquad \frac{\pi}{2} < \omega t \le \pi \qquad (9)$$

Hysteresis expressed from equations (8) and (9) will be:

$$I_{AS}(\varphi) = I_N(\varphi) + I_{CF}(\varphi) \qquad (10)$$

This equation is for the ascending part of hysteresis equation (8).

$$I_{DS}(\varphi) = I_N(\varphi) - I_{CF}(\varphi) \qquad (11)$$

This equation is for the descending part of hysteresis equation (9).

The functions $I_N(\omega t)$ and $I_{CF}(\omega t)$ are approximated by n and l piece-wise slopes $m_1 \ldots m_n$ and $q_1 \ldots q_l$, respectively, Fig.4.

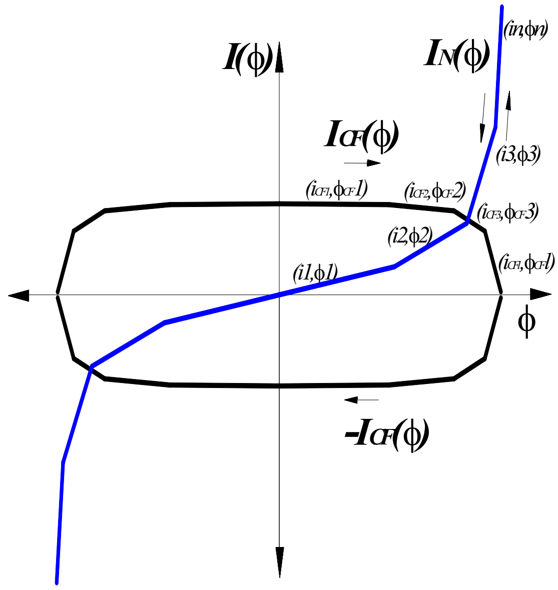

Fig.4. Two-Component Function with Piece-wise Approximation

For the $I_N(\omega t)$ function the n piece-wise approximations and $m_1 \ldots m_n$ slopes are:

$$I_N(\omega t) = (i_1 - m_1\varphi_1) + m_1\varphi, \quad \varphi_0 < |\varphi| \le \varphi_1,$$
$$I_N(\omega t) = (i_2 - m_2\varphi_2) + m_2\varphi, \quad \varphi_1 < |\varphi| \le \varphi_2,$$
$$I_N(\omega t) = (i_3 - m_3\varphi_3) + m_3\varphi, \quad \varphi_2 < |\varphi| \le \varphi_3,$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$I_N(\omega t) = (i_n - m_n\varphi_n) + m_n\varphi, \quad \varphi_{n-1} < |\varphi| \le \varphi_n, \qquad (12)$$

For the $I_{CF}(\omega t)$ function the l piece-wise approximations and $q_1 \ldots q_l$ slopes are:

$$I_{CF}(\omega t) = (i_{CF1} - q_1\varphi_{CF1}) + q_1\varphi, \quad \varphi_0 < |\varphi| \le \varphi_{CF1},$$
$$I_{CF}(\omega t) = (i_{CF2} - q_2\varphi_{CF2}) + m_2\varphi, \quad \varphi_{CF1} < |\varphi| \le \varphi_{CF2},$$
$$I_{CF}(\omega t) = (i_{CF3} - q_3\varphi_{CF3}) + q_3\varphi, \quad \varphi_{CF2} < |\varphi| \le \varphi_{CF3},$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$I_{CF}(\omega t) = (i_{CFl} - q_{CFl}\varphi_{CFl}) + q_{CFl}\varphi, \quad \varphi_{CFl-1} < |\varphi| \le \varphi_{CFl}, \qquad (13)$$

where: $\varphi = \varphi_m \sin(\omega t)$

Inserting equations (12) and (13) into (9) the excitation current is:

$$I_E(\omega t) = \sum_{n=1}^{q}(i_n - m_n\varphi_n) + m_n\varphi + \sum_{l=1}^{p}(i_{CFl} - q_{CFl}\varphi_{CFl}) + q_{CFl}\varphi$$

$$0 < \omega t \le \frac{\pi}{2}$$

$$I_E(\omega t) = \sum_{n=1}^{q}(i_n - m_n\varphi_n) + m_n\varphi - \sum_{l=1}^{p}(i_{CFl} - q_{CFl}\varphi_{CFl}) + q_{CFl}\varphi$$

$$\frac{\pi}{2} < \omega t \le \pi \qquad (5.10)$$

for $\phi_{n-1} < |\phi| \le \phi_n$, $n = 1,2,3....q$ and $\varphi_{CFl-1} < |\varphi| \le \varphi_{CFl}$, $l = 1,2,3....p$ (14)

Harmonic components, amplitudes and angles, of the excitation current are obtained by integrating the equation (14):

$$I_h = \sum_{n=1}^{q} \frac{2}{\pi} \int_{\alpha_{n-1}}^{\alpha_n} [(i_n - m_n\varphi_n) + m_n\varphi_n] \cdot$$
$$\cdot [(\sin((2k+1)\omega t) + j\cos((2k+1)\omega t)) d(\omega t)]$$
$$+ \sum_{l=1}^{p} \frac{2}{\pi} \int_{\alpha_{CFl-1}}^{\alpha_{CFl}} [(i_l - m_l\varphi_l) + m_l\varphi_l] \cdot$$
$$\cdot [(\sin((2k+1)\omega t) + j\cos((2k+1)\omega t)) d(\omega t)]$$
$$- \sum_{n=1}^{q} \frac{2}{\pi} \int_{\pi-\alpha_n}^{\pi-\alpha_{n-1}} [(i_n - m_n\varphi_n) + m_n\varphi_n] \cdot$$
$$\cdot [(\sin((2k+1)\omega t) + j\cos((2k+1)\omega t)) d(\omega t)]$$
$$\sum_{l=1}^{p} \frac{2}{\pi} \int_{\pi-\alpha_{CFl}}^{\pi-\alpha_{CFl-1}} [(i_l - m_l\varphi_l) + m_l\varphi_l] \cdot$$
$$\cdot [(\sin((2k+1)\omega t) + j\cos((2k+1)\omega t)) d(\omega t)] \quad (15)$$

for $\alpha_1 = \sin^{-1}(\frac{\varphi_1}{\varphi_m})$, $\alpha_p = \sin^{-1}(\frac{\varphi_p}{\varphi_m})$ and $\alpha_{CF1} = \sin^{-1}(\frac{\varphi_{CF1}}{\varphi_m})$,

$$\alpha_{CFp} = \sin^{-1}(\frac{\varphi_{CFp}}{\varphi_m}) \quad (16)$$

Only odd harmonics exist, $k = 0,1,2,3...$, $h = 2k+1$, because the excitation current is a symmetrical odd function with the period of the symmetry $\frac{T}{2}(\pi)$.

A. Real Part

The real part of the harmonic components of the excitation current, approximated with the $m_1...m_n$ and approximated with the $m_1...m_n$ and $q_1...q_l$ slopes, for the first harmonic $k = 0$ $h = 1$ is:

$$R_{E(1)} = \frac{4}{\pi} \sum_{n=1}^{p} (i_n - m_n\varphi_n)(\cos\alpha_{n-1} - \cos\alpha_n) +$$
$$+ \frac{4}{\pi} \sum_{n=1}^{p} (\frac{\alpha_n}{2} - \frac{\alpha_{n-1}}{2} + \sin 2\alpha_{n-1} - \sin 2\alpha_n) \quad (17)$$

the Describing function is:

$$A_{R(1)}(\varphi_m) = \frac{R_{E(1)}}{\varphi_m} \quad (18)$$

For $k = 1,2,3.......$ $h = 2k+1....$, the 3rd,5th,7th ,etc, harmonics of the real part of excitation currents are:

$$R_{E(h)} = \frac{2}{\pi} \sum_{n=1}^{p} \frac{1}{2k+1} (i_n - m_n\varphi_n)[\cos(2k+1)\alpha_{n-1} - \cos(2k+1)\alpha] +$$
$$+ \frac{1}{\pi} \sum_{n=1}^{p} m_n\varphi_m \left[\frac{1}{h} (\sin 2k\alpha_n - \sin 2k\alpha_{n-1}) + \right.$$
$$\left. + \frac{1}{h=1} (\sin(2k+1)\alpha_{n-1} - \sin(2k+1)\alpha_n) + \right] \quad (19)$$

the Describing function is:

$$A_{R(h)}(\varphi_m) = \frac{R_{E(h)}}{\varphi_m} \quad (20)$$

B. Imaginary Part

For the first harmonic $k = 0$ $h = 1$ the imaginary part is:

$$I_{M(1)} = \frac{4}{\pi} \sum_{l=1}^{p} (i_{CFl} - q_{CFl}\varphi_{CFl})(\sin\alpha_l - \sin\alpha_{l-1}) +$$
$$+ \frac{2}{\pi} \sum_{l=1}^{p} q_{CFl}\varphi_m (\sin\alpha^2{}_l - \sin\alpha^2{}_{l-1}) \quad (21)$$

$$B_{M(1)}(\varphi_m) = \frac{I_{M(1)}}{\varphi_m} \quad (22)$$

For $k = 1,2,3.......$ $h = 2k+1....$, the imaginary part of the harmonics, 3rd,5th,7th are:

$$I_{M(h)} = \frac{2}{\pi} \sum_{l=1}^{p} \frac{1}{h} (i_{CFl} - q_{CFl}\varphi_{CFl})(\sin\alpha_l - \sin\alpha_{l-1})$$
$$+ \frac{2}{\pi} \sum_{l=1}^{p} q_{CFl}\varphi_m \frac{\cos(1-h)\alpha_l - \cos(1-h)\alpha_{l-1}}{1-h} +$$
$$+ \frac{2}{\pi} \sum_{l=1}^{p} q_{CFl}\varphi_m \frac{\cos(1+h)\alpha_l - \cos(1+h)\alpha_{l-1}}{1+h} \quad (23)$$

The Describing Function is:

$C_{(h)}(\varphi_m) = \sqrt{A_R^2 + B_m^2}$, with phase angle $\Phi_n = \tan^{-1}(\frac{A_R}{B_M})$ (26)

IV. EXAMPLE OF THE APPLICATION OF THE MODEL

We tested the model on different transformer sizes . We use 2 kVA, 4160: 120 Control Power Transformer, Resin encapsulated Voltage Transformer 1440: 120, Vacuum Impregnated Distribution power transformer 480:120 , 45 kVA and data from reference [15], where magnetic material is tested under mechanical stress. We will present the results for the simulations only for the characteristics of the magnetic material under mechanical stress to show capability of the modeling process because of the irregular shape of the hysteresis.

The hysteresis was measured for grain-oriented silicon steel under a compressive stress of 15 MPa. The $I_N(\varphi)$ and $I_{CF}(\varphi)$ functions are approximated with the six slopes. Optimized input data is created in order to correctly recover the hysteresis curve. The intersection points of the piece-wise approximation are determined by the local extremes, minimum and maximum, of the difference of any two consecutive slopes of the measured data.

A. $I_N(\Phi)$ Function

For a six slope approximation the points of the slope intersections are:

$I_0 = 0A$ $\qquad$ $\varphi_0 = 0Wb$

$I_1 = 0.532A \quad \varphi_1 = 0.0006Wb$

$I_2 = 0.7985A \quad \varphi_2 = 0.0015Wb$

$I_3 = 0.955A \quad \varphi_3 = 0.0033Wb$

$I_4 = 1.1125A \quad \varphi_4 = 0.005Wb$

$I_5 = 1.275A \quad \varphi_5 = 0.0056Wb$

$I_6 = 1.48A \quad \varphi_6 = 0.0058Wb$

B. $I_{CF}(\Phi)$ Function

For a six slope approximation the points of the slope intersections are:

$I_0 = 0.36A \quad \varphi_{CF0} = 0Wb$

$I_{Cf1} = 0.261A \quad \varphi_{CF1} = 0.0012Wb$

$I_{CF2} = 0.22A \quad \varphi_{CF2} = 0.002Wb$

$I_{CF3} = 0.19A \quad \varphi_{CF3} = 0.0041Wb$

$I_{CF4} = 0.155A \quad \varphi_{CF4} = 0.0053Wb$

$I_{CF5} = 0.095A \quad \varphi_{CF3} = 0.0057Wb$

$I_{CF6} = 0.000A \quad \varphi_{CF4} = 0.0058Wb$

Table 1. Harmnics Excitation Current for 15 MPa, Measured and Simulated

Harmonic	Measured (A)	Simulated (A)
1	1.4628	1.4699
3	0.1953	0.1833
5	0.2163	0.2328
7	0.0664	0.0827
9	0.0764	0.0785
11	0.0329	0.0290
13	0.0248	0.0582
15	0.0192	0.0330

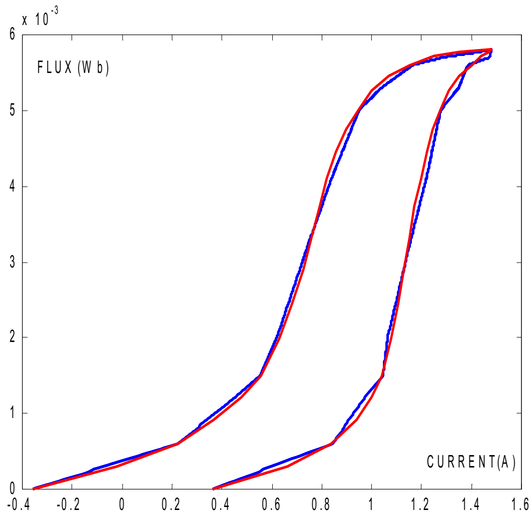

Figure 5. Hysteresis with Six Slopes approximation for the Grain-Oriented Silicon Steel under 15 MPa Compressive Stress

V. Conclusions

We were focused on the development of the models, and the recovery and the identification process of the transformer nonlinear characteristic with hysteresis. The model can also be used for regular and irregular shapes of hysteresis curves. It can be used in a variety of transformer calculations and analyses, in power transformers and instrument transformers. Although this research was focused on the transformer's hysteresis, it can be applied in the design and investigation of motors and generators. A direct harmonic prediction by the models is suitable for a steady-state and quasi steady-state of power system analysis, harmonic power flow, ferroresonance studies, and harmonic filter design.

For the application of the model only algebraic calculations are required, directly from the measured data.

The model developed in this research shows improvements on the modeling philosophy of the transformer nonlinear characteristic with hysteresis. This modeling approach offers accurate and almost complete resolution of complex shapes of hysteresis curves.

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VII. BIOGRAPHIES

Dr. Aleksandar Damnjanovic received B.S. degree in Electrical Power Engineering from the University "St.Cyril and Methodius", Skopje Yugoslavia, Masters and Doctorate Degree in Electrical Engineering from the Tshwane University of Technology/French South African Institute in Electronics (F'SATIE) Pretoria, South Africa. His experience includes ABB Transmission and Distribution, Instrument Transformers Inc/GE, Motortronics/Transformer Technologies Ltd., Power Quality International. He has been with the University of South Florida, Power Center for Utility Exploration (PCUE) since 2007, as Adjunct Professor, Research Scientist and Director of Technology Development where he is teaching and doing research in the area of smart grids and power systems. His research interests are smart grids and power systems: development and modeling tools , weather and reliability, power quality, power system dynamics, computational, applied electromagnetic and high voltage engineering.

Dr. Arif Islam received his B.Tech. degree in Electronics Engineering from A.M.U., India in 1994, and M.S degree in electrical and computer engineering from University of Florida, Gainesville, and Ph.D. degree in electrical engineering from the University of South Florida, Tampa. He joined Siemens in 1994 and has worked in the industry for more than a decade executing many multi-million dollar projects. He enjoys research and produces time bound results utilizing knowledge, experience and management tools learnt while achieving an MBA degree. He is now at the University of South Florida as Deputy Director of the Power Center for Utility Explorations and the Power & Energy Applied Research Laboratory. His fields of interest include power reliability, power electronics, motors and drives systems, understanding natural and manmade hazards and fiscal evaluation of alternative resources of energy.

Dr. Alex Domijan obtained his B.S.E.E. degree from the University of Miami, M.E. degree in electric power engineering from the Rensselaer Polytechnic Institute, Troy, N.Y. and Ph.D. degree in electrical engineering from the University of Texas at Arlington. He was a member of the electrical engineering faculty at the University of Florida and director of the Florida Power Affiliates and Power Quality Laboratory since 1987. He joined the faculty of the University of South Florida as a Professor of Electrical Engineering in 2005. He is the Director of the Power Center for Utility Explorations and the Power and Energy Applied Research Laboratory. He serves as the Editor-in-Chief of the International Journal of Power and Energy Systems, and Chair of many international conferences on energy systems. His research areas are Power Quality, Electricity Metering, Flexible AC Transmission Systems, Demand Response, Power System Reliability, Custom Power, Power Electronics and Motor Drive Systems, and FRIENDS (Flexible, Reliable and Intelligent Electrical Energy Delivery Systems).