Vector Hysteresis Model Associated to FEM in a Self-Excited Induction Generator Modeling

J. B. Padilha, P. Kuo-Peng, N.Sadowski *Senior Member IEEE*, N. J. Batistela *Member IEEE*

GRUCAD/EEL/CTC/UFSC, P. O. Box 476, 88040-900, Florianópolis, SC, Brazil
juliano.padilha@posgrad.ufsc.br, patrick.kuo.peng@ufsc.br, nelson@grucad.ufsc.br, jhoe.batistela@ufsc.br

This paper discusses the implementation of the inverse Jiles-Atherton (JA) vector hysteresis model with 2D FEM for the analysis of an induction machine operating as self-excited generator. A differential reluctivity tensor couples the hysteresis model with the magnetic vector potential based FE model. Experimental and simulated results are presented.

***Index Terms* – Finite Element Analysis, Hysteresis, Induction Generator**

I. INTRODUCTION

ALTHOUGH THE phenomenon of magnetic hysteresis can be neglected for the study of many electromagnetic devices, mainly when they present magnetic airgaps, in some cases its influence may be required in magnetic field modeling as, for instance, in the analysis of hysteresis motors, in transformers, or in situations where the remanent flux has influence on the behavior of the system as for self-excited induction generators.

Some studies ([1], [2], [3]) analyze the self-excited induction generator with FEM, however, in these works the phenomenon of magnetic hysteresis is not considered and the self-excitation is not naturally established by the residual magnetization of the ferromagnetic material.

In this context, this paper discusses the implementation of the inverse Jiles-Atherton (JA) vector hysteresis model ([4]) with FEM in 2D for the analysis of an induction machine operating as self-excited generator. The inverse vector model is here considered, because it has the magnetic induction as input variable and therefore it is suitable for vector potential formulations. The coupling between the FE and hysteresis models is carried out using a differential reluctivity tensor. Finite Element equations with hysteresis modeling are coupled to electrical circuit equations and the system is solved in a time-step procedure considering the rotor movement. To our knowledge, this modeling where all the phenomena are taken into account has been never presented in the literature and this is the main contribution of the paper. Calculation results are compared to experimental ones to show the effectiveness of the modeling procedures.

II. STUDIED TOPOLOGY AND FORMULATIONS

Figure 1 presents a scheme of the system composed by an induction generator feeding a three-phase resistive load and connected to a capacitor bank responsible, with the remnant magnetic flux, for the self-excitation of the machine.

a) External circuit and magnetic field modeling

The formulation of the 2D FEM coupled electromagnetic-electric problem using a magnetic vector potential formulation can be written in the following form [5]:

$$\begin{aligned}
&\mathbf{M}(t)\mathbf{A}(t)+\mathbf{N}\frac{d}{dt}\mathbf{A}(t)-\mathbf{P}\mathbf{I}(t)=\mathbf{M}(t-\Delta t)-\mathbf{D}(t-\Delta t)\\
&\mathbf{Q}\frac{d}{dt}\mathbf{A}(t)+[\mathbf{R}-\mathbf{G}_6(t)]-\mathbf{G}_4(t)\mathbf{X}(t)=\mathbf{G}_5(t)\mathbf{E}(t)\\
&\frac{d}{dt}\mathbf{X}(t)-\mathbf{G}_1(t)\mathbf{X}(t)-\mathbf{G}_3(t)\mathbf{I}(t)=\mathbf{G}_2(t)\mathbf{E}(t)
\end{aligned}\tag{1}$$

where t and $t-\Delta t$ represent two successive time steps. $\mathbf{M}$ is related to differential reluctivity of the magnetic materials, $\mathbf{N}$ to the electrical conductivity, $\mathbf{D}$ is the FE contribution due to the magnetic field of the previous time step and $\mathbf{P}$ and $\mathbf{Q}$ are FE contributions for the windings regions. The resistances of the windings are included in matrix $\mathbf{R}$. Matrices $\mathbf{G}_1$ to $\mathbf{G}_6$ and vector $\mathbf{E}$ are concerned to the external electric circuit. The unknowns of the problem are $\mathbf{A}$, $\mathbf{I}$ and $\mathbf{X}$, respectively, the magnetic vector potential in the FE nodes, the current in the machine windings and the state variables of the electrical circuit (here, the voltages across the capacitors).

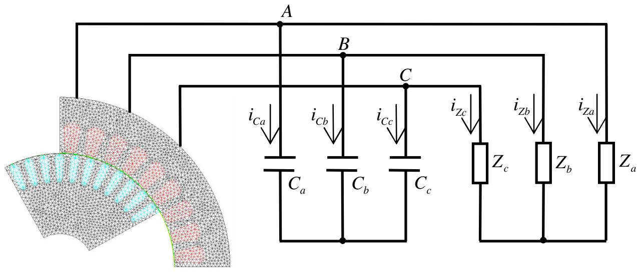

Fig. 1. Induction generator connected to a capacitor bank and a three-phase load.

b) Hysteresis modeling

As presented above, matrices $\mathbf{M}$ are function of the differential reluctivity which, in turn, evolves accordingly to a hysteresis cycle. The hysteresis cycle is modeled by an inverse JA vector model whose main equations are dependent on the effective field $\mathbf{H}_e$, the induction variation $d\mathbf{B}$ and of $\vec{\chi}_f=\vec{k}^{-1}(\mathbf{M}_{an}-\mathbf{M})$ which, in turn, is a function of the anhysteretic ($\mathbf{M}_{an}$) and total magnetizations ($\mathbf{M}$):

If $\left(\vec{\chi}_f d\mathbf{H}_e\right) > 0$ then

$$d\mathbf{M} = \frac{1}{\mu_0}\left[\mathbf{1} + \vec{\chi}_f \left|\vec{\chi}_f\right|^{-1} \vec{\chi}_f (\mathbf{1} - \vec{\alpha}) + \vec{c}\vec{\xi}(\mathbf{1} - \vec{\alpha})\right]^{-1} \cdot \left[\vec{\chi}_f \left|\vec{\chi}_f\right|^{-1} \vec{\chi}_f + \vec{c}\vec{\xi}\right] d\mathbf{B} \tag{2}$$

If $\left(\vec{\chi}_f d\mathbf{H}_e\right) \leq 0$ then

$$d\mathbf{M} = \frac{1}{\mu_0}\left[\mathbf{1} - \vec{c}\vec{\xi}(\mathbf{1} - \vec{\alpha})\right]^{-1} \cdot \left[\vec{c}\vec{\xi}\right] d\mathbf{B}$$

where $\vec{k}, \vec{\alpha}, \vec{c}$ are parameters obtained experimentally for each material and $\mathbf{1}$ is the unity matrix. On the other hand, tensor $\vec{\xi}$ depends on the derivatives of the anhysteretic functions with respect to the effective field components. From (2) and $d\mathbf{H} = (1/\mu_0)d\mathbf{B} - d\mathbf{M}$ the differential reluctivity tensor coupling the JA model and FEM to be applied in (1) can be written as:

$$\left\|\nu_d\right\| = \begin{bmatrix} dH_x/dB_x & dH_x/dB_y \\ dH_y/dB_x & dH_y/dB_y \end{bmatrix} \tag{3}$$

V. RESULTS

A specially constructed 1 HP three-phase, 60 Hz, induction machine with non-skewed slots was used in this study. A per phase 15 mF balanced bank of wye-connected capacitors is connected in parallel with the generator.

Figure 2 shows the experimental apparatus. The capacitor bank is switched after rotation is imposed on the generator by means of a DC motor and the process of self-excitation occurs due to residual magnetism of the machine as shown in Fig. 3.

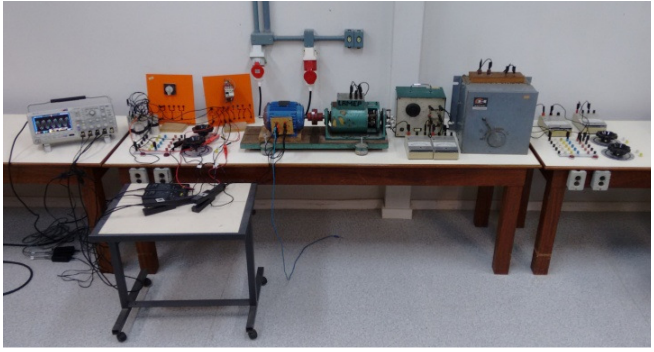

Fig. 2. Experimental apparatus.

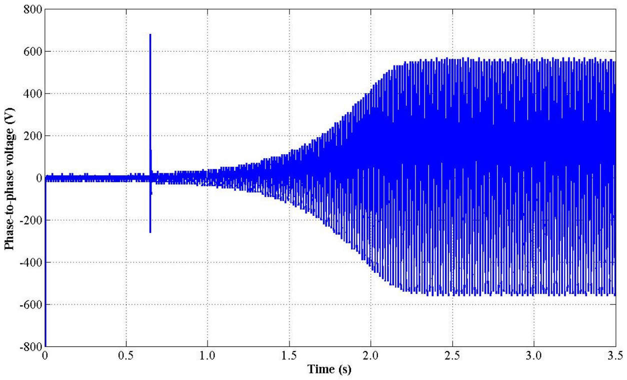

Fig. 3. Experimental phase to phase voltage establishment (spark corresponds to capacitors switching).

The *B(H)* loop in a stator tooth at steady state voltage operation is presented in Fig. 4. Figure 5 shows the steady-state voltage on one phase for a rotation of 1800 rpm imposed to the generator shaft. One can observe the ripple due to the non-skewed slots. Other results will be given in the extended version of the paper.

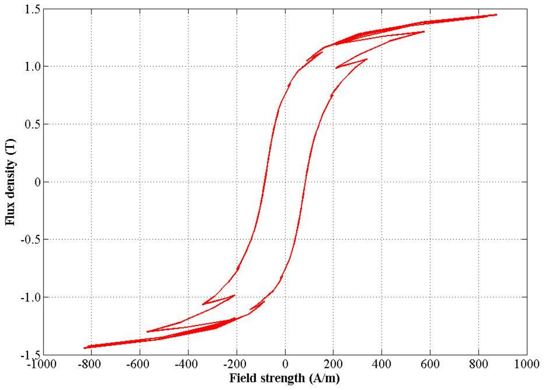

Fig. 4. *B(H)* loop in a stator tooth (radial component).

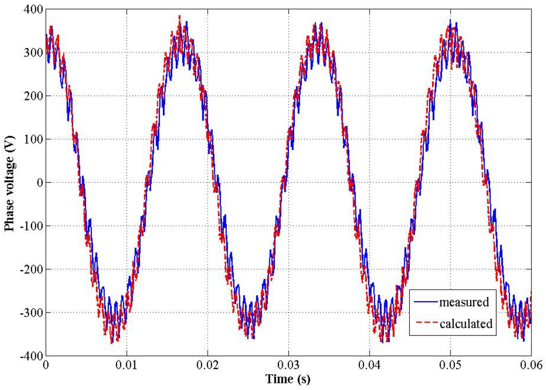

Fig. 5. One phase voltage.

VI. CONCLUSION

A self-excited induction generator is simulated in this work using a coupled 2D FEM field-circuit approximation, considering the inverse JA vector hysteresis model. Experimental and calculated results are presented for a specially constructed induction machine showing the effectiveness of the proposed methodology and developed simulation tools.

VII. REFERENCES

[1] T. Tudorache, L. Melcescu, S. V. Paturca "Finite Element Analysis of Self-Excited Induction Generator for Isolated Small Power Wind Turbines," *Clean Electrical Power, 2007 – International Conference*, May 2007, pp. 656-661, Publisher: IEEE.

[2] T. F. Chan, L. L. Lai, L. Yan, "Finite Element Analysis of a Single-Phase Grid-Connected Induction Generator With the Steinmetz Connection," *IEEE Trans. on Energy Conv.*, vol. 18, n. 2, June 2003, pp. 321-329.

[3] S. Brulé, A. Tounzi, F. Piriou, "Numerical Modeling of an Unbalanced Short Shunt Induction Generator using Finite Element Method", *COMPEL*, Vol. 19, N. 3, 2000, pp. 787-804.

[4] J. V. Leite, N. Sadowski, P. Kuo-Peng, N. J. Batistela, J. P. A. Bastos, A. A. Espíndola, "Inverse Jile-Atherton Vector Hysteresis Model," *IEEE Trans. on Magn.*, vol. 40, n. 4, July 2004, pp. 1769-1775.

[5] P.Kuo-Peng, N.Sadowski, J.P.A.Bastos, R.Carlson, N.J.Batistela, M.Lajoie-Mazenc, "A general method for coupling static converters with electromagnetic structures", *IEEE Trans. on Magn.*, Vol. 33, N. 2, March 1997, pp. 2004-2009.