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Co-Simulation by Indirect Coupling of a Brushless Single-Phase Synchronous Generator

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Abstract: This paper describes and simulates the transient process of self-excitation of a single-phase brushless capacitor-exciter synchronous generator (BCESG) by Finite Element Method (FEM). To simul the BCESG the coupling between the magnetic circuit and the electrical circuit the Method of Co-Simulation by Indirect Coupling is applied. The Total Harmonic Distortion of the terminal voltage is calculated and the main harmonics identified by Fast Fourier Transform (FFT).

Resumo: Este artigo descreve e simula o processo transitório de autoexcitação de um gerador síncrono monofásico sem escovas excitado por capacitor pelo Método dos Elementos Finitos (MEF). Para simular o BCESG, o acoplamento entre o circuito magnético e o circuito elétrico é utilizado o método de co-simulação por acoplamento indireto. A distorção harmônica total da tensão terminal é calculada e os principais harmônicos identificados pela Transformada Rápida de Fourier.

Keywords: single-phase synchronous generator, brushless machine, self-excited machine, rectifier, capacitor, Finite Element Method, Co-simulation

Palavras-chaves: gerador síncrono monofásico, máquina sem escovas, máquina auto-excitada, retificador, capacitor, Método de Elementos Finitos, Co-simulação

1. INTRODUCTION

In the 50's, the single-phase brushless capacitor-exciter synchronous generator has been proposed by Nonaka [1]. This generator uses a short-circuited field winding with a diode to obtain self-excitation in a brushless generator. The stator contains a two-phase winding similar to a conventional single-phase induction motor. The primary winding is connected to the electrical load, and the auxiliary winding has a capacitor connected across its terminals. The voltage induced in the field coil by the reverse revolving field due to single-phase armature reaction is converted from AC to DC by a half-wave rectifier, and self-excitation is obtained. Since the field current contains the series characteristic component proportional to the load current, the output voltage is kept automatically near-constant under a wide range of loads, [1]. Nowadays, this generator has widespread use as a portable engine generator.

In this paper, we review some foundation analysis issues initially written by Nonaka [2] in 1992, particular*ly* as simulation techniques. The Fast Fourier Technique (FTT) technique is used to compute and analyze the Voltage Harmonic Distortion (VHD) of the BCESG since in [2] that is not accomplished either. Another essential subject is the use of co-simulation in this paper instead of the direct coupling approach used in Nonaka's publication, where the magnetic and circuit equations are coupled directly together and solved simultaneously. In the co-simulation, the magnetic and the electrical circuit equations are treated as separated systems in a step-by-step process concerning time. At the same time, they exchange coupling coefficients in each step [3]. This approach is more flexible to allow the magnetic circuit and the electrical circuit to work independently, and the solution is more accurate and stable. This is because the winding currents and voltages are both free to change across the coupled windings by both the FEM simulator and the circuit simulator at each time step. In simpler terms, one can say that the electronic circuit can be changed without changing the electric machine finite element mesh. Besides, this approach allows a supporting level for a system simulation including FEM, circuits, state machines, and block diagrams [4] which is not possible with the Direct Coupling as suggested by Nonaka [2]. As an example, it can be cited the switching process, the use of mechanical inputs/outputs, and the use of a controlled source to simulate the self-excitation process. In this paper, the Maxwell-SIMPLORER® co-simulation is used to simulate the transient process of self-excitation and the steady-state period.

2. COUPLING SIMULATION METHODS

In this work, two techniques of modeling of the reluctance switched motor are used. The first uses finite elements for simultaneous resolution of the field equations with the converter circuit (strong coupling) and the second one where the field and the circuit simulator are treated as separated systems in a step-by-step process concerning time, while they exchange coupling coefficients in each step (co-simulation).

2.1 Direct Coupling

In this technique, the interaction between the magnetic and electrical circuits is taken into account by adding the equations of the external circuit to the finite element matrix [6]. According to [7] and [8], to simulate an electromagnetic device modeled by finite elements connected to an electric circuit, the following equations system can be used:

$$MA + N\frac{dA}{dt} - PI = D \tag{1}$$

$$Q\frac{dA}{dt} + [R - G_6]I + L\frac{dI}{dt} - G_4 X = G_5 E \tag{2}$$

$$\frac{dX}{dt} - G_1 X - G_3 I = G_2 E \tag{3}$$

In this equation system, the unknowns are *A* (the magnetic vector potential in the finite element nodes), *I* (the currents in the windings of the electromagnetic device), and *X* (the feeding circuit state-variables). *M* and *N* are respectively the assembling of elemental Finite Elements matrices related to permeability and conductivity [6]. *P* is the matrix that relates the elemental current to the elemental nodes. *D* is the excitation vector related to permanent magnets. *Q* is the matrix that represents the flux linkage of the windings. The end winding inductances and winding resistances are taken into account respectively through matrices *R* and *L*. *E* is the electric circuit voltage and/or current sources vector. *G1* to *G6* matrices depend only on the circuit topology and they are determined automatically according to the converter operation sequences [6]. The movement of the rotor is taken into account through the Movement Band technique with quadrilateral finite elements in the air gap [9]. Figure 1 shows the region of the air gap with the Movement Band in black, this region is the only one that will be re-meshed during the movement of the rotor.

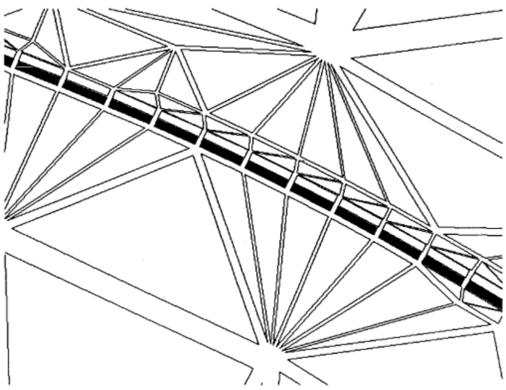

Fig. 1. Mesh in the region of the air gap with the region of the movement band in the dark.

In studies involving electromechanical transients, the equation that relates the electromagnetic torque (T_e) and the mechanical torque (T_L), as well as the Inertia (J) and Damping (B) of the entire system must be incorporated into the calculation process.

$$\frac{d\omega}{dt} = \frac{1}{J}\left[T_e - B\omega - T_L\right] \tag{4}$$

$$\frac{d\theta}{dt} = \omega \tag{5}$$

2.2 Indirect Coupling

Figure 2 illustrates the co-simulation coupling parameters for a one-winding device. The field side (finite-element side), the winding appears to the circuit simulator as a resistances R, inductances L, and back EMF E. On the circuit side, no matter how complicated the circuit system, the coupling nodes appear to the FEM simulator as a Norton equivalent circuit with current source I, conductance G. For the mechanical subsystem, on the field side, the FE simulator injects a torque T_e into the circuit simulator's mechanical model. The load is represented by the resistant torque T_r, by the damping B, and by the inertia J.

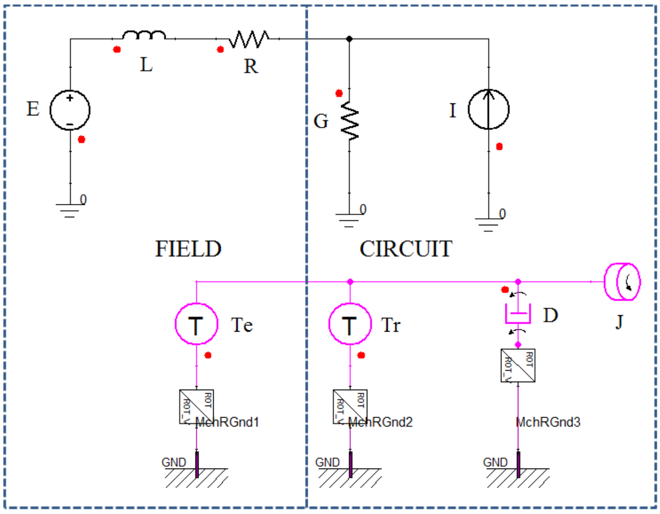

Fig. 2. General scheme of the Magnetic Circuit Simulator – Electrical Circuit Simulator transient coupling

3. BCESG PRINCIPLES

The BCESG comprehends three circuits as shown in Fig. 3. The stator has two windings, W_m and W_a, where W_m is the main winding connected to an electrical load and W_a is the auxiliary winding connected to a capacitor C. The rotor is composed only with of a coil and it is short-circuited by a diode D. The self-excitation starts when the rotor rotates employing a prime-mover. The residual magnetism through the rotor core cutting the W_m and W_a conductors to induce a small electromotive force (EMF). This leads to currents I_m and I_a with synchronous frequency f across W_m and W_a, respectively. The auxiliary winding has a capacitor C across its terminals that produces a phase shift between the currents of the main and auxiliary windings. Then, the main pulsating winding flux ϕ_m can be resolved into two revolving fluxes: ϕ_{fm} is forwardly revolving, and ϕ_{bm} is backwardly revolving. Similarly, the auxiliary pulsating winding flux ϕ_a is resolved into two revolving fluxes ϕ_{fa} and ϕ_{ba}.

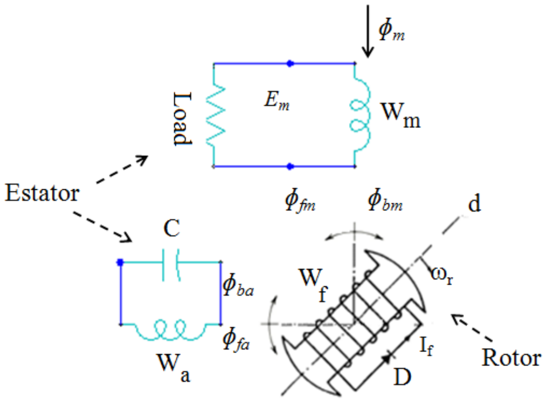

Fig. 3. Brushless self-excited single-phase synchronous generator.

The rotor slip, with respect to the forward field, is

$$s_f = \frac{\omega_s - \omega_r}{\omega_s} \tag{6}$$

The rotor rotates opposite to the rotation of the backward magnetic field. Therefore, the slip, with respect to the backward field, is

$$s_b = \frac{\omega_s - (-\omega_r)}{\omega_s} = \frac{\omega_s + \omega_r}{\omega_s} = 2 - s \tag{7}$$

Therefore, when the rotor speed ω_r hits the field synchronous speed ω_s, s_f is zero, then the forward fields induce some voltages across W_f. On the other hand, s_b is equal to 2, and the backward fields ϕ_{bm} and ϕ_{ba} produce a double frequency voltage across the rotor winding. That voltage is rectified by the diode D to create the DC excitation.

4. FINITE ELEMENT ANALYSIS

4.1- Softwares and Finite Element Model Analysis

Maxwell is an interactive, GUI-driven software package that applies the FEM to solve two-dimensional (2D) and (3D) electromagnetic field applications. To analyze a problem, the user specifies the geometry, material properties, sources of energy, boundary conditions and the driving circuits being supplied by a SIMPLORER® model. SIMPLORER® is a circuit and system simulator for the virtual prototyping of large-scale mechatronic, power electronic, and electromechanical systems. This co-simulation capability offers the user the combined accuracy of the finite element method solution of complex electromagnetic components such as electric motors, actuators, etc. and the complexity of the attached driving and control circuits [10].

Figure 4 shows the 2D-FEM model of the generator created utilizing Maxwell® software and Fig 5 the FEM mesh at 0.2 s, 3600 rpm, 210°. The one-phase distributed winding stator is composed of the main winding, which uses two-thirds of the number of slots, and the auxiliary winding uses the remaining one-third. The field winding and cage winding are embedded in the salient pole rotor.

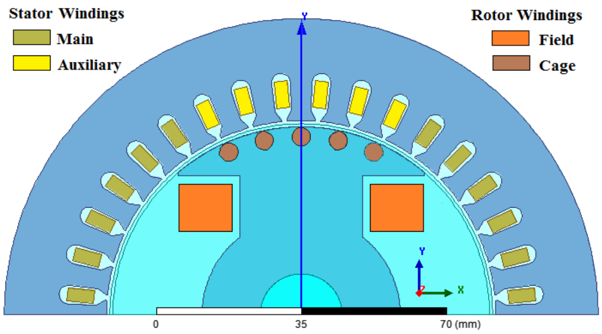

Fig. 4. BCESG 2D-FEM model.

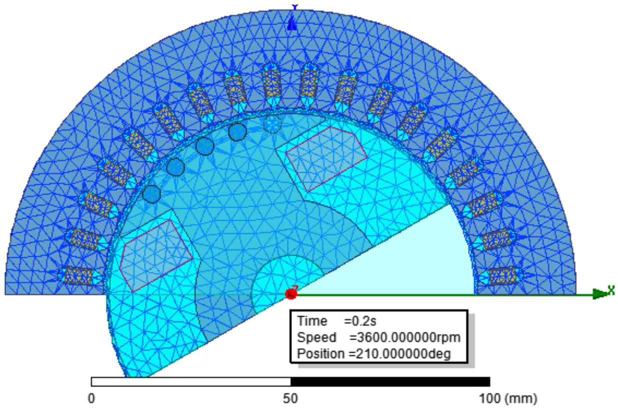

Fig. 5. BCESG FEM mesh.

Figure 6 refers to the Field model coupled to the electrical and mechanical components in SIMPLORER® to perform the co-simulation. The co-simulation is carried out by running the Field Model subsystem in a black-box manner exchanging data with the electrical circuit and the mechanical system represented by the prime mover.

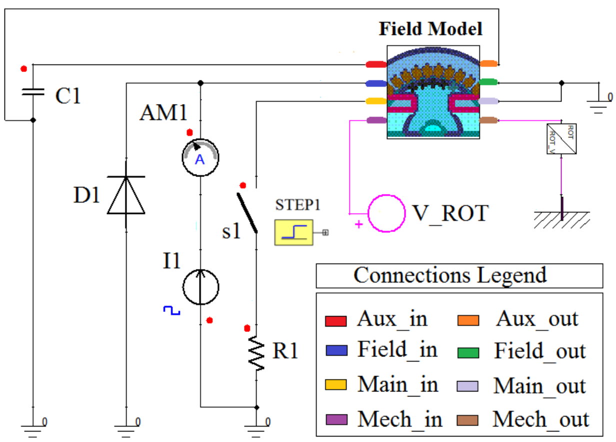

Fig. 6. BCESG SIMPLORER® model.

4.2-No-load Analysis

The core magnetizing curve of the stator winding determines the terminal voltage for a given magnetizing current through these windings. The BCESG operation as a function of the terminal voltage (at a given frequency) will require a magnetizing current to describe its action. This is determined by feeding the BCESG with different field currents to obtain the no-load terminal voltage for a given speed. The capacitive reactance will set the slope of a V-I straight line passing through zero as [5]

$$X_c = \frac{1}{\omega C} \tag{8}$$

The value of capacitor C can be chosen for a given rotation in such a way that the V-I straight line intercepts the magnetizing curve at the point of the desired rated voltage (V_{rated}) across winding terminals and under load. Figure 7 shows the magnetizing curve obtained by FEM at a speed of 3600 rpm. The V-I straight line intercepts the magnetization curve at approximately 123 V, which results in a capacitor of 120 µF. If the V-I straight line does not meet the magnetization curve, and the self-excitation does not take place.

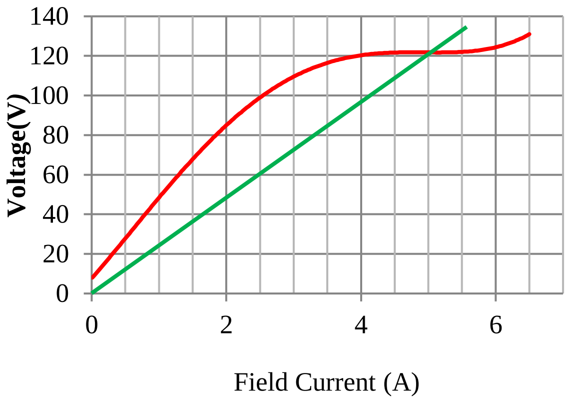

Fig. 7. Magnetization curve and V-I straight line at 3600 rpm.

4.3-Self-Excitation Simulation

As far as the model represented in Fig. 6, a constant mechanical speed source was applied to the generator through a speed source (prime mover) component V_ROTB. A value of 1-A pulse current is applied for a short time to Field_in terminal to represent the remanent magnetic flux in the core. A suitable value for self-excitation capacitance should be chosen from the magnetization curves to self-excite the generator at the rated voltage. The load R1 is switched on at t = 0.01 s by step controlled switched s1 after the generator been entirely excited. Figure 8 shows the variations of flux linkages in the windings along the transient and steady-state periods, considering a 5 ohms resistive load connected to the main winding and C1 = 120 µF connected across to the auxiliary winding. The diode rectifier (D1) has a bulk resistance of 1mΩ and a reverse voltage of 1000 V. The simulation was performed with a time step of 20 ms in a time interval of 1.6 s.

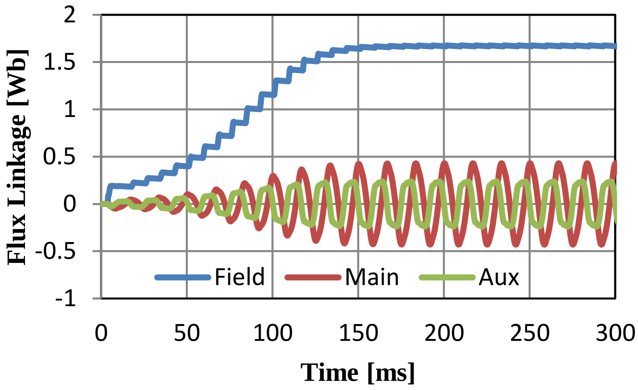

Fig. 8. Flux linkages along with transitory and steady-state for a 120µF capacitor.

Figure 9 shows the core fluxes when a 60-µF capacitor is incapable of self-exciting the generator.

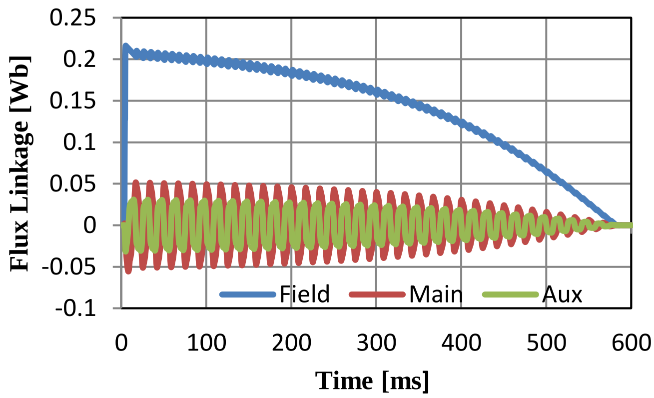

Fig. 9. Flux linkages along with transitory and steady-state for a 60µF capacitor.

4.4- Analysis of Steady-State Response

The main and auxiliary flux linkages have a sinusoidal wave shape; however, the field flux linkage is almost DC due to the large inductance of the rotor field coils. The field current has a pulsating wave shape, as shown in Fig. 10.

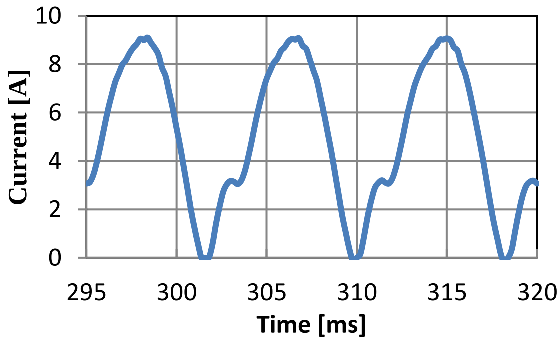

Fig. 10. The field winding current.

Fig. 11 presents its harmonic content, which contains the DC component (0 Hz) and some negative sequence harmonics, including the AC component 2f = 120 Hz caused by the backward fluxes ϕ_{bm} and ϕ_{ba} with origin in the armature.

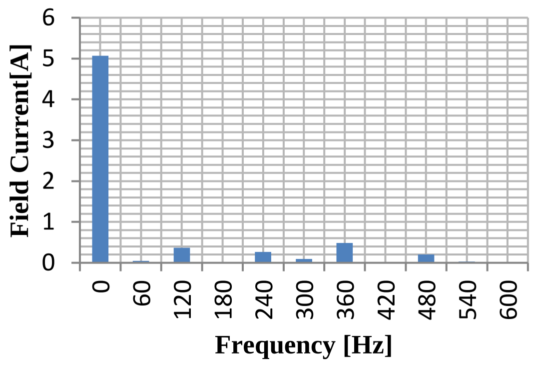

Fig. 11. FTT field winding.

Fig. 12 shows the auxiliary current waveform and Fig. 13 the respective harmonic spectrum with the fundamental f = 60 Hz and the most significant harmonic component, which is the third one (3f = 180 Hz), due to the saturation of the magnetic circuit.

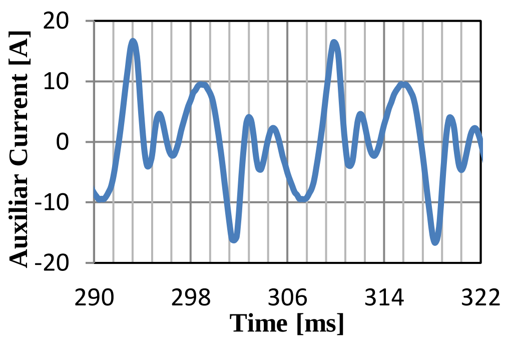

Fig. 12. Auxiliary winding current.

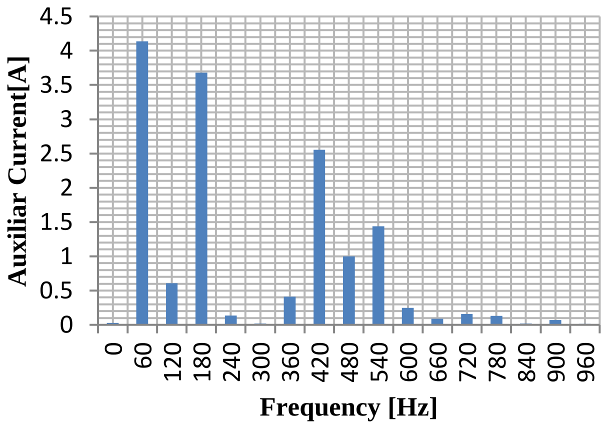

Fig. 13. FFT auxiliary current

Figure 14 shows the EMFs across the windings and the rated terminal voltage E_m and Fig. 15, its harmonic spectrum. The E_m presents 15.4% of Total Harmonic Distortion (THD). Usually, a total harmonic distortion (THD) of less than 5-6% is generally considered acceptable, but some gensets produce THD > 15%.

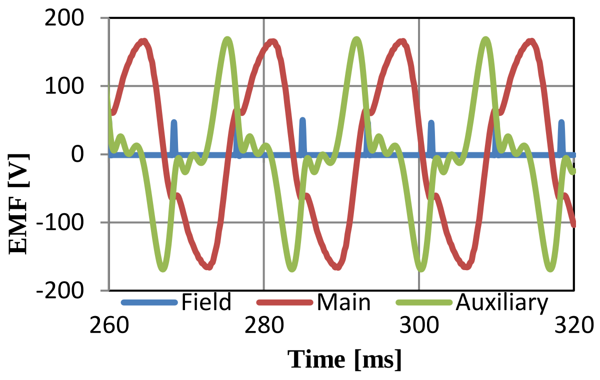

Fig. 14. Windings induced EMFs.

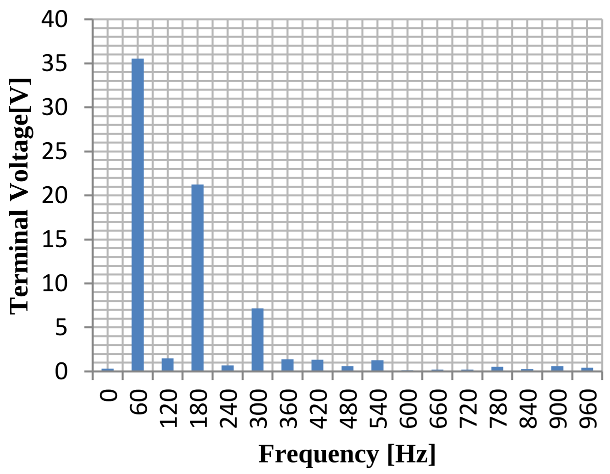

Fig. 15. FFT Terminal Voltage

By analyzing the spectrums of Fig. 15, one can see that the terminal voltage presents a high 180-Hz component. Hence, it can be concluded that these harmonics are the main responsible for such harmonic distortion.

6. CONCLUSÕES

In this paper, a review in terms of modeling and simulation issues of a 90's article wrote by Nonaka about a single-phase brushless capacitor-exciter synchronous generator is presented. The use of Co-Simulation instead of Direct Coupling used by Nonaka facilitates the modeling and simulation of BCESG since it permits to add electronic switches, mechanical variable inputs/outputs, and pulse-controlled sources. Besides that, it helps a better understanding of this subject due to the block diagrams, which permits us to understand what role each part plays in the working of a machine.

The main current harmonic components of the auxiliary and the field winding are obtained by FFT. As it was expected, the spectrum of the auxiliary winding current presents a third harmonic component, while the spectrum of the field winding current presents twice more harmonic components. The Total Harmonic Distortion of the terminal voltage is calculated and the main harmonics identified

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