Praise Worthy Prize

International Review on Modelling and Simulations (I.RE.MO.S.), Vol. 5, N. 6
ISSN 1974-9821
December 2012

Formulation of Harmonic Balance Finite Elements Method for a Linear Single-Phase Self-Excited Induction Generator

Behrooz Rezaeealam

Abstract – *This paper suggests a general method for analysis of a linear single-phase induction generator based on the harmonic balance finite elements method (HBFEM). By combining diffusion equation and circuit equations, a system of equations are obtained that could calculate the minimum required capacitance to produce the self-excited mode. It also gives the steady-state response without analysis of the transient mode of operation. By using the calculated value of the minimum required capacitance for self-excitation process as an initial value, and gradually increase of the capacitance using iterative procedure, the required capacitance for obtaining the proposed voltage of a fixed load. To verify the recommended method, the results obtained from the proposed method and the time stepping finite elements method (TSFEM) are compared.*

***Keywords**: Harmonic Balance Finite Element, Self-Excited Induction Generator, Excitation Capacitor*

Nomenclature

W	Width of the machine
N_{dq}	Windings turns
N	Number of nodes
υ	Reluctivity
σ	Conduction coefficient
U_{dq}	Terminal voltage
R_{dcdq}	Dc resistance
S_{dq}	Cross section of wire
S_{dq}	Cross section of coil
Δ_e	Area of element e
V_x	Speed in x direction
w	Fundamental angular frequency
H	Magnetic field intensity
B	Magnetic flux density
e_d, e_q	Emf of windings d and q
LH,RH	Left hand and right hand sides of the coils

I. Introduction

Induction generators are inexpensive and with no separate excitation, they can operate for a long period with no particular maintenance. Therefore, self-excited induction generators (SEIG) are important for electricity generator in the area far from the power system grids and where non-conventional energies such as wind energy are available. However, SEIGs have own disadvantages including large dependency of the output voltage on the generator speed and load and the stator terminal capacitance requirement, which requires to account for the speed and load variations [1],[2]. Two problems are considered in this paper. The first is finding the minimum required capacitance to build up the self-excitation and second in obtaining generator steady-state voltage and current waveforms. The models that are used for analysis of the SEIG are classified into two major groups.

In the first group, phase equivalent circuit is utilized; in this case nodal-admittance method or loop-impedance method is used to establish relationships between the machine-related parameters such as load, speed and capacitance [3]. The second group uses d-q-axes model and other equations expressing dependency between steady-state parameters of the machine are obtained using the harmonic balance method [4],[5]. In the above-mentioned methods, an attempt has been made to solve a non-linear equation by an iterative procedure, where experimental equations of the magnetization inductance versus magnetization current are available.

This paper uses finite elements method for modeling induction generators. Since saturation is unavoidable in SEIGs, the third harmonic currents and voltages are appeared. It means that it is not possible to assume sinusoidal waveforms for voltages and currents and therefore frequency domain finite elements method is not applicable [6],[7],[8].

So, analysis of SEIGs is carried out using time domain finite element method (TSFEM) [9],[10] and this requires a long computation time for simulation of the transient mode up to the steady-state mode. In this paper a general method of HBFEM [11], [12], [13], [14], [15]

Manuscript received and revised November 2012, accepted December 2012

is recommended for analysis of SEIGs; in this manner, solving SEIG equations using TSFEM is converted to solving the matrix form of static FEM equations, where they are used to obtain the minimum required capacitance of the self-excitation process and waveforms of the state variables of steady-state operation of SEIG for a given load. As an example, a linear single-phase SEIG, shown in Fig. 1, is considered and its performance is studied using HBFEM.

II. HBFEM Formulation for SEIG

Two-dimensional magnetic field equations in an electrical machine are given as follows:

For main (q) and auxiliary (q) winding:

$$\frac{\partial}{\partial x}\left[\upsilon\frac{\partial A}{\partial x}\right]+\frac{\partial}{\partial y}\left[\upsilon\frac{\partial A}{\partial y}\right]=-J_{dq} \quad (1)$$

For secondary conductor:

$$\frac{\partial}{\partial x}\left[\upsilon\frac{\partial A}{\partial x}\right]+\frac{\partial}{\partial y}\left[\upsilon\frac{\partial A}{\partial y}\right]=\sigma\frac{\partial A}{\partial t}+\sigma V_x\frac{\partial A}{\partial x} \quad (2)$$

For air and iron:

$$\frac{\partial}{\partial x}\left[\upsilon\frac{\partial A}{\partial x}\right]+\frac{\partial}{\partial y}\left[\upsilon\frac{\partial A}{\partial y}\right]=0 \quad (3)$$

where A is the magnetic vector potential.

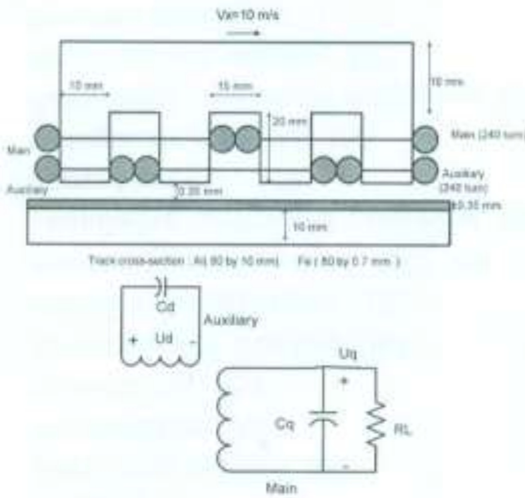

Fig. 1. A linear single-phase SEIG

The current density in the main and auxiliary windings (J_{dq}) is as follows:

$$J_{dq}=\frac{1}{R_{dcdq}S_{dq}}\left(\frac{d\lambda_{dq}}{dt}-U_{dq}\right) \quad (4)$$

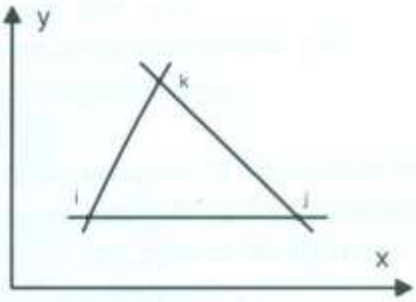

Fig. 2. Triangular nodes with nodes i, j and k

The flux-linkage of the main and auxiliary windings λ_{dq} is as follows:

$$\lambda_{dq}=\frac{WN_{dq}}{3S_{cdq}}\left(\sum_{e}^{LH}\Delta_e\sum_{i=1}^{3}A_{ei}-\sum_{e}^{RH}\Delta_e\sum_{i=1}^{3}A_{ei}\right) \quad (5)$$

which can be rewritten as follows:

$$\lambda_{dq}=\frac{WN_{dq}}{3S_{cdq}}V_{dq}^{T}A_{V} \quad (6)$$

V_{dq} is a column vector where the components corresponding to the elements on the main and auxiliary windings are unit and remaining components are zero. A_V is also a column vector consists of the nodal magnetic potential.

Since the geometry of the machine does not vary due to the movement, speed term V_x has been considered in Maxwell equations and mesh movement has not been made.

Based on the harmonic balance method, the magnetic vector potential variables for node i, U_{qd} voltages and magnetic flux density for element e in the steady-state can be expressed using Fourier series as follows:

$$A^i=\sum_{n=1,3,5,\cdots}\left\{A_{ns}^{i}\sin(nwt)+A_{nc}^{i}\cos(nwt)\right\} \quad (7)$$

$$B_x^e=\sum_{n=1,3,5,\cdots}\left\{B_{xns}^{e}\sin(nwt)+B_{xnc}^{e}\cos(nwt)\right\} \quad (8)$$

$$B_y^e=\sum_{n=1,3,5,\cdots}\left\{B_{yns}^{e}\sin(nwt)+B_{ync}^{e}\cos(nwt)\right\} \quad (9)$$

The magnetic saturation curve of the iron is expressed as follows:

$$H(B)=H_{sat}(B) \quad (10)$$

where $B=\sqrt{B_x^2+B_y^2}$. Reluctivity for element e in the Fourier series is as follows: