Analysis of linear induction generator with harmonic finite element method

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This paper suggests a self-excited linear induction generator (SELIG) for a system of free-piston generator. Its operation at steady-state and transient modes and the stability domain are investigated using a time-stepping numerical method. the numerical method of the coupled Finite Element-Boundary Element (FE-BE) is employed because of its advantage to consider the relative motion easily. The results agree well with those obtained with pure Finite Element (FE) method.

Key words: Linear Induction Generator, Self-Excitation, reciprocating motion, coupled FE-BE

1. Introduction

A free-piston generator system has major advantages compared with the normal rotating generator having crankshaft[1]. The only linear generators that have been proposed for free-piston system require movable permanent magnets on the translator[1,2((Fig. 1). These types of linear generators have a good power to volume ratio. Their disadvantage is the permanent magnet fatigue due to high temperature and armature reaction in high load and short circuit. There is thermal limitation of isolation between the permanent magnets and combustion cylinders. Other limitation is suffering from large and repeated forces by the permanent magnet that applies on the movable part.

This paper suggests a SELIG for free-piston generator system (Fig. 2). The SELIG enables to generate electrical energy with high reliability. This type of generator has some advantages such as: lower cost, robust structure, with no dc excitation, lower maintenance cost and needless to high thermal isolation. These advantages are more important than some disadvantages such as dependency of the induction generator on the load and non-optimal use of the iron.

In this paper a reciprocating SELIG with tubular structure as shown in Fig. 2, is considered. It has two windings d and q, shunt exciting capacitances (C_q, C_d) and resistant loads. Its model is nonlinear, because of magnetic saturation, longitudinal end-effect and unbalanced winding distribution that make the model being difficult to deal with by analytical methods so numerical methods are employed to analyze it. Transverse edge-effect does not exist due to cylindrical construction.

This paper uses coupled FE-BE method for modeling reciprocating SELIG[3,4]. FE method is used for iron and copper parts to deal with nonlinearity and eddy currents, while BE method is used for the air gap between moving parts using free space Green function. This method is especially suitable when linear motion is involved in the electromagnetic devices to uncouple the moving and the stationary meshes. For the particular case of a two-dimensional (2-D) coupled FE-BE model of linear machine, it only requires elementary manipulations of Green function and its normal derivative in a fundamental period. The

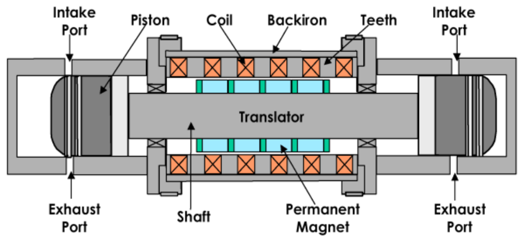

Fig. 1. Free-piston alternator-engine with movable permanent magnet[1]

proposed method causes global matrix that is symmetrical for particular boundary conditions. However, this symmetry does not hold in general for BE method.

The results agree well with those obtained with time stepping pure FE methods.

2. Coupled FE-BE method

2.1 Finite element regions The primary and secondary domains were meshed using three-node triangular finite elements as shown in Fig. 3. The equations are obtained using the Galerkin method. If F denotes the finite element region, by considering the equivalent circuits in Fig. 2, the coupled field-circuit matrix equation of the proposed reciprocating SEIG is[3,4,5]:

$$\begin{bmatrix} \mathbf{C}_{11} & \mathbf{C}_{12} & \mathbf{C}_{13} & \mathbf{C}_{14} \\ \mathbf{0} & \mathbf{C}_{22} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{C}_{33} & \mathbf{0} \end{bmatrix} \begin{bmatrix} A'_F \\ e \\ u \\ \frac{\upsilon_0}{r} A'^n_F \end{bmatrix} + \begin{bmatrix} \mathbf{D}_{11} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{C}^T_{12} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{C}^T_{13} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} A'_F \\ e \\ u \\ \frac{\upsilon_0}{r} A'^n_F \end{bmatrix} = 0 \quad (1)$$

A_F ($A'_F = rA_F$) is the magnetic potential and $[A'^n_F]_{\Gamma_e} = \frac{\partial A'_F}{\partial n}$ is its normal derivative for those elements which have a side shared with the exterior domain Γ. The exterior domain is broadened to lie outside the magnetic iron core and υ_0 is the reluctivity of air.

$e = [e_q \ \ e_d]^T$ and $u = [u_q \ \ u_d]^T$ are the electromotive forces and terminal voltages of the windings q and d, respectively.

$[C_{11}]$ stiffness sparse symmetrical matrix

$[D_{11}]$ damping symmetrical matrix due to eddy currents

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