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Reciprocating Flux-Concentrated Induction Generator for Free-Piston Generator

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This paper presents and examines a self-excited tubular induction generator for a free-piston generator system. The induction generator utilizes flux concentration by eddy currents. The paper shows that leakage flux is thereby reduced in the proposed generator and its performance is greatly improved. A three-dimensional finite-element method is employed to investigate its performance. A comparison of the calculated and measured results for standstill thrust force confirms the validity of the model.

Index Terms—Finite-element method, free-piston generator, induction generator, leakage flux, self-excitation.

I. INTRODUCTION

A free-piston generator system has been proposed for auxiliary power generating and hybrid electric vehicle application [1], [2]. This system has high reliability and efficiency and is compact and lightweight. In [1] and [2], permanent-magnet (PM) machines have been used where magnets are placed on the mover part of the machine. PM machines have a higher thrust force density (1.2 N/cm^2) compared with induction machines ($0.2\text{--}0.3 \text{ N/cm}^2$ in case of high saturated machine up to 0.4 N/cm^2). PM linear synchronous motors have been proposed for many applications such as ground transportation reciprocating service system for their high performance [3]. However, PMs have aging problems due to the high temperature and pulse forces and they require high maintenance cost, as well as exact alignment between the PM and stator poles. Also, the active length of the mover part is shorter than the length of the stator and this increases the leakage flux, as shown in Fig. 1. The main problem in this machine is the high mass of PMs, because the majority of the mover mass belongs to the PMs. A low mover mass is essential in order to keep output power capacity at a reasonable level.

This paper presents an induction-type generator for the free-piston generator that merits a lightweight mover, low maintenance, and robust structure.

Also, the active length of the mover part can be longer than the length of the stator because there is no magnet on the mover and this causes the reduction of the leakage flux as shown in Fig. 2. The mass of the lower mover of the induction type increases the reciprocating frequency, so the output power capacity increases that compensates the low thrust force density of the induction type.

The previously developed flux-concentrated (FC) tubular induction machine [4] is investigated as a self-excited reciprocating generator (SETIG). A general method for analysis of a reciprocating self-excited induction generator based on the cou-

Fig. 1. Free-piston alternator-engine with movable permanent magnet [1]. (Color version available online at <http://ieeexplore.ieee.org>.)

pled finite-element/boundary-element method in a harmonic domain has been suggested in [5]. The idea is to insert copper plates inside the stator slots to decrease the leakage flux using the effect of flux-concentration by eddy currents. Its model is nonlinear, because of magnetic saturation, longitudinal end effect, reciprocating motion, and unbalanced winding distribution. These factors make the model difficult to deal with by analytical methods, therefore, numerical methods are employed to analyze it. A time-stepping three-dimensional finite-element method (3-D FEM) is used that requires considering linear motion (mesh movement), external circuit, and magnetic saturation of the iron core (Newton–Raphson iteration).

The validity of the numerical method is examined by comparison of the calculated results and the measured ones for standstill thrust force.

II. CONSTRUCTIONAL FEATURES AND 3-D FEM

Fig. 2 shows a flux-concentration type 4-pole induction generator, which has an annular-linear configuration [4]. The conducting plate, along with the coils of 38 turns is inserted in each of the 12 slots. The conducting plate has an air hole in its center and a slit in the radial direction, as shown in Fig. 3. Eddy currents in the conducting plate flow around the air hole and the induced field due to this eddy current is directed in the same direction as that of the applied field in the air gap.

The plate has high reluctance, therefore, the majority of the magnetic flux is flowing through yoke, air gap, and mover core. Thus, the plate with radial slit provides some sort of magnetic

Fig. 2. Structure, boundary conditions and equivalent circuit of the proposed generator. (Color version available online at <http://ieeexplore.ieee.org>.)

shield which results in reduction of the leakage flux between the yokes; the concentration air gap flux enhances the developed thrust.

Steel-silicon thin sheets are used for magnetic core of the stator structure. The back iron of the mover structure is however made of solid iron, which is covered by a layer of copper (top cap) with thickness of 0.4 mm.

Fig. 2 shows the analyzed model of FC-SETIG. The symmetrical structure of the generator allows modeling one half of the whole region. The fundamental equations of the magnetic field, taking into account the eddy currents, can be written as follows [6], [7]:

$$\text{rot}(\nu \text{rot}(\vec{A})) = \vec{J}_0 + \vec{J}_e \quad (1)$$

$$\vec{J}_e = -\sigma(\partial \vec{A} / \partial t + \text{grad} \phi) \quad (2)$$

$$\text{div}(\vec{J}_e) = 0 \quad (3)$$

Fig. 3. Conducting plate used inside the stator slots.

where $\vec{A}$ is the magnetic vector potential; ν is the reluctivity; $\vec{J}_e$ is the eddy current density; $\vec{J}_0$ is the exciting current density and ϕ is the electric scalar potential.

Assuming that the weight function is the same as the shape function N , the integral forms for (1)–(3) using the Galerkin's procedure will be as follows:

$$\begin{aligned} \int \int \int_{\Omega} N [\text{rot} \{ \nu \text{rot}(\vec{A}) \}] d\Omega + \sigma \int \int \int_{\Omega} N (\partial \vec{A} / \partial t \\ + \text{grad}(\Phi)) d\Omega = \int \int \int_{\Omega} N \vec{J}_0 d\Omega \end{aligned} \quad (4)$$

$$\int \int \int_{\Omega} N \text{div} \{ \sigma (\partial \vec{A} / \partial t + \text{grad}(\Phi)) \} d\Omega = 0. \quad (5)$$

By applying the following to the first term of (4):

$$a(\text{rot}(\vec{b})) = -\text{grad}(a) \times \vec{b} + \text{rot}(a \vec{b}) \quad (6)$$

and then using Gauss's theorem leads to the following equation:

$$\begin{aligned} - \int \int \int_{\Omega} \text{grad} N \times \{ \nu (\text{rot}(\vec{A})) \} d\Omega + \int \int_S (N \{ \nu (\text{rot}(\vec{A})) \}) dS \\ + \sigma \int \int \int_{\Omega} N (\partial \vec{A} / \partial t) d\Omega \\ + \sigma \int \int \int_{\Omega} N \text{grad} \phi d\Omega = \int \int \int_{\Omega} N \vec{J}_0 d\Omega \end{aligned} \quad (7)$$

where $\vec{dS} = \vec{n} ds$ (S is the surface of the region Ω). Also, using the following formula:

$$a(\text{div}(\vec{b})) = -(\text{grad}(a) \cdot \vec{b} + \text{div}(a \vec{b})) \quad (8)$$

and then, Gauss's divergence theorem, (5) is rewritten as follows:

$$\begin{aligned} - \int \int \int_{\Omega} \text{grad} N \cdot \{ \sigma (\partial \vec{A} / \partial t + \text{grad}(\Phi)) \} d\Omega \\ + \int \int_S N \{ \sigma (\partial \vec{A} / \partial t + \text{grad}(\Phi)) \} \cdot \vec{dS} = 0. \end{aligned} \quad (9)$$

TABLE I
GENERATOR PARAMETERS

Active length of the generator	224 mm
Number of poles	4
Pole pitch	54 mm
Outer diameter of the stator	126 mm
Inner diameter of the stator	32 mm
Diameter of the stator conductor	1.6 mm
Outer diameter of the mover	31.4 mm
Thickness of the copper tube (mover conductor)	0.4 mm
No. of slots	12
No. of turns per slot	38
Mechanical clearance between the stator and the mover (air gap)	0.3 mm
Tooth width	8 mm
Slot width	10 mm
Slot depth	39 mm
Mover back iron thickness	8 mm
Stator yoke thickness	8 mm

The surface integration of (7) can be written as follows:

$$\begin{aligned} \int \int_S (N \vec{dS} \times \{\nu(\text{rot}(\vec{A}))\}) &= \int \int_S N \vec{n} \times \{\text{rot}(\vec{A})\} ds \\ &= - \int \int_S N \{\text{rot}(\vec{A})\} \times \vec{n} ds = \int \int_S \vec{H}_t N ds. \end{aligned} \quad (10)$$

In case of Neumann's boundary condition $\vec{H}_t = 0$ and in case of Dirichlet's boundary condition $N = 0$, (10) on the surface tends to zero.

The surface integration in (9) is also rewritten as follows:

$$\begin{aligned} \int \int_S N \{\sigma(\partial \vec{A} / \partial t + \text{grad}(\Phi))\} \cdot \vec{dS} \\ = \int \int_S N \{\sigma(\partial \vec{A} / \partial t + \text{grad}(\Phi)) \cdot \vec{n}\} ds = \int \int_S N \vec{J}_{\text{en}} \cdot \vec{dS}. \end{aligned} \quad (11)$$

On the surface of the conductor, $\vec{J}_{\text{en}} = 0$ and (11) tends to zero. Thus, (4) is satisfied in the whole region and becomes

$$\begin{aligned} - \int \int \int_{\Omega} \text{grad} N \times \{\nu \text{rot}(\vec{A})\} d\Omega + \sigma \int \int \int_{\Omega} N (\partial \vec{A} / \partial t) d\Omega \\ + \sigma \int \int \int_{\Omega} N \text{grad}(\Phi) d\Omega = \int \int \int_{\Omega} N \vec{J}_0 d\Omega \end{aligned} \quad (12)$$

and the supplementary condition for the eddy-current region is

$$- \int \int \int_{\Omega} \text{grad} N \cdot \{\sigma(\partial \vec{A} / \partial t + \text{grad}(\Phi))\} d\Omega = 0 \quad (13)$$

and for the eddy-current free region

$$\int \int \int_{\Omega} \text{grad} N \cdot \text{grad} \Phi d\Omega = 0 \quad (14)$$

Each term of the equations is calculated in the Cartesian coordinates.

Fig. 4. Eddy current flow inside the conducting plates.

The inter-linkage flux Ψ of the stator coils are represented using the magnetic vector potential A as follows:

$$\Psi = \frac{n_c}{S_c} \int \int \int_{\Omega_c} \vec{A} \cdot \vec{n}_s d\Omega \quad (15)$$

where n_c and S_c are the number of turns and the cross-sectional area of the coil, respectively, $\vec{n}_s$ is the unit vector along the direction of exciting current, and Ω_c is the coil area.

The induced voltage $e^{(t)}$ at time t is given as follows:

$$e^{(t)} = \frac{\Psi^{(t)} - \Psi^{(t-\Delta t)}}{\Delta t} \quad (16)$$

where $\Psi^{(t)}$ is the inter-linkage flux of the stator coil at the time t and Δt is the calculation time step.

External linear circuit equations are easily coupled to the field equations. The coupled equations of the self-excited system have no external input, and the self-excitation process begins with an initial charge on exciting capacitors.

Fig. 5. Comparison of leakage fluxes by considering the cross-sections at $\theta = 0$ and $\theta = \pi$. (a) With conducting plates. (b) Without conduction plates.

III. RESULTS

The whole mesh includes 11 520 nodes and it takes around 67 h for 1000 time steps using the computer Celeron 2400 MHz PC. Calculations include nonlinear iterations where the number in the step time is variable.

The stroke length is considered to be equal to the pole pitch ($\tau = 54$ mm) and the imposed motion profile of the mover is assumed to be sinusoidal

$$X(t) = \tau \sin(2\pi f) \quad (m). \quad (17)$$

Self-excitation of the generator is begun by the action of either a residual air-gap flux linkage or charge on the excitation capacitors. This residual flux linkage with the moving translator induces voltage in the stator windings. With sufficient capacitance, the process continues and the induced stator voltage increases until it settles down; this is determined by the saturated flux of the air gap.

Fig. 4 shows the distribution of eddy-current density vectors in the copper plate. It is found that the eddy-current density vectors distribute widely in the regions opposite to the stator cores.

The flux lines for z -component of magnetic vector potential A_z at $\theta = 0$ and $\theta = \pi$ (Fig. 2) has been depicted in Fig. 5 for two cases of FC-SETIG and SETIG (removed copper plates), and it shows the reduction of leakage flux for the FC-SETIG compared with the SETIG case.

Also, the distribution of current density vectors in the mover conductor (top cap) is depicted in Fig. 6 for two different scales that show the direction of current flow.

Fig. 7 shows the standstill thrust force versus phase voltage characteristics of the FC-SETIG and the SETIG (removed copper plate), which are the average values of the thrusts at the steady-state mode. For sinusoidal supply at 60 Hz and 30 Hz,

Fig. 6. Current flow in the mover conductor. (a) Unreal scale. (b) Real scale.

a three-phase inverter varies the input voltage and a load cell measures the thrust force. It is found that the calculated results agree well with the measured values.

Fig. 8 shows the self-excitation process for four cases of the SETIG and the FC-SETIG at 30 and 60 Hz, respectively. The period of self-excitation for FC-SETIG (0.15 s at 60 Hz and 0.5 s at 30 Hz) is shorter than that obtained for the SETIG (0.5 s at 60 Hz and 0.7 s at 30 Hz). It is evident that the current and voltage build-up at the frequency of 60 Hz is much quicker than

Fig. 7. Standstill thrust force versus phase voltage (with conducting plates). (Color version available online at <http://ieeexplore.ieee.org>.)

Fig. 8. Comparison of transient periods of self-excitation.

that obtained at 30 Hz. The copper plate is more effective at higher frequencies.

Fig. 9. No-load phase currents.

Fig. 10. Thrust force waveform versus displacement and time.

Magnetizing currents (no-load currents) at steady state have been shown in Fig. 9. It is interesting to note that the phase currents and voltages are not balanced. One reason is that the linear motion is limited by the angular displacement, and the coupling flux to the three-phase windings are not balanced, so the induced voltages are unbalanced. The other reason is the variable oscillating speed, which is not symmetrical in all the

Fig. 11. Thrust force peak versus exciting capacitance characteristics at 30 Hz. (Color version available online at <http://ieeexplore.ieee.org>.)

Fig. 12. Thrust force peak versus exciting capacitance characteristics at 60 Hz. (Color version available online at <http://ieeexplore.ieee.org>.)

phases. If the stator is long and has enough poles, the output voltages should be more symmetrical.

The depicted steady-state waveforms of the thrust force between the stator and mover parts in Fig. 10 shows a pulsed power due to the reciprocating linear motion. The thrust waveform has been plotted versus position and time.

The self-excitation process simulation shows that there is a steady-state mode even though this steady-state is not the conventional defined sinusoidal type steady-state. Stable operation of the SETIG is always a concern because of its load dependence characteristics. In the following section, some steady-state simulation results are presented based on different capacitors (with constant R_L).

Figs. 11 and 12 show the calculated thrust versus capacitance characteristics of the FC-SETIG and SETIG (removed copper-plate) at reciprocating frequencies of 30 and 60 Hz. The FC-SETIG not only provides a higher thrust force but also improves the stability; and for a wider range of exciting capacitors, self-excitation occurs.

For different exciting capacitances the fundamental frequency does not vary, because it is determined by the fundamental frequency of the imposed motion profile. As the exciting capacitances increase, the saturation level and the peak value of the thrust force increases as shown in Figs. 11 and 12. There

Fig. 13. Efficiency versus exciting capacitor characteristics at 30 Hz. (Color version available online at <http://ieeexplore.ieee.org>.)

Fig. 14. Efficiency versus exciting capacitor characteristics at 60 Hz. (Color version available online at <http://ieeexplore.ieee.org>.)

Fig. 15. Output power versus exciting capacitor characteristics at 30 Hz. (Color version available online at <http://ieeexplore.ieee.org>.)

is no self-excitation if the capacitances are smaller than C_{min} or larger than C_{max} and voltage de-excitation occurs [8].

In the FE calculations, the copper and core losses have been taken into account [9]. The efficiency variation with the capacitances is shown in Figs. 13 and 14. Although some copper losses occur in the plate, however the overall efficiency of the FC-SETIG improves due to the more effective flux.

Fig. 16. Output power versus exciting capacitor characteristics at 60 Hz. (Color version available online at <http://ieeexplore.ieee.org>.)

The maximum calculated efficiency is 75% that gradually reduces as the exciting capacitance increases.

Output power versus exciting shunt capacitance characteristics are depicted in Figs. 15 and 16. The output power increases significantly by using copper plates inside the slots, the difference of the output powers at reciprocating frequencies of 30 and 60 Hz is noticeable. As the frequency increases, the copper plates are more effective and the maximum output power approaches 330 W for the reciprocating frequency of 60 Hz.

IV. CONCLUSION

The paper has presented a new linear generator (SETIG) for free-piston generator application. A time-stepping 3-D FEM has been employed to analyze its performance. The finite-element model has been verified by comparing the numerical results with the measurements of the standstill thrust force. The performance of the generator significantly improves due to the flux-concentration by the eddy currents and the reduction of leakage flux. Higher thrust force, larger stability range for capacitor and load resistance values, shorter transient period, and higher output power have been obtained.

Although the efficiency of the induction type is lower than the one provided by the permanent-magnet type (>90%), the proposed FC-SETIG has acceptable output power capacity and is more suitable for the challenging conditions of the free-piston generator system.

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