Magnetostrictive electric generator

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A Magnetostrictive Electric Generator

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Abstract **–An electric generator based on the magnetostrictive effect is presented. Longitudinal oscillations of a Terfenol-D rod give rise to a varying flux which induces a current in a coil wound around the rod. The present article deals with a small prototype of such a device and both calculations and experiments have been performed. The problem of eddy current losses is addressed.**

I. Introduction

In most devices based on highly magnetostrictive materials, the opportunity of transduction of magnetic energy to mechanical energy is utilized. One interesting potential application of the reverse phenomenon is a magnetostrictive generator as a power supply to electronic equipment located in places where direct access is difficult due to nuclear radiation, high electric potential, environmental reasons etc. In this paper the feasibility of such an electric generator is investigated with respect to some critical design factors.

II. Functional Principle

The functional principle of the magnetostrictive generator is shown in Fig. 1. The magnetostrictive rod, with length l and cross-sectional area A, is magnetically biased to H_0 and mechanically prestressed to T_0. Contrary to actuators, where magnetic energy is transformed to mechanical energy, the generator must be magnetically biased. The net magnetization in one direction of the rod can then be modulated by the applied oscillating stress $Te^{j\omega t}$ because of the magnetostrictive effect. The flux variation obtained in the rod induces an emf in a coil with n turns. The prestress T_0 must at least be of the size of the stress amplitude $|T|$ to prevent tensional stresses in the rod.

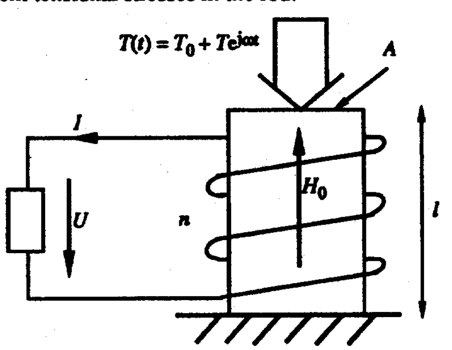

Fig. 1. U is the voltage over the load Z_0, $T(t)$ is the applied total stress on the magnetostrictive rod and H_0 is the magnetic bias from permanent magnets.

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If no magnetic bias were imposed, the rod would be nonmagnetized in its axial direction and hence no flux variation would be caused by the varying stress.

III. Electromechanical Modelling

A. The Linear Model

A linear model is appropriate for the case of a harmonic small-signal operation around the bias point (H_0, T_0). The linearized constitutive equations [1], [2] give the coupled magnetomechanical relations

$$\begin{pmatrix} S \\ B \end{pmatrix} = \psi \begin{pmatrix} s^H & \chi d \\ \chi d & \chi\mu^T \end{pmatrix} \begin{pmatrix} T \\ H \end{pmatrix} \qquad (1)$$

$$\chi = \frac{2j\, e^{j3\pi/4}\, J_1(e^{j3\pi/4} qa)}{qa\, J_0(e^{j3\pi/4} qa)} \qquad q = \sqrt{\omega\mu^T(1-k^2)\sigma}$$

$$k = \sqrt{d^2/s^H\mu^T} \qquad \psi = \frac{1-k^2}{1-\chi k^2}$$

where S, T, B are phasors of the averages of strain, stress and flux density over the cross-section, and H is the magnetic field at the surface of the rod. The differential parameters s^H, d and μ^T are the elastic compliance at constant magnetic field, the piezomagnetic constant and the permeability at constant stress, respectively. k is the static coupling coefficient. J_0 and J_1 are first kind Bessel functions of zeroth and first order. σ is the conductivity and ω is the angular frequency. The eddy current factor χ relates the average magnetic field to the magnetic field on the surface, with q as the penetration coefficient and a as the radius of the rod. ψ is a help factor. It is important to realize that using this eddy current formalism requires that the magnetic field is known at the boundary surface of the rod. Only when an ideal magnetic circuit is used to close the fluxlines from the rod, can this be the case. Also, hysteresis is treated as negligible. It is possible that one could include hysteresis by using a complex differential permeability.

By slightly modifying the magnetomechanical relations and including coil induction, leakage and magnetic circuit, one finds that

$$\begin{pmatrix} B \\ H \end{pmatrix} = \begin{pmatrix} j\omega nA & j\omega L_c \frac{l}{n} \\ 0 & \frac{l}{n} \end{pmatrix} \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \begin{pmatrix} T \\ S \end{pmatrix} \qquad (2)$$

where

$$\alpha = \chi\psi d - \frac{\mu^T\psi s^H}{d} \qquad \beta = \frac{\mu^T}{d} \qquad \gamma = -\frac{s^H}{\chi d} \qquad \delta = \frac{1}{\chi\psi d}$$

$$L_c = \frac{\mu_0 g f n}{l} \qquad f = \frac{n}{2}\left(1+(3+D/a)^{-1}\right) \qquad g = \frac{\pi}{3} D\,(3a+D)$$

L_c is a leakage inductance obtained from an assumption of the magnetic field linearly decaying to zero in the coil. f is the effective number of turns and g is the effective area of the coil for this field approximation, with D as the thickness of the coil.

The load Z_0 consists of an actual load Z_l and a coil resistance r_c, i.e. $Z_0=Z_l+r_c$. If the voltage over the actual load is U_l, one arrives at two fundamental equations

$$\frac{T}{S}=-\frac{\delta\left(1+\frac{j\omega L_c}{Z_0}\right)l+\beta\frac{j\omega n^2}{Z_0}A}{\gamma\left(1+\frac{j\omega L_c}{Z_0}\right)l+\alpha\frac{j\omega n^2}{Z_0}A} \tag{3}$$

$$\frac{U_l}{T}=\frac{Z_l}{Z_l+r_c}\,\frac{j\omega nlA}{\delta\left(1+\frac{j\omega L_c}{Z_0}\right)l+\beta\frac{j\omega n^2}{Z_0}A} \tag{4}$$

These equations are transfer functions for the longitudinally oscillating rod. One notes that (3) has the form of a load and frequency dependent elastic modulus. The inherent assumptions are that quasistatic conditions are present and that the rod can be treated as massless, so that there is no inertia and consequently the stress is constant in the axial direction. This last assumption is valid as the mass and the stiffness of the fixture are much higher than those of the rod.

To calculate the electrical and mechanical complex power it is used that

$$P_{elec}+jQ_{elec}=\frac{|U_l|}{2Z_l^*} \qquad P_{mech}+jQ_{mech}=-\frac{j\omega Al}{2}TS^* \tag{5}$$

when peak scale phasors are used for the electrical and mechanical entities. Complex conjugate is denoted by a superstar. The reactive power will oscillate back and forth between the rod and the force transmission to the rod and will thus be of interest when dimensioning the transmission system.

Calculations have been performed for a rod with 15 mm radius and 25 mm length. The coil has 100 turns and 0.22 Ω resistance. The small-signal parameters have been measured with the incremental technique [2] at a bias of 25 MPa and 40 kA/m, giving $s^H=3.46\times10^{-11}$ m²/N, $d=1.43\times10^{-8}$ m/A and $\mu^T/\mu_0=7.15$. The applied stress amplitude is kept constant at 0.9 MPa in the calculations. Two cases have been investigated. Fig. 2 shows the behaviour of a solid rod with eddy currents for different load levels. σ is here 1.66×10^{6} S/m. Fig. 3 shows the effect of eddy current limiting. This is done by substituting the penetration coefficient, here as $q\rightarrow q/4$, corresponding to a decrease in conductivity with a factor of 16. It can also be seen as a reduction of the radius when calculating the eddy current factor, giving an idea of the effect of laminating the rod. In this case the filaments would be 7.5 mm in diameter.

The calculations show the necessity of using a rather high frequency together with a relatively low impedance load to achieve high induction and current levels in the coil. This results in high efficiency, low reactive mechanical power and reasonable voltage levels. The need for lamination is obvious.

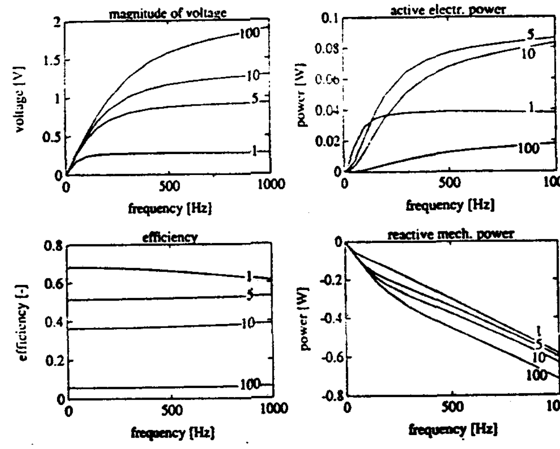

Fig. 2. Calculated voltage U_l, active electric power Pelec, efficiency P_{elec}/P_{mech} and reactive mechanical power Q_{mech} as functions of frequency for different loads Z_l in Ohms.

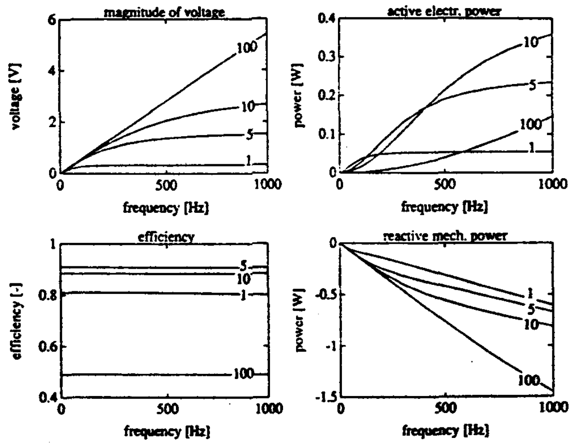

Fig. 3. Calculated results for lowered eddy currents, corresponding to a reduction of the conductivity with a factor of 16.

B. The Nonlinear Model

A nonlinear magnetostrictive element model [3] has been used to estimate the voltage induced in the generator. In the model a finite difference discretization of the quasistationary magnetic penetration equation and the one-dimensional elastic wave equation is used to describe the magnetomechanical coupling, and Ampere's and Faraday's laws provide the relation between the circuit and the field quantities. The input to the model are static material properties obtained from measurements. A harmonic stress is prescribed. In Fig. 4 the voltage induced in the generator is plotted together with the experimental data.

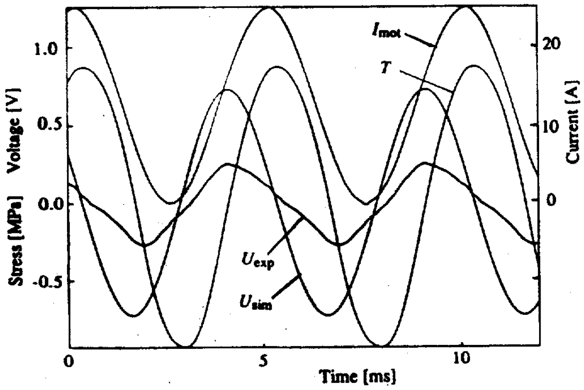

Fig. 4. Shapes of mechanical stress T (MPa) and generated voltage U_{exp}(V) for a magnetizing motor current I_{mot} (A) with amplitude 13.5 A and DC offset 16.5 A. Also shown is the simulated voltage U_{sim}.

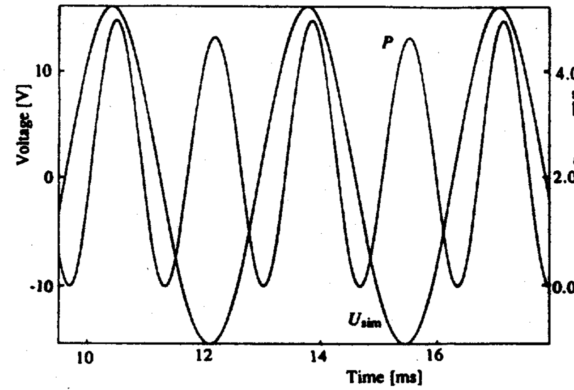

Fig. 5. Simulated output voltage and power for a resistive load of 50 Ω, when n=600, l=50 mm and A=700 mm^2.

IV. Experiments

The principle of the magnetostrictive generator has been tested in a set-up used for dynamic measurements on highly magnetostrictive materials [2]. It consists of a fixture wherein two magnetostrictive drive units are placed opposite to each other. One drive unit acts as the electric generator while the other drive unit, the motor drive unit, is the mechanical power source. Both drive units include a Terfenol-D rod with length 25 mm and diameter 30 mm, a magnetizing coil and a magnetic circuit for flux return. Both coils have n=100. Furthermore the generator drive unit is equipped with permanent magnets giving a bias magnetic field of approximately 40 kA/m. The magnetic bias of the motor drive unit is provided by the magnetizing coil. The prestress is adjusted by changing the fixture height, and is approximately set to 12 MPa in these experiments.

Fig. 4 shows the shape of the mechanical stress and the generated voltage when the motor drive unit is fed by a magnetizing current I_{mot} of 13.5 A at 200 Hz, with a superposed DC bias current of 16.5 A. The experimental set-up is not designed for the forces that would appear in a real application. Therefore the stress T has a magnitude of only 0.9 MPa. The phase shift between the current I_{mot} and the stress T is due to induced eddy currents in the Terfenol-D motor rod. The induced voltage U_{exp} of the generator drive unit clearly leads the stress by approximately 90°, which is expected. The harmonics in U_{exp} are a result of the nonlinear material characteristics of Terfenol-D.

V. Design Considerations

In the simulations and in the experiments presented above, the applied stress on the magnetostrictive generator was prescribed. In reality there might be limitations in the obtainable force from the mechanical power source. This implies that extra care must be taken in the mechanical design, which could mean special treatments of the comprising mechanical parts so that no strain is lost on bad surfaces or bad tolerances in the generator construction. A related problem in the case of a limited force is to assure that the displacement of the fixture is not too large.

Furthermore, the design of the magnetic circuit is a critical point. A generator must be magnetically biased by permanent magnets, which usually make the circuit for the dynamic flux more complicated and less effective. The problem of transmitting large mechanical forces to the generator makes it even more important to succeed with the magnetic design.

VI. Estimated Performance

On the basis of the calculations and experiments performed, an attempt is made to estimate the performance of a real generator. In the linear model approach nonlinearity, magnetic circuit reluctance and actual biasing conditions are not accounted for. This gives an overestimation of the output voltage which is observed experimentally. The nonlinear approach gives a better correspondence between calculated and experimental data. The remaining discrepancy is primarily due to mechanical imperfections in the experimental setup which is of pronounced significance at low stress levels.

In a real application the stress levels are considerably higher implying that the nonlinear model in that case can give a rough estimate of the generator performance. In Fig. 5 the output voltage and power are shown for a resistive load of 50 Ω, when n=600, l=50 mm and A=700 mm^2. It was found that this load gave maximum output power. The magnetic bias field is 72 kA/m and the prestress is 35 MPa.

VII. Conclusions

The suggested generator concept has been evaluated and found to have potential performance apt for application as a power supply to electronic equipment located in demanding environments.

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