Theoretical Power Output from a Capacitive-Coupled Power Extraction Magnetohydrodynamic Generator with a Sinusoidal Alternating Magnetic Field

Sho TAKAYANAGI, Kazumasa TAKAHASHI, Toru SASAKI, Takashi KIKUCHI, Tsukasa ASO and Nob. HARADA

Nagaoka University of Technology, Niigata 940-2188, Japan

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A capacitive-coupled power extraction magnetohydrodynamic (MHD) generator has electrodes outside a channel, that carries a combustion gas; the channel functions as a capacitor. By applying an alternating magnetic field, this MHD generator can extract power from the capacitors. Because the configuration prevents the electrodes from exposure to the gas, this kind of generator offers the advantage of being able to operate over a long time. Based on a theoretical model, the performance of the generator is evaluated when a sinusoidal alternating magnetic field is applied. From the results, we assess the feasibility of obtaining electrical power from this device.

Keywords: MHD generation, AC MHD generator, capacitive-coupled power extraction MHD generator

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Magnetohydrodynamic (MHD) generation is an efficient method for generating power. MHD generation extracts electrical power from the electromotive force generated by a conductor moving in a magnetic field [1]. Combustion gas, which is the MHD fluid, passes across the magnetic field through a channel composed of an insulator. When the combustion gas moves with velocity u through a magnetic field B, an electrical voltage V is generated between electrodes separated by distance l.

$$V = uBl. \tag{1}$$

Power is extracted by the electrodes and applied to an external load. In this MHD generator, the electrical output P is

$$P = \sigma u^2 B^2 S\, l\, K (1 - K), \tag{2}$$

where $K = R_{\mathrm{load}} / (R_{\mathrm{MHD}} + R_{\mathrm{load}})$ is the load factor, σ is the electrical conductivity of the combustion gas, S is the area of the electrodes, R_{load} is the resistance of the external load, and $R_{\mathrm{MHD}} = l/\sigma S$ is the resistance of the gas.

Equation (2) shows that any increase in the electrical conductivity is an important factor for increasing the power output. To improve the electrical conductivity, we can increase the gas temperature or add a seed material or perform both. However, because of exposure to the gas, the electrodes are damaged by thermal and chemical stresses.

To prevent damage to the electrodes, alternating current (AC) MHD generators can be considered. An AC MHD generator applies a traveling wave magnetic field [2–5]; such a generator is similar to an induction generator and hence is called an MHD induction generator. Another AC MHD generator temporarily changes the magnetic field or supplies MHD fluid intermittently. This type of AC MHD generator is called a capacitive-coupled power extraction MHD generator [6].

Figure 1 (a) depicts an overall view of a capacitive-coupled power extraction MHD generator. In the generator, electrodes are located outside an insulator channel. The inside of the channel is filled with combustion gas, forming virtual electrodes in the channel. Capacitors are formed by dielectrics sandwiched between the real electrodes and the virtual electrodes. Electrical magnets apply alternating magnetic fields across the combustion gas. When the magnetic field is applied in the positive x direction, an induced electrical voltage appears in the positive y direction. Inversely, when the magnetic field is applied in the negative x direction, an induced electrical voltage appears in the negative y direction. For example, when a sinusoidal magnetic field is applied, a sinusoidal electrical voltage appears.

Figure 1 (b) depicts the equivalent circuit of the capacitive-coupled power extraction MHD generator. The equivalent circuit contains an electrical voltage v_{MHD}, a combustion gas resistance R_{MHD}, a channel wall capacitance C_{wall}, and an external load resistance R_{load}.

The electrical voltage v_{MHD} is assumed to be a sinusoidal wave expressed by

$$v_{\mathrm{MHD}} = \sqrt{2} V \sin \omega t, \tag{3}$$

where V is the electrical voltage shown in Eq. (1) for a conventional MHD generator, ω is the angular frequency of

author's e-mail: takayanagi@stn.nagaokaut.ac.jp

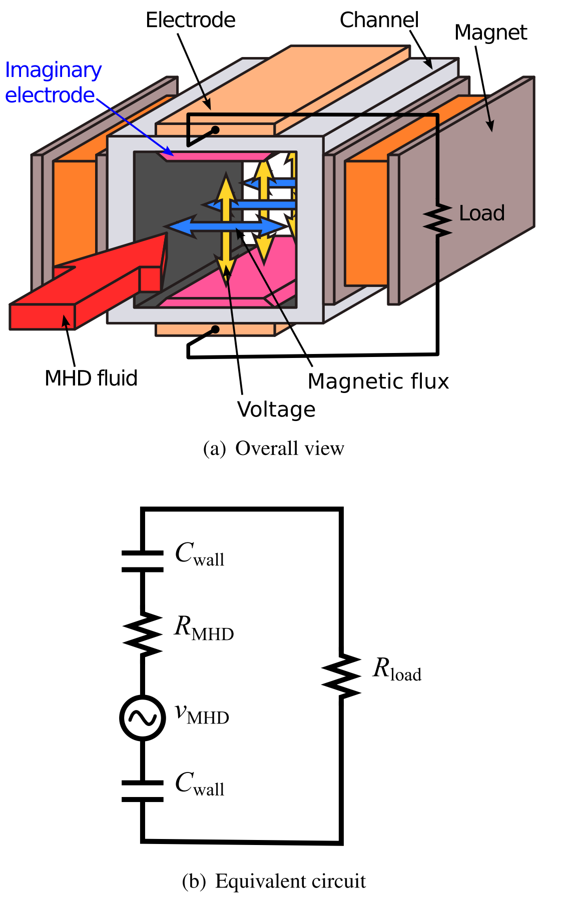

Fig. 1 Capacitive-coupled power extraction MHD generator.

the electrical voltage, and v_{MHD} is the instantaneous value of the electrical voltage.

For a phasor, v_{MHD} is expressed by

$$\dot{V}_{\mathrm{MHD}} = V e^{j0}. \tag{4}$$

The impedance of the equivalent circuit is

$$\dot{Z} = R_{\mathrm{MHD}} + R_{\mathrm{load}} + \frac{2}{j\omega C_{\mathrm{wall}}}. \tag{5}$$

The current in the equivalent circuit is

$$\dot{I} = \frac{\dot{V}_{\mathrm{MHD}}}{\dot{Z}} = \frac{V}{|\dot{Z}|} e^{-j\theta}, \tag{6}$$

where

$$|\dot{Z}| = \sqrt{(R_{\mathrm{MHD}} + R_{\mathrm{load}})^2 + \left(\frac{2}{\omega C_{\mathrm{wall}}}\right)^2}, \tag{7}$$

$$\theta = -\arctan\left[2/\left\{(R_{\mathrm{MHD}} + R_{\mathrm{load}})\,\omega C_{\mathrm{wall}}\right\}\right]. \tag{8}$$

The power output obtained at R_{load} is given by

$$P = R_{\mathrm{load}}|\dot{I}|^2 = R_{\mathrm{load}}\left(\frac{V}{|\dot{Z}|}\right)^2. \tag{9}$$

At the maximum power output R'_{load} is given by

$$R'_{\mathrm{load}} = \sqrt{R_{\mathrm{MHD}}{}^2 + \left(\frac{2}{\omega C_{\mathrm{wall}}}\right)^2}, \tag{10}$$

and the maximum power output $P_{\max}$ is

$$P_{\max} = \frac{V^2}{2\left(R_{\mathrm{MHD}} + R'_{\mathrm{load}}\right)}. \tag{11}$$

Equation (11) states that the maximum power output of a capacitive-coupled power extraction MHD generator is lower than that of a conventional MHD generator. To extract power comparable to that of a conventional MHD generator, the capacitor loss in the capacitive-coupled power extraction MHD generator must be reduced.

To extract maximum power, a compensation inductor can be connected in series with the wall capacitors. The compensation inductor improves the power factor, and thus an output power comparable to that from a conventional MHD generator can be obtained at optimum inductance.

If we assumed $S = 10\,\mathrm{m}^2$, $l = 1\,\mathrm{m}$, the thickness of the channel $d = 1\,\mathrm{mm}$, the relative permittivity of the channel $\epsilon_s = 10$, the gas velocity $u = 1000\,\mathrm{m/s}$, the maximum applied magnetic field $B_{\max} = 2\,\mathrm{T}$, and the frequency of the electrical voltage $f = \omega/(2\pi) = 60\,\mathrm{Hz}$, then the maximum induction voltage $V_{\max}$, C_{wall} and compensation inductor L_{com} were estimated to be 2 kV, 0.89 μF and 15.8 H respectively. Here, $d = 1\,\mathrm{mm}$ is assumed from the thermal barrier coating using gas turbine breads [7]. The values, $B_{\max} = 2\,\mathrm{T}$ and $f = 60\,\mathrm{Hz}$ are assumed from an eddy-current type multilayer coil previously constructed [8].

From the maximum induction voltage, the required dielectric strength of the channel is 1 kV/mm in the unloaded condition. A previous study [6] considered reducing the eddy current loss resistance of the MHD fluid, R_{MHD}, attributed only to the extraction power of the MHD generator. However, eddy current losses can be recovered by a gas turbine cascaded with the capacitive-coupled power extraction MHD generator because of the thermal energy recovered by the turbine. This means that the capacitive-coupled power extraction MHD generator combined with another energy system can mitigate the dielectric strength of the capacitive wall. The maximum power output of the capacitive-coupled power extraction MHD generator, assuming an electrical conductivity $\sigma = 1\,\mathrm{S/m}$ for the MHD fluid is estimated to be 5 MW.

In this rapid communication, an expression was derived for the theoretical power output from a capacitive-coupled power extraction MHD generator. To achieve a power output comparable to that of a conventional MHD generator at the same effective value of the electrical voltage, capacitor losses in the capacitive-coupled power extraction MHD generator should be reduced. However, by cascading a gas turbine and using a compensation inductor, the capacitor-coupled power extraction MHD generator is feasible for generating sufficient electrical power.

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