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Review Article

REVIEW ON MHD GENERATORS

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The Magneto-Hydrodynamic (MHD) generator transforms thermal energy and kinetic energy directly into electricity. MHD generators are different from traditional electric generators in that they operate at high temperatures without moving parts. MHD concept is used to heat the boilers of a steam power plant by using the hot exhaust gas of an MHD generator, increasing overall efficiency. MHD was developed as a topping cycle to increase the efficiency of electric generation, especially when burning coal or natural gas. MHD dynamos are the complement of MHD propulsors, which have been applied to pump liquid metals and in several experimental ship engines.

Keywords: MHD generator, Topping cycle, Bottoming cycle, Power, Faraday, Hall, Disk

INTRODUCTION

An MHD generator, like a conventional generator, relies on moving a conductor through a magnetic field to generate electric current. The MHD generator uses hot conductive plasma as the moving conductor. MHD generators are technically applicable for fossil fuels, but have been overtaken by other, less expensive technologies, such as combined cycles in which a gas turbine's or molten carbonate fuel cell's exhaust heats water to power a steam turbine. MHD generators typically reduce the temperature of the conductive substance from plasma temperatures to just over 1000 °C.

Natural MHD dynamos are an active area of research in plasma physics and are of great interest to the geophysics and astrophysics communities, since the magnetic fields of the earth and sun are produced by these natural dynamos.

PRINCIPLE

The Lorentz Force Law describes the effects of a charged particle moving in a constant magnetic field. The simplest form of this law is given by the vector equation.

$$F = Q.(v \times B)$$

where

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F is the force acting on the particle,

Q is the charge of the particle,

v is the velocity of the particle, and

B is the magnetic field.

The vector *F* is perpendicular to both *v* and *B* according to the right hand rule.

POWER GENERATION

Typically, for a large scale power station to approach the operational efficiency of device, steps must be taken to increase the electrical conductivity of the conductive substance. The heating of a gas to its plasma state easily can be ionized like the salts of alkali metals. In practice, a number of issues must be considered in the implementation of an MHD generator: generator efficiency, economics, and toxic byproducts. These issues are affected by the choice of one of the three MHD generator designs: the Faraday generator, the Hall generator, and the disc generator.

FARADAY GENERATOR

A simple Faraday generator would consist of a wedge-shaped pipe or tube of some non-conductive material. When an electrically conductive fluid flows through the tube, in the presence of a significant perpendicular magnetic field, a charge is induced in the field, which can be drawn off as electrical power by placing the electrodes on the sides at 90° angles to the magnetic field.

There are limitations on the density and type of fluid used. The amount of power that can be extracted is proportional to the cross sectional area of the tube and the speed of the conductive flow. The conductive substance is also cooled and slowed by this process.

The main practical problem of a Faraday generator is that differential voltages and currents in the fluid are short through the electrodes on the sides of the duct. The most powerful waste is from the Hall Effect current. This makes the Faraday duct very inefficient. Further refinements of Faraday generators have tried to solve this problem. The optimal magnetic field on duct-shaped MHD generators is a sort of saddle shape. To get this field, a large generator requires an extremely powerful magnet. Many research groups have tried to adapt superconducting magnets to this purpose, with varying success.

HALL GENERATOR

The most common solution is to use the Hall Effect to create a current that flows with the fluid. The normal scheme is to place arrays of short, vertical electrodes on the sides of the duct. The first and last electrodes in the duct power the load. Each other electrode is shorted to an electrode on the opposite side of the duct. These shorts of the Faraday current induce a powerful magnetic field within the fluid, but in a chord of a circle at right angles to the Faraday current. This secondary, induced field makes current flow in a rainbow shape between the first and last electrodes.

Losses are less than a Faraday generator, and voltages are higher because there is less shorting of the final induced current. However, this design has problems because the speed of the material flow requires the middle electrodes to be offset to "catch" the Faraday currents. As the load varies, the fluid flow speed varies, misaligning the Faraday current with its intended electrodes, and making the generator's efficiency very sensitive to its load.

DISC GENERATOR

The third and, currently, the most efficient design is the Hall Effect disc generator. A disc generator has fluid flowing between the center of a disc, and a duct wrapped around the edge. The magnetic excitation field is made by a pair of circular Helmholtz coils above and below the disk. The Faraday currents flow in a perfect dead short around the periphery of the disk. The Hall Effect currents flow between ring electrodes near the center and ring electrodes near the periphery.

Another significant advantage of this design is that the magnet is more efficient. First, it has simple parallel field lines. Second, because the fluid is processed in a disk, the magnet can be closer to the fluid, and magnetic field strengths increase as the 7th power of distance. Finally, the generator is compact for its power, so the magnet is also smaller. The resulting magnet uses a much smaller percentage of the generated power.

GENERATOR EFFICIENCY

As of 1994, the 22% efficiency record for closed-cycle disc MHD generators was held by Tokyo Technical Institute. The peak enthalpy extraction in these experiments reached 30.2%. Typical open-cycle Hall and duct coal MHD generators are lower, near 17%. These efficiencies make MHD unattractive, by itself, for utility power generation, since conventional Rankine cycle power plants easily reach 40%.

However, the exhaust of an MHD generator burning fossil fuel is almost as hot as the flame of a conventional steam boiler. By routing its exhaust gases into a boiler to make steam, MHD and a steam Rankine cycle can convert fossil fuels into electricity with an estimated efficiency up to 60%, compared to the 40% of a typical coal plant.

A MHD generator might also be heated by a Nuclear reactor (either fission or fusion). Reactors of this type operate at temperatures as high as 2000 °C. By pumping the reactor coolant into a magnetohydrodynamic generator before a traditional heat exchanger an estimated efficiency of 60% can be realised. One possible conductive coolant is the molten salt, since molten salts are electrically conductive.

MHD generators have also been proposed for a number of special situations. In submarines, low speed MHD generators using liquid metals would be nearly silent, eliminating a source of tell-tale mechanism noise. In spacecraft and unattended locations, low-speed metallic MHD generators have been proposed as highly reliable generators, linked to solar, nuclear or isotopic heat sources.

ECONOMICS

MHD generators have not been employed for large scale mass energy conversion because other techniques with comparable efficiency have a lower lifecycle investment cost. Advances in natural gas turbines achieved similar thermal efficiencies at lower costs, by having the turbine's exhaust drive a Rankine cycle steam plant. To get more electricity from coal, it is cheaper to simply add more low-temperature steam-generating capacity.

A coal-fueled MHD generator is a type of Brayton power cycle, similar to the power cycle of a combustion turbine. However, unlike the combustion turbine, there are no moving mechanical parts; the electrically conducting plasma provides the moving electrical conductor. The side walls and electrodes merely withstand the pressure within, while the anode and cathode conductors collect the electricity that is generated. Ideal Brayton cycles also have an ideal efficiency equal to ideal Carnot cycle efficiency. Thus, the potential for high energy efficiency from an MHD generator. All Brayton cycles have higher potential for efficiency as higher the firing temperature. While a combustion turbine is limited in maximum temperature by the strength of its air/water or steam-cooled rotating airfoils; there are no rotating parts in an open-cycle MHD generator. This upper bound in temperature limits the energy efficiency in combustion turbines. The upper bound on Brayton cycle temperature for an MHD generator is not limited, so inherently an MHD generator has a higher potential capability for energy efficiency.

The temperatures at which linear coal-fueled MHD generators can operate are limited by factors that include: (a) the combustion fuel, oxidizer, and oxidizer preheat temperature which limit the maximum temperature of the cycle; (b) the ability to protect the sidewalls and electrodes from melting; (c) the ability to protect the electrodes from electrochemical attack from the hot slag coating the walls combined with the high current or arcs that impinge on the electrodes as they carry off the direct current from the plasma; and (d) by the capability of the electrical insulators between each electrode. Coal-fired MHD plants with oxygen/air and high oxidant preheats would probably provide potassium seeded plasmas of about 4200 deg. F, 10 atmospheres pressure, and begin expansion at Mach 1.2. These plants would recover MHD exhaust heat for oxidant preheats, and for combined cycle steam generation. There is simply an inadequate reliability track record to provide confidence in a commercial coal-fueled MHD design.

U25B MHD testing in Russia using natural gas as fuel used a superconducting magnet, and had an output of 1.4 megawatts. A coal-fired MHD generator series of tests funded by the US Department of Energy (DOE) in 1992 produced MHD power from a larger superconducting magnet at the Component Development and Integration Facility (CDIF) in Butte, Montana. None of these tests were conducted for long-enough duration to verify the commercial durability of the technology. Neither of the test facilities were in large-enough scale for a commercial unit.

Superconducting magnets are used in the larger MHD generators to eliminate the power needed to energize the electromagnet. Superconducting magnets, once charged, consume no power, and can develop intense magnetic fields about 4 Teslas and higher.

Because of the high temperatures, the non-conducting walls of the channel must be constructed from an exceedingly heat-resistant substance such as yttrium oxide or zirconium dioxide to retard oxidation. Similarly, the electrodes must be both conductive and heat-resistant at high temperatures. The AVCO coal-fueled MHD generator at the CDIF was tested with water-cooled copper electrodes capped with platinum, tungsten, stainless steel, and electrically conducting ceramics.

TOXIC BYPRODUCTS

MHD reduces overall production of hazardous fossil fuel wastes because it increases plant efficiency. If molten metal is the armature fluid of an MHD generator, care must be taken with the coolant of the electromagnetics and channel. The alkali metals commonly used as MHD fluids react violently with water. Also, the chemical byproducts of heated, electrified alkali metals and channel ceramics may be poisonous and environmentally persistent.

SERBIAN DEVELOPMENT

Over more than a ten-year span, Serbian engineers in Bosnia, in the Institute of Thermal and Nuclear Technology (ITEN), Energoinvest Co., Sarajevo, had built the first experimental Magneto-Hydrodynamic facility power generator in 1989.

US DEVELOPMENT

In the 1980s, the US Department of Energy began a vigorous multiyear program, culminating in a 1992 50 MW demonstration coal combustor at the Component Development and Integration Facility (CDIF) in Butte, Montana. This program also had significant work at the Coal-Fired-In-Flow-Facility (CFIFF) at University of Tennessee Space Institute.

This program combined four parts:

- An integrated MHD topping cycle, with channel, electrodes and current control units developed by AVCO, later known as Textron Defence of Boston. This system was a Hall Effect duct generator heated by pulverized coal, with a potassium ionisation seed. AVCO had developed the famous Mk. V generator, and had significant experience.
- An integrated bottoming cycle, developed at the CDIF.
- A facility to regenerate the ionization seed was developed by TRW. Potassium carbonate is separated from the sulphate in the fly ash from the scrubbers. The carbonate is removed, to regain the potassium.
- A method to integrate MHD into preexisting coal plants. Westinghouse Electric performed a study based on the Scholtz Plant of Gulf Power in Sneads, Florida. The MHD Development Corporation also produced a study based on the J.E. Corrette Plant of the Montana Power Company of Billings, Montana.

Initial prototypes at the CDIF were operated for short durations, with various coals: Montana Rosebud, and a high-sulphur corrosive coal, Illinois No. 6.

JAPANESE DEVELOPMENT

The Japanese program in the late 1980s concentrated on closed-cycle MHD. The belief was that it would have higher efficiencies, and smaller equipment, especially in the clean, small, economical plant capacities near 100 megawatts (electrical) which are suited to Japanese conditions. Open-cycle coal-powered plants are generally thought to become economical above 200 megawatts.

The first major series of experiments was FUJI-1, a blow-down system powered from a shock tube at the Tokyo Institute of Technology. These experiments extracted up to 30.2% of enthalpy, and achieved power densities near 100 megawatts per cubic meter. This facility was funded by Tokyo Electric Power, other Japanese utilities, and the Department of Education. This system was a disc generator with a helium and argon carrier gas and potassium ionization seed.

In 1994, there were detailed plans for FUJI-2, a 5 MW (electrical) continuous closed-cycle facility, powered by natural gas, to be built using the experience of FUJI-1. The basic MHD design was to be a system with inert gases using a disk generator. The aim was an enthalpy extraction of 30% and an MHD thermal efficiency of 60%. FUJI-2 was to be followed by a retrofit to a 300 MWe natural gas plant.

AUSTRALIAN DEVELOPMENT

In 1986, Professor Hugo Karl Messerle at The University of Sydney researched coal-fueled MHD. This resulted in a 28 MWe topping facility that was operated outside Sydney.

ITALIAN DEVELOPMENT

The Italian program began in 1989 with a budget of about 20 million US$, and had three main development areas:

1. MHD Modeling.
2. Superconducting magnet development. The goal in 1994 was a prototype 2 m long, storing 66 MJ, for an MHD demonstration 8 m long. The field was to be 5 teslas, with a taper of 0.15 T/m. The geometry was to resemble a saddle shape, with cylindrical and rectangular windings of niobium-titanium copper.
3. Retrofits to natural gas powerplants. One was to be at the Enichem-Anic factor in Ravenna. In this plant, the combustion gases from the MHD would pass to the boiler. The other was a 230 MW (thermal) installation for a power station in Brindisi that would pass steam to the main power plant.

CHINESE DEVELOPMENT

A joint US-China national programme ended in 1992 by retrofitting the coal-fired No. 3 plant in Asbach. A further eleven-year program was approved in March 1994. This established centres of research in:

- The Institute of Electrical Engineering in the Academica Sinica, Beijing, concerned with MHD generator design.
- The Shanghai Power Research Institute, concerned with overall system and superconducting magnet research.
- The Thermo-energy Research Engineering Institute at the Nanjing's Southeast University, concerned with later developments.

The 1994 study proposed a 10 MW (electrical), 108 MW (thermal) generators with the MHD and bottoming cycle plants connected by steam piping, so either could operate independently.

RUSSIAN DEVELOPMENTS

In 1971 the natural-gas fired U-25 plant was completed near Moscow, with a designed capacity of 25 megawatts. By 1994, Russia had developed and operated the coal-operated facility U-25, at the High-Temperature Institute of the Russian Academy of Sciences in Moscow. U-25's bottoming plant was actually operated under contract with the Moscow utility, and fed power into Moscow's grid. There was substantial interest in Russia in developing a coal-powered disc generator.

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APPENDIX

Figure 1: MHD Generator

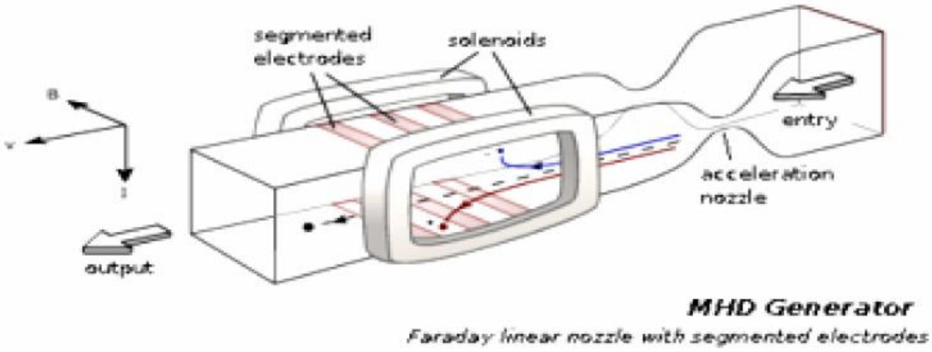

Figure 2: Disk MHD Generator Showing Current Flows

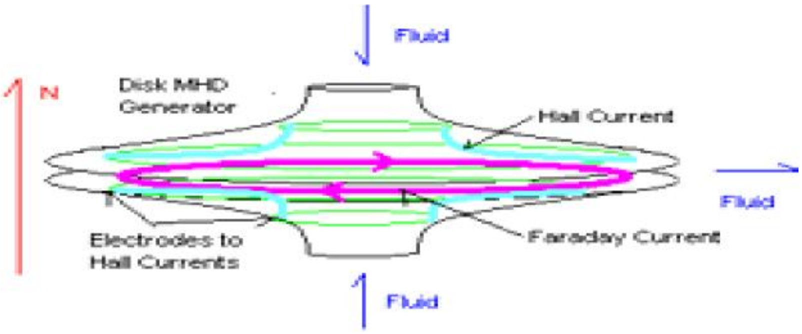

Figure 3: U-25