A Magnetohydrodynamic (MHD) Power Generating System: A Technical Review

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Abstract: A magnetohydrodynamic (MHD) power generation technique is a nonconventional electric power harvesting modality in which the electricity is generated from an ionised fluid flow under a magnetic field. The ionized fluid moving under a magnetic field works as a moving electrical conductor and the MHD generator generates electrical energy according to the Faraday’s electromagnetic principle. The concept of MHD based electric power generation was first time introduced by Michael Faraday in 1832, and since then the MHD power generation method has been studied by several groups of researcher. In this paper the MHD technique has been discussed in details followed by a discussion on its components and instrumentation. A technical review on the research works conducted on MHD power generation has been presented and the major developments have been highlighted. The present scenario and the future trends are also discussed along with the challenges of the technology.

Keywords: magnetohydrodynamic (MHD) power generation, nonconventional power generation, conducting fluid, green energy, MHD generator.

1. Introduction
Electric power plants [1] are developing to generate electrical power to fulfil the energy demands in our day to day life. Electrical machines called electrical generators are used to generate electricity in electrical power plant where some form of energy is converted into the electrical energy utilizing electromechanical energy conversion [2] technique. A magnetohydrodynamic (MHD) power generation [3-8] technique is a nonconventional electric power generation [9] modality which generates the electricity directly from a moving stream of ionised fluid flowing through a magnetic field. An ionized fluid moving under a magnetic field works as a moving electrical conductor [10] and hence it can generate electrical energy according to the Faraday’s electromagnetic principle. The magnetohydrodynamic power generator or the magnetohydrodynamic converter acts as a fluid dynamo in which the flow (motion) of the conducting fluid (conductor) under a magnetic field causes a voltage to be generated across the fluid, perpendicular to both the magnetic field and the fluid flow and according to Fleming's Right Hand Rule. In 1832, the concept of MHD power generation technique was first time practically studied by Michael Faraday [11] during his lecture delivered to the Royal Society. Since then MHD power generation technique has been studied and explored by a number of research groups. The MHD generation has many applications [12-15], are being used in recent time when a green energy harvesting process seems important and very much required as a renewable energy source for the sustainable development. In this paper the MHD power generation technique has been presented in followed by a discussion on its components and instrumentation. A technical review on the research works conducted on MHD power generation has been presented. The recent advances of this technology and its major developments have been highlighted. The future trends of the MHD power generation process are also discussed along with the challenges of the technology.

2. MHD Power Generation Principle
The MHD generator generates electric energy by converting the kinetic energy directly into electricity. The major constructional difference of an MHD generator from a conventional electric
The MHD generator uses the ionized fluids (gas or liquid or plasma) as the electrical conductors. In a MHD generator, an ionized fluid is forced to move at a particular velocity through a powerful magnetic field, an electromotive force (e.m.f.) is generated, which can be suitably utilized to harvest the electric energy by placing two electrodes across fluid stream (Fig. 1). The direction of the generated e.m.f. could be found by applying the Fleming’s right hand rule. If the fluid moves along a direction perpendicular to the magnetic field, the e.m.f. will be found to be developed perpendicular to the direction of fluid motion and that of the magnetic field. According to the principle of Faraday’s electromagnetic induction the amplitude of the generated e.m.f. will be proportional to the fluid velocity and to the magnitude of the magnetic flux density. In a MHD Generator, if the velocity of the fluid and the magnetic field density are denoted by \( V \) and \( B \) respectively, the e.m.f. induced \( (E_{\text{ind}}) \) across the MHD conductor is given by:

\[
E_{\text{ind}} = V \times B
\]

Therefore, the induced current density \( (J_{\text{ind}}) \) will be given by,

\[
J_{\text{ind}} = \sigma E_{\text{ind}}
\]

Where, \( \sigma \) = electric conductivity and \( E_{\text{ind}} \) is the electric field intensity.

The retarding force on the conductor is the Lorentz force which will be represented by

\[
F_{\text{ind}} = J_{\text{ind}} \times B
\]

In a practical MHD system as shown below (Fig. 2) the fuel is used to generate heat to make the gas ionized. The combustion chamber takes the fuel and air to produce the ionized gas or plasma. The gas-plasma is passed through a nozzle to decrease the gas-pressure to increases the speed of gas. As the gas speed is increased the power output is increased as described by the Eq. 1. The gas exhausted from the MHD chamber is passed through a heat exchanger which takes the air as an input and feed the air to the compressor after raising its temperature. Compressor takes the hot air from the heat exchanger and supplies it to the combustion chamber for producing plasma.

3. MHD Generator Components

3.1. MHD Fluid Channel

The fluid flow in a MHD generator is guided and confined within a pipe or duct made up of insulating materials. The shape or geometry of the duct may be different such as duct with rectangular cross section or circular cross section. Also the inlet diameter is smaller compared to the outlet diameter to reduce the pressure for increasing the speed of the flow to generate higher amount of electricity.
performance of the MHD generator depends on the geometry of the fluid flow, MHD duct [16] and other components.

Figure 2. Block diagram of the MHD power generation process.

### 3.2. Magnetic Field
The voltage generation depends on the properties of the magnetic field [17] used in the MHD system. The density of the magnetic field of a MHD generating system should be very high which can be obtained ideally by a superconducting magnet [18]. A superconducting magnet is an electromagnet which is developed with the current carrying conductor/coil made up of superconducting wire. The superconducting wires can be considered as special electrical conductors which are developed from superconducting materials. Superconducting materials are the materials which exhibit no electrical resistance at their superconducting state and hence they can conduct a considerably large amount of electric currents than conventional electrical conductors. Therefore the superconducting magnets can be supplied with a large amount of electrical current producing a huge amount of magnetic fields which can be very useful in many applications where a large magnetic field is required such as MHD generating system, magnetic resonance imaging system (MRI) etc. Different types of magnetic coils for MHD generators have been discussed by Kayukawa, N. (2004) [19].

### 3.3. Fluid Conductor
The conducting medium in MHD generation is produced either by heating a gas to its plasma state or to add the salts of alkali metals which are other easily ionizable substances and hence they can enhance the conductivity. The MHD power generation can be performed either using gas-plasma or the liquid metal flow or else. The Plasma MHD is a MHD generator when the conducting fluid used in it is plasma. Plasma [20], which is often called “the fourth state of matter”, is an ionized gas comprising of electrons (negatively charged particles and the ions. Therefore, the plasma is superheated gaseous matter in which all or most of the electrons are found freely moving as the electrodes are ripped away from the atoms by applying extra energy to the atoms making them ions and making the gas ionized. As a conducting fluid flow through a magnetic field can generate electric voltage, in plasma MHD the plasma is passed through a channel kept in a magnetic field and the motion of the conducting plasma through this magnetic field induces a voltage across the plasma. The direction of the emf will be perpendicular to the direction of the plasma flow as well as the direction of the magnetic field. Utilizing thermal ionization process gas-plasma is produced for the MHD generators. In thermal ionization process the temperature of the gas is raised up to the point at which the electrons are ripped away from the atoms by applying extra energy and can move freely along with the ionized atoms (ionized after losing the electrodes) and hence the gas becomes electrically conductive and makes the gas-plasma. Sometimes some seeding materials are mixed with the gas to bring down the temperature at which the gas becomes ionized as a considerable high temperature is required to convert the gas to gas-plasma applying the heat energy only. If some chemical agents (like alkali metal, salts etc.) are mixed with the chemicals helps the gas to get ionized easily even at the lower temperatures.

### 3.4. MHD Generator Electrodes
The MHD electrodes [21-25] are used to collect the electricity generated in the MHD system. Generally electrodes are metal components in MHD systems though the other materials are also
possible to be used. The geometry and position of the electrodes in MHD systems are very crucial as the MHD performance depends on the electrode geometry and positions. MHD generators are developed with multi-electrode configuration also [26].

4. Types of MHD Generators
The design of a MHD generator several points are essential to be considered such as efficiency, cost, and by-products and their toxicity etc. which are influenced by the different designs of MHD generators such as: the Faraday generator, the Hall generator, and the disc generator.

4.1 Faraday MHD Generator
A Faraday generator [27-30] is developed with a pipe or tube material kept under a magnetic field created either by a permanent magnet or by an electromagnet (Fig. 3). The pipe should be developed with an insulating material which will allow an electrically conducting fluid to flow through it. Under a strong magnetic field (perpendicular to the pipe) as soon as a conductive fluid flows through the pipe, an e.m.f. is induced across the conductor which will be perpendicular to both the magnetic field and the fluid stream. The emf can be utilized to extract the electrical power by placing two electrodes across the fluid flow (along the direction of e.m.f.). In the Faraday generator, the magnitude of the electrical power available at the generator output is found to be not only proportional to the cross sectional area of the tube and but also to the speed of the conductor (conductive fluid flow).

The major drawback of the Faraday generating system is that there may be short circuit path through the electrodes on the sides of the pipe used. Moreover, the design is also suffer from the limitations imposed the density of the fluid as well as the type of magnetic field used. Due to the flow of the fluid the temperature and the velocity of the fluid are reduced [27-28]. The system also suffers from the problem created by the Hall-effect current [31-32] which makes the Faraday generator very inefficient. A large Faraday generator needs an extremely powerful magnetic field which can be developed with superconducting magnets.

4.2. Hall MHD generator
In Faraday MHD generation, the large amount of current produced at the generator output interacts with the magnetic field present in the system and hence results in the displacement of charge particle towards the perpendicular direction of the fluid flow path which is known as the Hall Effect [31-32]. As a result, a transverse current is produced perpendicular to the fluid flow direction and the total current produced is found as the vector sum of the components of traverse current components and axial current component. To overcome this problem and to reduce the energy loss and to improve efficiency, other MHD configurations are developed which such as the Hall MHD generator. In Hall MHD generator, each of the rectangular electrodes are split into an array of segments and placed side by side on both the side of the fluid channel. To harvest the electrical power at a higher voltage with a lower current amplitude, all the electrode segments of same side of the channel are kept insulated.
from each other but all the segments are connected in series are connected with their corresponding opposite electrodes.

The Hall generator is developed with the arrays of segmented short electrodes which are used in place of single rectangular electrodes. The electrical power is collected from the first and last electrodes and among all other intermediate electrode one electrode is shorted to the electrode placed just opposite to that electrode placed on the other side of the fluid channel. As a result, the losses of the Hall generator are found less compared to a Faraday generator. The induced voltage is also obtained with a higher value because there is less shorting of the final induced current. However, this design has problems because the generator’s efficiency very sensitive to its load.

Sometimes the electrode segments of a Hall MHD system are shorted with the diagonal electrodes of the opposite side of the channel making the skewed arrangement of the electrodes. In this skewed electrode Hall MHD systems the electrodes are connected in a skewed pattern to align the electrode axes with the direction of the vector sum of the Faraday and Hall Effect currents. This skewed structure of the segmented and shorted electrode arrangement allow us to extract the maximum amount of electrical energy from the conductive fluid [11]. The Segmented electrode Faraday MHD system, Hall MHD system, Skewed electrode MHD system type [33] have been shown in the Fig. 4a, Fig. 4b and Fig. 4c respectively.

![Figure 4. Types of MHD generator: (a) Segmented electrode Faraday MHD system, (b) Hall MHD system, (c) Skewed electrode MHD system type [33].](image)

4.3. Disc MHD Generator
The Hall Effect Disc Type MHD generator [19] is developed with a disc type MHD chamber through which the fluid can flow through between the centres of the disc exhausted through the ducts placed around the edge of the discs (Fig. 5). The magnetic field is produced by a two circular Helmholtz coils above and below the disk. Two pairs of the ring electrodes (RE) are placed inside the disc chamber to provide the paths to flow the Hall Effect current. One pair of ring electrodes with smaller diameter (RE\text{Small}) is placed near the inlet duct at the disc centre where as the other pair of ring electrodes with larger diameter (RE\text{Large}) is placed at near the periphery of the disc. In this MHD system, the Faraday currents are conducted through the periphery of the disk and the Hall Effect currents are passed between the RE\text{Small} and the RE\text{Large}. The wide flat gas flow, parallel magnetic field lines and increased magnetic field strength enhance the efficiency of the system.

4.4. Coal-fired MHD Systems
The Coal-fired MHD systems [11] use coal as the fuel to produce the plasma in which coal is burned at a temperature sufficient to provide thermal ionization. However, as the fluid passes through the MHD chamber and expands along the length of the chamber, the electrical conductivity as well as the temperature decreases. A Coal-fired MHD system could be coupled with a conventional thermal power plant to increase the power generation efficiency. In a MHD coupled thermal power plant the hot plasma is first passed through the MHD generator to generate electrical power through magnetohydrodynamic principle and then the plasma exhausted from the MHD
channel outlet is used to generate electricity using the steam turbine based electrical power generation technique.

![Figure 5. A disk type MHD system with a race track-type magnet coil [19].](image)

4.5. Liquid Metal MHD
Liquid metal MHD generators [11, 35] use the liquid metals as their electrically conducting fluids and hence they are known as the Liquid metal MHD generators. As the electrical conductivity of the metals are extremely high and as the liquid metals can be converted into a fluid flow, the liquid metals can suitably be used as the conducting fluids in MHD generating systems. The Liquid metal MHD generators can be operated at lower temperature as the high temperature is not required for the producing of plasma. The liquid metals are first combined with a driving gas or are accelerated by a thermodynamic pump and then separated from the driving gas before it passes through the MHD channel [11].

4.6. Open and Closed Cycle MHD
Depending on the flow paths of the conducting fluids the MHD systems can be classified as the open cycle MHD system [19] or the closed cycle MHD systems [36]. In open cycle MHD systems the working fluid is discharged to the atmosphere after the generation of the electricity whereas the closed cycle MHD system recycles the working fluid heat sources to utilize the heat energy present in the fluid after it comes out from the MHD chamber (after the MHD based electricity generation).

5. Advantages and Limitations of MHD Systems
Conventional coal-fired thermal power plants can achieve a maximum efficiency of about 35% whereas this efficiency can be enhanced up to 50% - 60% [19] by implementing the MHD generators which utilize the energy from the hot gas-plasma [37] prior to send it to standard steam turbines. The MHD generator generates electrical energy by recycling the heat energy from the hot plasma which remains sufficiently hot to boil water to drive the steam turbines to produce additional power. In MHD generators there are no solid moving parts and hence frictional or mechanical losses are very less. Also wear and tear is almost negligible. Running cost is less compared to the conventional thermal power plant. Compared to the conventional thermal power plants MHD generators contribute less in pollution in the atmosphere as it is not generating any waste or pollutants. CO₂ emission is negligible and could be avoided in the MHD power generation schemes [38]. The higher cost of the required for the construction of MHD systems is one of the major hurdles in applications of MHD systems. Huge amount of magnetic field is required which needs a special design, higher cost and magnetic shielding in some case. Plasma or ionized fluid velocity must be high for large amount of energy generation.

6. Discussion and Conclusions
Electrical energy generation is essential for the survival of the modern society. Fossil fuels are limited and create pollution. Also the conventional power generation systems using fossil fuel have lesser efficiency due to a higher amount of losses in different sections of the plants. MHD is found as a nonconventional energy generation system which has the capability to enhance the thermal power plant efficiency significantly. Also the MHD systems can be utilized alone to harvest the electrical energy from hot plasma in many industrial applications. The channel geometry, electrode geometry, fluid properties and the other design parameters are extremely crucial for the performance and
efficiency of the MHD system. As the velocity and magnetic field strength are two major parameters for electric power generation the superconducting magnets are promising to enhance the system performance. Also plasma generation needs seeding elements to reduce the heat energy requirement in MHD systems. Though the liquid metals can provide a highly conductive paths in MHD systems but its velocity is reduced compared to the gas-plasma. MHD generation is very promising in the multimodal power generation systems when coupled with the thermal power plant. With the development of the computational fluid dynamics and other computer simulation tools the opportunities to explore the MHD technique and the systems are open in recent time. More research investigation are required in various parts of the MHD systems such as fluid, electrodes, magnetic field and the system geometry.

7. Acknowledgement
The author acknowledges the National Institute of Technology Durgapur (NITDgp) for providing the research opportunity and infrastructure to conduct this study.

8. Conflict of Interest:
The author hereby confirms that there is no ConFLICT of Interest for this research work.

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