Magnetohydrodynamic Power Generation

Ajith Krishnan R*, Jinshah B S**

*Department of Mechanical Engineering, Government Engineering College, Kozhikode, Kerala, India
**Department of Mechanical Engineering, Government Engineering College, Kozhikode, Kerala, India

Abstract- Magnetohydrodynamic (MHD) power generation process is basically based on the physics background of space plasma. The basic principle is the Faradays Law of electromagnetic induction. In this device plasma (Ionized gas) is the working fluid similar to the mechanism that happening in the magnetosphere of our earth's atmosphere. Except here the process is controlled and we increase the fluid density and pressure to get maximum efficiency in the generating power. Most problems come from the low conductivity feature in the gas at high temperature. High temperature gaseous conductor at high velocity is passed through a powerful magnetic field and a current is generated and extracted by placing electrodes at suitable position in the gas stream, and hence the thermal energy of gas is directly converted in to electrical energy. In this paper the process involved in MHD power generation will be discussed in detail along with the simplified analysis of MDH system and recent developments in magnetohydrodynamics and their related issues.

Index Terms- Electromagnetic induction, Hall Effect, Magneto hydrodynamics, MHD generator, Plasma

I. INTRODUCTION

We all are aware of power generation using hydel,thermal and nuclear resources.In all the systems,the potential energy or thermal energy is first converted in to mechanical energy and then the mechanical energy is converted in to elecrtrical energy. The conversion of potential energy in to mechanical energy is considerably high (70 to 80%) but conversion of thermal energy in to mechanical energy is considerably poor(40 to 45%).In addition to this the mechanical components required for converting heat energy in to mechanical energy are large in number and considerably costly.This requires huge capital cost as well as maintenance cost also.

The scientists are thinking to eliminate the mechanical system and convert thermal in to direct electrical energy for the last 50-years and more.Unfortunately, no system is yet developed in large capacity(MW) to compete with conventional systems.In addition to this the efficiency of such conversion remained considerably poor(less than10%)therefore,these power generating systems are not developed on large scale.

I.I Thermodynamic energy conversion

The electricity generation process, most often, is characterised by the transition of primary or secondary energy, from thermal to mechanical and then to electricity. At the current state of development, most of the power plants are based on processes known as conventional. The production of electricity, through conventional forms or commercial of primary energy, concern only the hydroelectric and thermal power station, where the thermal power stations are different for use of primary source (usually fossil fuels such as natural gas, oil, coal, etc., wood and biomass, municipal or industrial solid wast, etc., or nuclear fuels and more rarely geothermal energy). In the hydroelectric power generation, mechanical energy, in different forms (kinetic, potential and pressure) from flowing fluid, is converted into electricity with a water turbine and an alternator. In the thermal power plants the thermal energy is converted into mechanical energy and from this machine the mechanical energy into electricity. The majority of thermal power plants are powered by fuels, usually fossil or nuclear. Apart some cases, such as power plants that use thermal energy available in nature (primarily solar and geothermal), the form of energy at the base of each of processes is the chemical potential energy of the fuel.

The potential energy of the fossil fuel is converted into heat energy through a chemical exothermic reaction (combustion), characterized by generation of thermal energy equivalent, in absolute value, to the enthalpy variation for the same reaction. In the case of nuclear fuels there is a fission reaction. The heat is then transmitted to elastic working fluid evolving in appropriate machines (usually gas turbine or reciprocating engine) producing mechanical work. In that case, it has converted thermal energy to mechanical (thermodynamics conversion). The mechanical work produced is finally transferred to an electric generator, which operates the last conversion of energy in electric form. It should be noted that in any conversion process one can not fully convert the energy from one form to another, each of the steps being characterized by a conversion efficiency, a coefficient that takes into account the fraction of the energy initially available, which is converted in the desired form.[1]

I.II Direct energy conversion systems

The possibilities of improving significantly the conventional energy conversion processes are mainly related to technological progress. They still have small margins and for this reason the researchers have turned to the development of other systems, so-called no-conventional. In the conventional conversion systems a significant loss of energy occurs in the transition from thermal to mechanical energy (thermodynamic conversion). Research is focusing its efforts on conversion processes that do not use this step. The absence of moving mechanical parts may allow the achievement of operating temperatures much higher than those typical of conventional processes, resulting therefore, at least potentially, a higher conversion efficiency. These processes are known as direct conversion, as primary and secondary energy is converted directly into electricity without the need to pass through a stage of mechanical energy [2]. The direct energy conversion methods that nowadays are taken into account in terms of industrial application are:

- Photovoltaic generation systems (Photovoltaic Solar Cells)[3]
- Electrochemical energy conversion (Fuel Cells) [4]
- Magnetohydrodynamic generation(MHD)[5]
- Electrogasdynamic generation(EGD)[6]
- Thermoeletric power generation [7]

In the first two processes the conversion fromthe primary to the secondary energy form takes place avoiding the conversion in the intermediate thermal energy. The Figure 1 shows the energy conversion stages in the direct generation of electric energy.

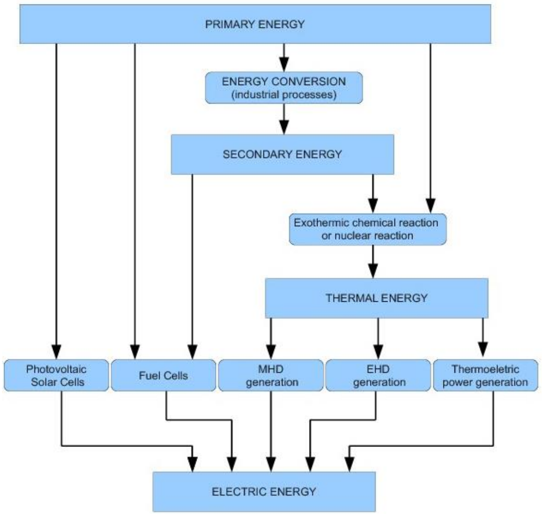

Figure 1: Direct energy conversion stages

The design of an energy converter is often dictated by the type of energy to be converted, although it is the duty of the engineer to seek out new and more efficient ways of transforming the primary sources of the energy into electricity. There are many reasons for the use of new and direct conversion schemes. These can be grouped into three important areas: efficiency, reliability, and the use of new sources of energy. It is hoped that when a processes occurs directly, rather than passing through several steps, it is likely to be more efficient. This will lead to less expenditure of the primary energy reserve and a lower investment per installed unit power. Efficiencies are, however, still low at this stage of development of most direct energy conversion schemes. As for reliability, there are places where energy conversion equipment must run for years without breaking down and without maintenance. These are situation where the ultimate reliability is required. Finally, the possibility of using new sources of energy seems enhanced by the development of the new direct energy converters.

There are many ways whereby the direct energy conversion of thermal to electrical energy can be obtained. In the following section the main one, magnetohydrodynamic power generation , is mentioned very briefly to give an overall background picture of the interest in direct conversion

II. MAGNETOHYDRODYNAMIC POWER GENERATION

The magnetohydrodynamic power generator[8] is a device that generates electric power by means of the interaction of a moving fluid (usually a ionized gas or plasma) and a magnetic field. As all direct conversion processes the MHD generators can also convert thermal energy directly into electricity without moving parts. In this way the static energy converters, with no moving mechanical part, can improve the dynamic conversion, working at temperature more higher than conventional processes. The typical configuration of MHD generator is shown in Figure 2.

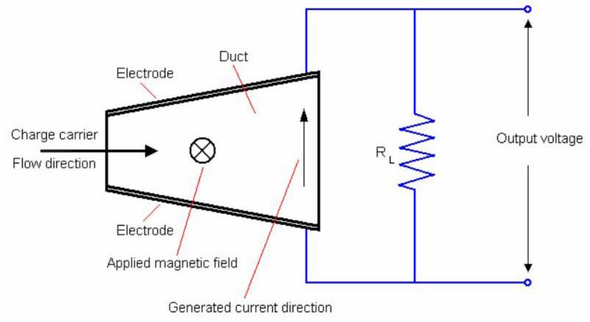

Figure 2: MHD channel

The underlying principle of MHD power generation is elegantly simple. Typically, an electrically conducting gas is produced at high pressure by combustion of a fossil fuel. The gas is then directed through a magnetic field, resulting due to the Hall effect. The MHD system constitutes a heat engine, involving an expansion of the gas from high to low pressure in a manner similar to that employed in a conventional gas turbogenerator. In the turbogenerator, the gas interacts with blade surfaces to drive the turbine and the attached electric generator. In the MHD system, the kinetic energy of the gas is converted directly to electric energy as it is allowed to expand.

It is known, that if we have a current flowing in a conductor immersed in a magnetic field, in the same conductor will be generated a Lorentz force that is perpendicular to the direction of the magnetic field and to the current.

The induced emf(E) is given by

$$E_i = \vec{u} \cdot \vec{B}$$

where $\vec{u}$ is the velocity of ionized gas and $\vec{B}$ is the strength of magnetic field intensity.

the induced current density is given by

$$\vec{I}_i = \sigma . \vec{E}$$

where σ is the electrical conductivity of gas.

The retarding force on the conductor is the Lorentz force given by

$$F_i = \vec{I} \cdot \vec{B}$$

In an MHD converter the electrical conductor is replaced by a plasma current at high speed and with high temperature to be partially ionized . So, the current flow is not only made of electrically neutral molecules but also with a mix of positive ions and electrons. When an high velocity gas flows into convergent-divergent duct and passes through the magnetic field an e.m.f is induced, mutual perpendicular to the magnetic field direction and to the direction of the gas flow. Electrodes in opposite side walls of the MHD flow channel provide an interface to an external circuit. Electrons pass from the fluid at one wall to an electrode, to an external load, to the electrode on the opposite wall, and then back to the fluid, completing a circuit. Thus the MHD channel flow is a direct current source that can be applied directly to an external load or can be linked with a power conditioning converter to produce alternating current. The electric energy produced is proportional to the reduction of kinetic energy and enthalpy of the fluid current. MHD effects can be produced with electrons in metallic liquids such as mercury and sodium or in hot gases containing ions and free electrons. In both cases, the electrons are highly mobile and move readily among the atoms and ions while local net charge neutrality is maintained. Any small volume of the fluid contains the same total positive charges in the ions and negative charges, because any charge imbalance would produce large electrostatic forces to restore the balance.

Most theoretical and experimental work and power plant development and application studies have focussed on high-temperature ionized gas as the working fluid. Unfortunately, most common gases do not ionize significantly at temperatures obtainable with fossil fuel chemical reactions. This makes it necessary to seed the hot gasses with small amounts of ionizable materials such as alkali metals. Materials such as cesium and potassium have ionization potentials low enough that they ionize at temperatures obtainable with combustion reaction in air. Recovery and reuse of seed materials from the MHD channel exhaust are usually considered necessary from both economic and pollution standpoints.

Interest in MHD power generation was originally stimulated by the observation that the interaction of a plasma with a magnetic field could occur at much higher temperatures than were possible in a rotating mechanical turbine. The limiting performance from the point of view of efficiency of a heat engine is limited by the Carnot cycle. A system employing an MHD generator offers the potential of an ultimate efficiency in the range of 60 to 65%. This is much better than the 35 to 40% efficiency that can be achieved in a modern conventional thermal power station.

The power output of an MHD generator for each cubic metre of its channel volume is proportional to the product of the gas conductivity, the square of the gas velocity, and the square of the strength of the magnetic field through which the gas passes. For MHD generators to operate competitively with good performance and reasonable physical dimensions, the electrical conductivity of the plasma must be in a temperature range above about 1800K.

Apart of the MHD power generator, other apparatus are necessary to form the overall MHD system. It is necessary to burn the fuel and the oxidizer, to add the seed, and to make arrangements for exporting the generated electrical power. The fuel is usually fossil and the oxidizer is air, for obvious economic reasons. For large systems, some precautions should be taken to limit the amount of losses. The air may be enriched with more oxygen, and preheating of the incoming oxidizer becomes necessary to allow thermal ionization. In practice a number of issues must be considered in the implementation of a MHD generator: Generator efficiency, Economics, and Toxic products. These issues are affected by the choice of one of the three MHD generator designs. These are the Faraday generator, the Hall generator, and the disk generator

II.I 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 perpendicularmagnetic 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 degree angles to the

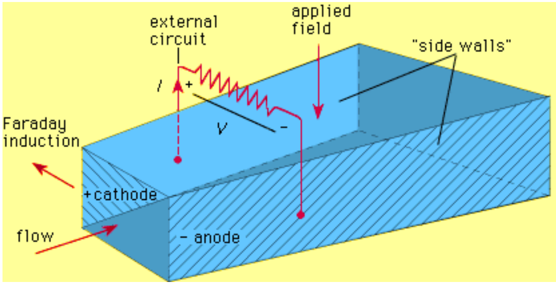

Figure 3: Faradys generator

magnetic field. The main practical problem of a Faraday generator is that differential voltages and currents in the fluid short through the electrodes on the sides of the duct. The most powerful waste is from the Hall effect current.

II.II Hall generator

The most common answer is to overcome the problems of faradys generator is 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 supply the load. Each other electrode is shorted to an electrode on the opposite side of the duct. Losses are less than that of 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 efficiency very sensitive to its load.

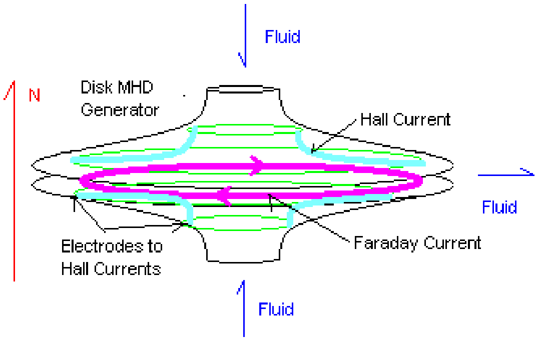

Figure 4: Disk generator

II.III Disk generator

The third, currently most efficient answer is the Hall effect disk generator. This design currently holds the efficiency and energy density records for MHD generation. A disk generator has fluid flowing between the center of a disk, 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.

III. POWERCYCLE FOR MHD-GENERATOR

MHD generator replaced the gas turbine used in conventional cycle is shown in Figure 5. A compressor is used to elevate the pressure and then heat is added to increase the gas temperature which is sufficient to ionize the gas.Then the gas flow is accelerated by passsing through the nozzle before entering MHD generator.The gas passing through the MHD generator is deaccelerated and electrical energy is generated

It is obvious that the MHD-cycle is thermal power cycle and the thermal efficiency is given by

$$\eta = \frac{Workoutput}{Heatinput} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)}$$

where indicated enthalpies are stagnation values which takes into account the K.E of the flowing gas The stagnation enthalpy of the followin gas is given by

$$h_o = h + \frac{u^2}{2}$$

where u is the velocity of the flowing gas.

In actual MHD-generator, the gas velocity is sufficiently high (sonic and ebove) so that the K.E of the flowing gas represents substantial portion of the total enegy.

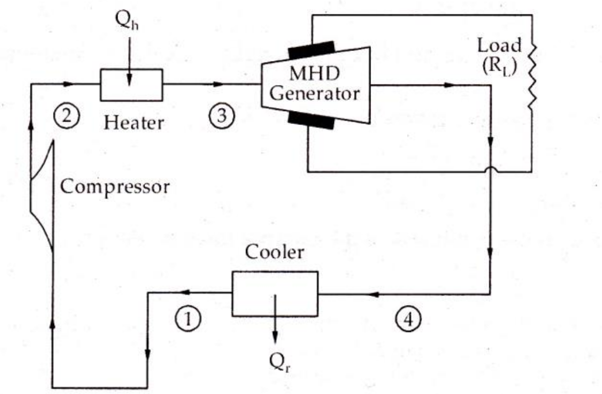

Figure 5: Power cycle for MHD power generation

III.I **Simplified analysis of MHD Generator**

The following assumptions are made in the analysis of the MHD generator.

1. working gas is an ideal gas
2. gas flowing at constant velocity and pressure
3. magnetic flux generated remains constant
4. no heat transfer to the surroundings
5. gas flow is uniform

When the high velocity ionized gas flows through the magnetic field,the induced EMF tries to slow down the motion of the gas as it acts in the opposite direcion.The duct is made diverging as the gas velocity decreases along the flow direction.The elecrical energy is extracted from the thermal energy of the gases keeping axial velocity constant.The electrical energy is produced when the condutive gas cuts the magnetic lines of force.The gas is accelerated to restore its velocity with decrease of temperature and axial velocity held constant,large power is developed if the applied magnetic flux density and gas velocity are high.The lorentz force induced on electrons acts in the direction of retarding the gas flow.The direction of Lorentz force is opposite to the velocity of conducting gas. The induced emf generated is given by

$$E_i = \vec{u} \cdot \vec{B}$$

The electromagnetic force acting on the gas particle in the presence of electric field E is given by

$$F=Q(E+E_i)=Q[E+u.B]$$

The force F acts on the particle at right angles to both magnetic field and gas velocity.Gas particles flow in the direction of the electric field . Current intensity between the electrode connected externally in perpendicular direction is given by,

$$E_z=-\frac{V}{\delta}$$

where δ is the distance between the electrodes.

Total electric fieldE_{zt} is given by

$$E_{zt}=E_i+E_z=u.B-\frac{V}{\delta}=\frac{(u.B.\delta)-V}{\delta}$$

B=Magnetic field(w/m^2)

u=Gas velocity(w/m)

E=Electric field($volts/m$)

δ=Distance between the electrode(m)

V_o=Open circuit voltage(volts)

For open circuit voltage E_{zt} becomes zero

$$V_o=u.B.\delta$$

If R_g is internal resistance and R_L is the load resistance and I is the flowing current,then

$$I=\frac{v_o}{R_g+R_L}$$

W(power output from MHD generator)

$$V_oI=I^2R_g=\left(\frac{v_o}{R_g+R_L}\right)^2.R_g$$

The condition for maximum power,

$$R_g=R_L \quad W_{max}=\frac{v_o^2}{4R_g}=\frac{(u.B.\delta)^2}{4R_g}$$

but $R_g=\frac{\delta}{\sigma.A}$ where σ is gas conductivity(mho/m) and A is electrode surface area(m^2)

$$W_{max}=\frac{u^2.B^2.\delta^2}{4.\sigma}*\sigma.A$$

$$=\frac{u^2.B^2.\sigma}{4}(A.\delta)$$

where($A.\delta$) becomes the volume of MHD generator.

$$W'_{max}=\frac{u^2.B^2.\sigma}{4}/m^3 of MHD generator$$

This shows that W'_{max} is proportional to the square of magnetic flux ,therefore it needs strong magnetic field to make the generator compact.

Conversion efficiency of MHD (η_c),

$$\eta_c=\frac{V_{max}}{u.B}$$

$$V_{max}=u.B.\delta-I_{max}\frac{\delta}{\sigma.A}$$

$$I_{max}=\frac{V_o}{R_g+R_L}=\frac{UB\delta}{2R_g}=\frac{u.B.A.\sigma}{2}$$

$$\eta_c=\left(\delta-\frac{\delta^2}{2\sigma}\right)=\delta\left(1-\frac{\delta}{2\sigma}\right)$$

$$\eta_c=\frac{[uB\delta-(\frac{uBA\delta}{2})]*(\delta/2\sigma)}{uB}$$

IV. MHD PHENOMENA DESCRIPTION

IV.I MHD Equations

The complete set of magnetohydrodynamic equations for a Newtonian, constant property fluid flow includes, the Navier-Stokes equations of motion (i.e., momentum equation), the equation of mass continuity, Maxwell's equations, and Ohm's Law . In differential form they constitute the following system of equations:

$$\varrho(\frac{\partial u}{\partial t}+(u.\nabla)u)=-\nabla p+jxB+\mu_f\nabla^2u+\varrho g$$

Navier-Stokes equations of motion

(i.e., momentum equation) where MHD body force is

(j* B) and $j=\sigma(E+uB)$

$\frac{\partial\varrho}{\partial t}+\nabla.\varrho u=0$ .... equation of mass continuity

$E=-\frac{\partial B}{\partial t}$.... Maxwells equations

$\nabla*B=\mu_m j$ ....Ohms Law

ϱ=*fluiddensity*

u=*fluidvelocity*

μ_m=*magneticpermeability*

μ_f=*fluiddynamicviscosity*

B=*magneticfieldintensity*

E=*electircfield*

σ=*electricalconductivity*

IV.II Dimensionless parameters

Fluid mechanics equations typically are cast in dimensionless form so that the relative strengths of the different terms can be inferred by the size of any multiplying factors. The equation of motion can be written in dimensionless form by making the substitutions:

$$j^*=\frac{j}{\sigma u_o B_o}$$

$$p^*=\frac{p}{\sigma u_o B_o^2 a}$$

$$\nabla^*=\frac{1}{a}\nabla \qquad u^*=\frac{u}{u_o} \qquad B^*=\frac{B}{B_O}$$

where a, u_o and B_o are characteristic values of length, velocity and applied magnetic field. Characteristic values of the current density and pressure have been selected carefully in order to scale the phenomena of interest; different values could have been selected, leading to different systems of non-dimensionalization. Using this system, the equation of motion (excluding gravity) becomes,

$$\frac{1}{N}(\frac{\partial u^*}{\partial t}+(u^*.\nabla)u^*)=-\nabla p^*+j^**B^*+\frac{1}{Ha^2}\nabla^2u^*$$

The characteristic parameters Re, Ha and N are the Reynolds number, the Hartmann number, which is an average measure of the ratio of magnetic to viscous forces, and the interaction parameter, which is a measure of the ratio of magnetic to inertial forces. They are defined as:

$$Re=\frac{\varrho u_o a}{\mu_f} \qquad Ha=aB_o\sqrt{\frac{\sigma_f}{\mu_f}}$$

$$N=\frac{Ha^2}{Re}=aB_o^2.\sigma_f/\varrho u_o$$

When the Hartmann number and interaction parameter are both sufficiently large, the momentum equation throughout the bulk of the fluid can be reduced to the simple form:

$$\nabla p=j*B$$

Table 1 gives representative values of these characteristic dimensionless parameters for example cases of interest.

Parameter	NaK (100degC)	Hg (20degC)	Electrolyte (20degC) 15% KOH	Air (3000degC) with 2% K
Re	$1.6x10^{5}$	$9.1x10^{5}$	$4.3x10^{4}$	350
Ha	6800	2700	17.5	98
N	290	8.2	$7x10^{-}3$	27
Re_m	0.30	0.14	$1.2x10^{5}$	$1.3x10^{5}$

Table 1: Typical values of Re, Ha, N, and Re_m for several materials (assuming a=0.1 m, B=1 T, v=1 m/s)

The dimensionless product ωτ , often called the Hall parameter, is an important characteristic number in MHD design. The conductivity tensor is anisotropic due to the Hall component unless ωτ∠∠1 On a microscopic scale, the Hall parameter indicates the average angular travel of electrons between collisions.Since the mean free path is inversely proportional to pressure, lower pressure and higher values of B give larger values of ωτ .[11]

V. DIFFERENT MHD SYSTEMS

As of 1994, the 22%efficiency record for closed-cycle disk MHD generators was held by Tokyo Technical Institute. Typical open-cycle Hall duct coa lMHD 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 percent, compared to the 40 percent of a typical coal plant. Repowering of existing thermal power plants is possible with a significant increase of the efficiency of the plant. Efficiencies greater than 65-70% can be reached if a triple cycle, including an MHD generator, a gas turbine and a steam turbine, is utilized. The abundance of coal reserves throughout much of the world has favoured the development of coal-fired MHD systems for electric power production. Coal can be burned at a temperature high enough to provide thermal ionization. However, as the gas expands along the duct or channel, its electrical conductivity drops along with its temperature. Thus, power production with thermal ionization is essentially finished when the temperature falls to about 2500 K. To be economically competitive, a coal-fired power station would have to combine an MHD generator with a conventional steam plant in what is termed a binary cycle. The hot gas is first passed through the MHD generator (a process known as topping) and then onto the turbogenerator of a conventional steam plant (the bottoming phase). An MHD power plant employing such an arrangement is known as an opencycle , or once-through, system.

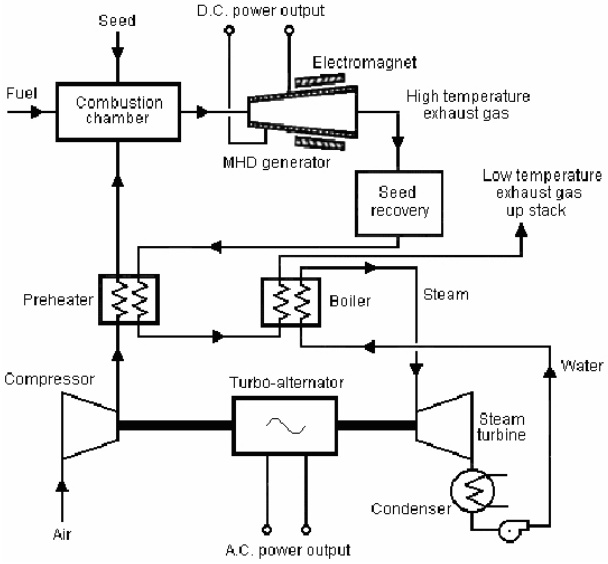

Figure 6: The typical open cycle scheme for a coal-firedMHD systems[9]

The Figure 6 shows the typical open cycle scheme for a coal-fired MHD systems for electric power production Coal combustion as a source of heat has several advantages[9]. For example, it results in coal slag, which under magnetohydrodynamic conditions is molten and provides a layer that covers all of the insulator and electrode walls The electrical conductivity of this layer is sufficient to provide conduction between the gas and the electrode structure but not so high as to cause significant leakage of electric currents and consequent power loss. The reduction in thermal losses to the walls because of the slag layer more than compensates for any electrical losses arising from its presence. However, the dust could degrade the MHD generator elements. In fact, an important item in the development of the MHD generator is the development of a durable electrode. The development of suitable materials for use in MHD generator is one of the most challenging areas. The very high temperatures (2700 K) coupled with the highly corrosive seed-laden atmosphere limit the choice of materials in contact with the plasma. These materials in contact with the high temperature plasmas in MHD generator are simultaneously subjected to stresses of mechanical, thermal, chemical and electromagnetic nature. The use of a seed material in conjunction with coal offers environmental benefits. In particular, the recombination chemistry that occurs in the duct of a MHD generator favours the formation of potassium sulphate in the combustion of high-sulfur coals, there by reducing sulphur dioxide emissions to the atmosphere. The need to recover seed material also ensures that a high level of particulate removal is built into an MHD coal-fired plant. Finally, by careful design of the boiler and the combustion controls, low levels of nitrogen oxide emissions can be achieved. The problems due to the direct combustion of coal can be overcome combining the MHD generator on the Integrated Gasification Combined Cycle (IGCC), it is a technology that turns coal into gas synthesis gas (syngas). All the treatments on the gas are performed before the combustion, so that the electrostatic precipitator is no longer necessary. On the other hand, eliminating the most part of the sulphur before the Claus/Scot process is a great advantage, in particular in the cases of coal with a high percentage of sulphur. In addition to natural gas as a fuel source, more MHD power generation systems have been proposed.

A magnetohydrodynamic generator might be heated by a Nuclear reactor (either fission or fusion). Reactors of this type operate at temperatures as high as 2000^0C. By pumping the reactor coolant into a magnetohydrodynamic generator before a traditional heat exchanger an estimated efficiency of 60% can be realised. The Figure 7 shown the typical close-cycle system for nuclear source[10].

In theory, solar concentrators can provide thermal energy at a temperature high enough to provide thermal ionization. Thus, solar-based MHD systems have potential, provided that solar collectors can be developed that operate reliably for extended periods at high temperatures. 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 turbines 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. Presently, the most often considered use if MHD generator is as a topping device for conventional steam plants. The fact there are no moving mechanical parts will make operation at high temperature feasible. The upper limit temperature in a steam plant is about 750^0C, which is far below the temperatures reached by MHD generators (about 2700^0C). To obtain good conducting gases, it is necessary to add cesium or potassium as seed materials and to solve the problem of corrosion. Advances in refractory material are needed. The cost of seeding increases substantially the cost of installed power. The cost of wall material is an important part of the total cost of an MHD generator. Good insulating and refractory materials working for a reasonably long time without deterioration should be found. The problem of high temperatures could be alleviated by the use of some type of non thermal ionization. This can also make the possibility of a nuclear reactor MHD generator coupling feasible, with the advantage of having an entirely static power plant. From the tremendous amount of work done in this field, both theoretically and experimentally, it seems that a fossil fueled MHD topper is the most promising MHD generator and most probably will be the first to be operating to on the industrial level. Many problems need to be solved before an MHD power plant becomes competitive: seed recovery, superconductivity for the magnet, high temperature materials, AC power generation, and progress in non equilibrium ionization techniques.

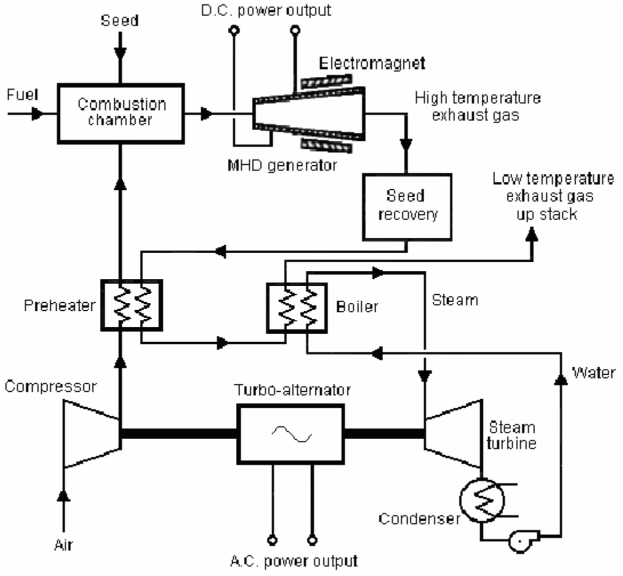

Figure 7: The typical close cycle scheme for nuclear source[10]

VI. NEAR FUTURE POWER GENERATION SYSTEM

VI.I Energy Re-Circulating LNG/MHD System

Figure 8 shows proposed energy re-circulating type MHD power generation system with LNG heat source which has been proposed by Prof. Y. Okuno at Tokyo Institute of Technology. The system does not combined with any other system and is called closed cycle MHD single system. We can see that plant efficiency is expected over 60% even the enthalpy extraction ratio of the MHD generator is only 30%. Thermal input to the MHD generator is 200% and electric output is 60% in spite of only 100% input thermal energy to the system because 100 of heat is recovered by regenerator. Enthalpy extraction ratio of above 30 achieved by experiments with shock tube facility. So this estimation of efficiency is considered to be realistic in near future[12].

VI.II Energy Re-Circulating Nuclear/Gas Turbine System

It is pointed out that efficiency of power generation system with nuclear fission reactor must be increased in order to reduce CO_2 emission. Energy re-circulating type gas-turbine single system with nuclear reactor is proposed. Schematic of this system is shown in Figure 9.

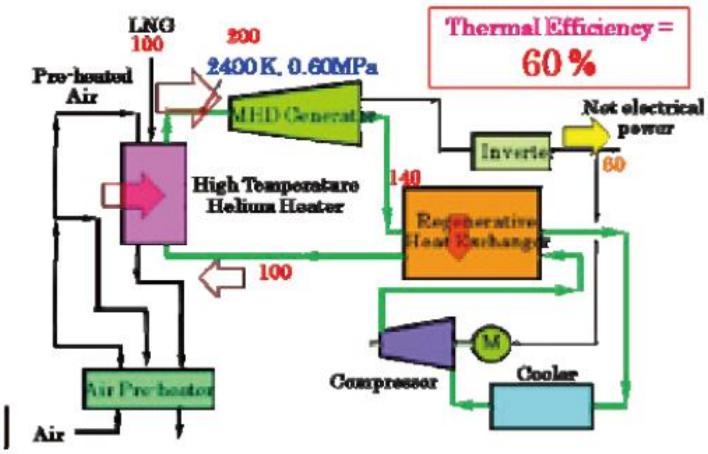

Figure 8: Energy Re-circulating type MHD single system with LNG as heat source.[12]

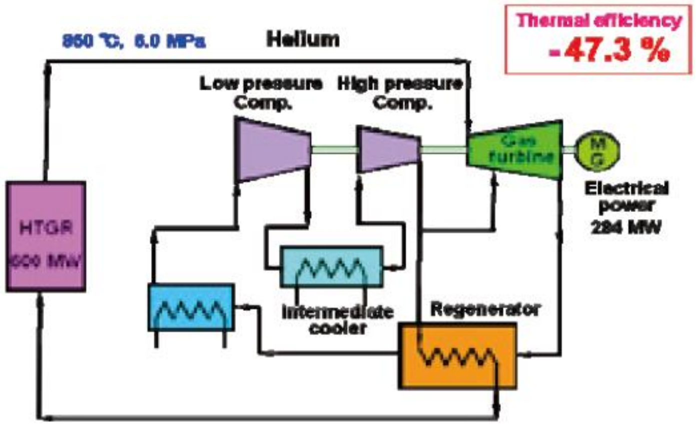

Figure 9: Energy Re-circulating type gas-turbine single system with nuclear reactor as heat source.

Here, working gas is re-circulating helium and high temperature gas-cooled reactor (HTGR) is considered to be used in this system. We can expect high plant efficiency about 47% in contrast with 35% for the case of BWR/steam-turbine system. This remarkable increase in efficiency results in saving by over 25% of nuclear fuel consumption. Main issue may be development of increase operating temperature.

VI.III Energy Re-Circulating Nuclear/MHD System

Because, in previous nuclear/gas-turbine system, highest working temperature is considered to be 850^{0}C owing to requirement from difficulty in developing HTGR, its efficiency is relatively low. A system using MHD generator to achieve higher efficiency is proposed as shown in Figure 10. This system is a special power generation system driven by HTGR directly connected with MHD single power generation system for space applications. Typical gas dynamic parameters of heat, Q in MW, temperature, T in K, and pressure, P in MPa are shown in this figure. Working medium of helium mixed with xenon is used so as to connect closed cycle MHD system directly to HTGR. We exclude alkali-metal seed from the system. Mixed inert gas (MIG) system has been studied to eliminate system complexity of seed injection, mixing and recovery. Ionization potential of MIG working medium is much higher than that of inert gas seeded with alkali-metal, and therefore, ionization level, namely electrical conductivity, is not enough at the temperature of the reactor exit, 1800K. So, it must be pre-ionized electrically. Disk shaped Hall-type MHD generator is used for simple geometry, fewer electrode connections and simple structure of superconducting magnet. Regenerator which is installed just downstream of the MHD generator can regenerate heat exhausted from the generator in order to minimize waste heat radiated from the radiation cooler and to improve plant efficiency. Other components are staged compressor with intercoolers and radiation cooler[13].

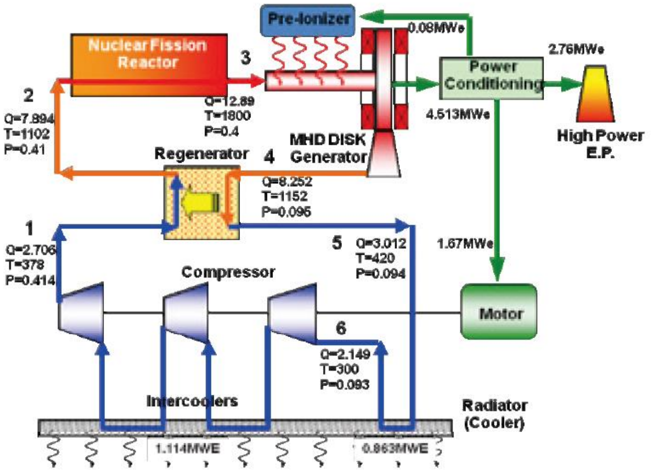

Figure 10: Energy Re-circulating type MHD single system with nuclear reactor as heat source for space applications

Input power from the HTGR is fixed as 5MW. Thermal input to the MHD generator is about 13MW which is the sum of input thermal energy from HTGR of 5MW and recovered one from the regenerator of about 8MW. Enthalpy extraction ratio, which is the ratio of output electrical power to thermal input, is assumed to be reasonable value of 35%. Generated electric power is 4.5MW and net output is 2.76generated power is used for compressor power. Finally, total plant efficiency reached to 55 to this system and 2.76MW net output electric power. Main reasons of high efficiency are high operating temperature and thermal energy recovery by regenerating heat exchanger. We have to note that we can reduce fuel consumption and recognized that this system will be an important candidate in near future.

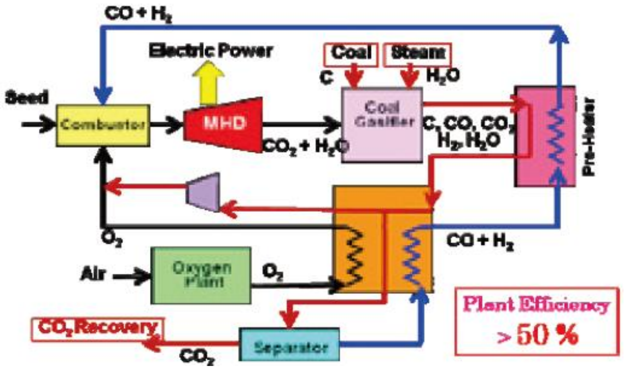

Figure 11: CO_2 Recovery type MHD generator plant.

VI.IV CO_2 Recovery Type MHD Power System

To reduce CO2 emission is one of the urgent requirements to reduce global climate change based on green house effect. If we burn fossil fuel, CO2 must be exhausted. Therefore, we have to develop two directions; 1) increase plant efficiency which leads to reduce fuel consumption and 2)CO2 recovery type power generation system. We discuss how to increase plant efficiency using MHD generator previously. We would like to discuss how to design CO2 recovery type plant. At first, if we burn fossil fuel with air, exhaust gas contains so much N2 and we have to separate CO2 from N2 and H2O. This process requires so much energy and again increases CO2 production. If combustion exhaust contains only CO2 and H2O, it is easy to separate CO2 from H2O. This can be achieved by burning fuels with pure oxygen. Of course some amount of energy loss to produce oxygen takes place. However, temperature of combustion gas can be increased and if this increase in temperature can be effectively used to increase of plant efficiency, such penalty can be compensated. Basic ideas of CO_2 recovery type MHD power generation system are as follows: Heat source is coal synthesized gas burning with pure oxygen. Coal must be considered as a heat source in near future with in 200 years instead of LNG or oil. Nitrogen free with oxygen separate plant is included. Figure 11 shows typical CO_2 recovery type MHD generator plant proposed by Prof. N. Kayukawa at Hokkaido University. In this system, H_2 and CO is burned with pure oxygen to drive MHD generator at the temperature around 2800^0C. Downstream part after MHD generator, heat is recovered by regenerative coal gasification process, fuel pre-heating, and steam decomposition. Energy penalty for oxygen production plant can be recovered due to operate at high temperature with high efficiency of the MHD generator. It is known that only MHD generators can be operated such high temperature regime. Total plant efficiency can be expected as over 50% with CO_2 recovery.

VII. CONCLUSION

In the conventional conversion systems a significant loss of energy occurs in the transition from thermal to mechanical energy (thermodynamic conversion). The performance from the point of view of efficiency of a heat engine is limited by the Carnot cycle. The Carnot efficiency is governed solely by the extreme temperatures of the cycle. The low temperature of the cycle is related to the temperature of the environment, the maximum temperature is rather related to the mechanical resistance of the material at high temperature. Nowadays, gas turbines are the technologies that can work to the highest value of temperature cycle, with values around 1500 K. These technologies are usually used as a topper in a combined cycle gas turbine (CCGT) plant. The Carnot efficiency for a thermal engine that works on those temperatures is about 80%.

In the MHD generator the advantage of having no moving parts allows to work at higher temperatures than a conventional energy conversion. It is possible to work with temperature around 3000K, and a these temperature the maximum theoretical efficiency would be near 90%. In the section of near future MHD power generation system the plant efficiency can be increased by increasing the working temperature, do not use condenser of steam-turbine to reduce exhaust heat, and to construct energy re-circulating type system.

Also, in order to reduce CO_2 emission, use nuclear power with high efficiency. We have to construct nuclear powered energy re-circulating type system. Also idea of CO2 recovery type power generation system must be developed. Energy re-circulating type Nuclear/MHD power system was proposed to achieve high efficiency using high operating temperature and eliminating bottoming cycle. For reduction of CO_2 emission, CO_2 recovery type generator system was proposed, which has special features of using coal synthesized gas burning with pure oxygen and heat recovery systems.

REFERENCES

[1]. Mark Waldo Zemansky and Richard Dittman. Heat and thermodynamics : an intermediate textbook /MarkW. Zemansky, Richard H. Dittman. New York ; London : McGraw-Hill, 7th ed edition, 1997. [cited at p. 4-21]

[2]. M. Ali Kettani. Direct energy conversion / [by] M. Ali Kettani. Reading, Mass. : Addison-Wesley Pub. Co, 1970. [cited at p. 11]

[3]. Alan L Fahrenbruch and 1927 Bube, Richard H. Fundamentals of solar cells : photovoltaic solar energy conversion / Alan L. Fahrenbruch, Richard H. Bube. New York : Academic Press, 1983. [cited at p. 11]

[4]. V. S. (Vladimir Sergeevich) Bagot skii. Fuel cell: problems and solutions, Vladimir S. Bagotsky. Hoboken, N.J. : JohnWiley Sons, 2009. [cited at p. 11]

[5]. R. A. (Ronald Alan) Coombe and Ronald Alan Coombe. Magnetohydrodynamic generation of electrical power / ed. by R.A. Coombe. Lond. : Chapman and Hall, 1964. [cited at p. 11]

[6]. Clement M Lefebvre. Electric power : generation, transmission, and efficiency / Clement M. Lefebvre. New York : Nova Science Publishers, 2007. Includes index. [cited at p. 11]

[7]. Irving Bernard Cadoff and Edward Miller. Thermoelectric materials and devices / Lectures presented during the course on thermoelectric materials and devices sponsored by the Dept. of Metallurgical Engineering in co-operation with the Office of Special Services to Business and Industry, New York University, N.Y., June 1959 and 1960. Edited by B.Cadoff and E.Miller. N.Y. : Reinhold Pub. Corp, 1960. [cited at p. 11]

[8]. Richard J Rosa. Magnetohydrodynamic energy conversion / Richard J. Rosa. Washington : Hemisphere Pub. Corp, rev. print edition, 1987. [cited at p. 12- 41]

[9]. Naoyuki Kayukawa. Open-cycle magnetohydrodynamic electrical power generation: a review and future perspectives. Progress in Energy and Combustion Science, 30(1):33 60, 2004. [cited at p. 17]

[10]. P. Satyamurthy, T. K. Thiyagarajan, and N. Venkatramani. A conceptual scheme for electrical power generation from nuclear waste heat using liquid metal magnetohydrodynamic energy converter. Energy Conversion and Management, 36(10):975 987, 1995. [cited at p. 18]

[11]. M. S. Tillack and N. B. Morley.Magnetohydrodynamics, Standard Handbook for Electrical Engineers,14th Edition- 1998

[12]. N. Harada, et al., Improvement of Enthalpy Extraction over 30Swirl, Energy Conversion and Management, vol. 36, no. 5, 1995.[cited at p. 355-364]

[13]. N. Harada, L. C. Kien and T. Tashiro,Closed Cycle MHD Generator using He/Xe Working Plasma,AIAA Paper, 2002-2144, Proc. of the 14th International Conference on MHD Power Generation and High Temperature Technologies,2002.[cited at p.163-171]

[14]. HARADA, "Magnetohydrodynamics For Advanced Power Generation System" Nobuhiro Nagaoka University of Technology,The International Conference on Electrical Engineering 2008,No. O-043,[cited at p.3-5]

AUTHORS

First Author – Ajith Krishnan R, Post Graduate student in Energy System Analysis and Design (Mechanical Engineering Department), Government Engineering College, Kozhikode, Kerala, India, E-Mail id- ajithjec@gmail.com

Second Author – Jinshah B S, Post Graduate student in Energy System Analysis and Design(Mechanical Engineering Department), Government Engineering College, Kozhikode, Kerala, India, E-mail id- jan2live@gmail.com