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Integration of MHD System to The Gas Turbine and The Steam Turbine Power Plant: A Brief Review

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ABSTRACT

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 higher amount of losses in different sections of the plants. The Magnetohydrodynamic (MHD) is found as a nonconventional energy generation system which has the capability to enhance the thermal power plant efficiency significantly. The MHD is a direct energy conversion system that describes the interactions of a magnetic field and an electrically conductive fluid to produce electrical power. The system is simple and it avoids the difficulty of choosing a rotating turbine or engine and massive number of complex calculations. The high temperature tolerable materials can be used in the system due to the exponential development of material science. In MHD system, energy of plasma or ionized gas is directly converted into electric power. The conversion process of the system is based on the principle of Faraday's Laws of electromagnetic induction and fluid dynamics. The MHD generator uses hot conductive ionized gas or plasma as the moving conductor whereas in the mechanical dynamo, in contrast, uses the motion of mechanical devices to accomplish this. Seeding materials such as potassium carbonate, potassium sulphates are used to enhance the conductivity of the ionized gas. The focus of the present study is to investigate alternative methods through which an MHD power generator can be coupled to the existing gas turbine and steam plants. In doing so, the thermal cycle efficiency of these conventional plants can be improved. A case study is also presented to calculate the power output and efficiency in a simple way.

Keywords: MHD generator; plasma; seeding materials; convergent-divergent nozzle

INTRODUCTION

The field of MHD was initiated by Hannes Alfven, father of MHD, for which he received the Nobel Prize in Physics in 1970. The fundamental concept behind MHD is that magnetic fields can induce currents in a moving conductive fluid, which in turn polarizes the fluid and reciprocally changes the magnetic field itself. Though technically substantial progress has been achieved, today financial constraints are impeding speedy commercialization [1].

MHD power generation utilizes the high temperature plasma incising magnetic force line to induce electromotive force [2]. When the conducting fluid (conductor) moves through the magnetic field; it produces an electrical field perpendicular to the magnetic field. This process of electric power generation through MHD is based on the principle of Faraday's laws of electromagnetic induction. In all other conventional power plant, first the thermal energy of the gas or steam is converted into mechanical energy and after that the mechanical energy is converted into electrical energy. But in MHD, thermal and kinetic energy of the fluid is directly converted into electrical energy. Hence it is known as direct energy conversion system. The MHD power plants are classified into open and closed cycle based on the nature of processing of the working fluid.

The efficiencies of all modern thermal power generating system lies between 35-40% as they have to reject large quantities of heat to the environment [2]. It is concluded by the researchers in that field that that MHD systems can give higher efficiencies when they are retrofitted with the thermal or gas plants. With the present research and development activities, the MHD power generation may play an important role in the power industry to help alleviate present crisis of power to some extent. The focus of this study is to further investigate an MHD power generator system that can convert plasma energy into electricity. The MHD is chosen because of its high-power generating efficiency and retrofitting capability of operation with gas turbine and steam turbine power plant

The plasma

Plasma is a quasi-neutral gas of charged and neutral particles which displays collective behaviors. When the temperature of a gas is increased to higher levels, the gas becomes ionized and electrons are separated from the atoms of the gas. Consequently, the high temperature flue gas becomes electrically conductive and forms plasma.

Plasma is available in the earth and other planetary bodies such as stars and solar systems trapped within their respective magnetic fields and sometimes in electrical equipment. Low temperature plasmas can be used inside the MHD generator to produce electric power if seeded with alkali metals such as potassium nitrate, rubidium, cesium, sodium and lithium [3]. These alkali metals are required because of their high electrical conductivity, which make them to ionize easily at lower temperatures. The temperature of plasma species such as electrons, ions and neutrals are always equal in thermal equilibrium state [4]. The electron density and the ion density are always equal in the quasi-neutral state of plasma [5]. Low temperature plasma can be created inside a combustion chamber if an inert gas is seeded with small number of alkaline metals such as potassium carbonate and cesium. Several plasmas can also be created in the laboratory. Among these plasmas are the reactive ion etcher plasma, the flame discharge plasma, the inductively coupled plasma, the electron cyclotron resonance plasma, the radio frequency inductive plasma, the helicon wave plasma and the microwave induced plasma. For MHD power system air plasma is generally used.

Plasma is a mixture of particles, each with different mass, temperature and electric charge [1]. When a plasma temperature is increased, the mean translational energy of each species within the plasma is increased. Plasma can also be characterized using the specific average temperature of each species which include the ion temperature and the electron temperature [2]

Energy transfer between electrons and heavy particles

Plasma particles, due to their haphazard motion generally cause collisions amongst themselves. These collisions can be divided into two categories: elastic and inelastic collisions. In the elastic collision, particles like electrons and heavy particles such as neutral atoms, ions, and neutral molecular fragments collide with each other, and the collision does not result to the excitation of the heavy particles. On the other hand, inelastic collision is collision which occurs between electrons and heavy particles and the collision result to the excitation, ionization and dissociation of the heavy particles. In thermal equilibrium state, the velocity distribution of plasma particles is Maxwellian. The one-dimensional Maxwellian electron velocity distribution function, is given by equation (1) as [2]:

$$F(V) = B_r \exp(\frac{\frac{1}{2} m\, V_e^2}{K_B T_e}) \qquad (1)$$

$F(V) is$ the one-dimensional Maxwellian electron velocity distribution function. The relationship between the constant B_r and electron velocity $F(V)$ is given by equation (2):

$$B_r = n_e \left(\frac{m_e}{2\pi K_B T_e} \right)^{\frac{1}{2}} \qquad (2)$$

Where T_e is the gas temperature and $K_B = 1.38\text{x}\ 10^{-23}$ is Boltzmann's constant m_e is the particle mass, V_e is electron velocity, T_e is the excitation temperature and m_e is the electron mass. Where,

$$n_e = \int_{-\alpha}^{\alpha} F(V) dV (3) \qquad (3)$$

Figure 1 shows a typical Maxwellian electron velocity distribution. The distribution is mostly characterized by the temperature of electrons.

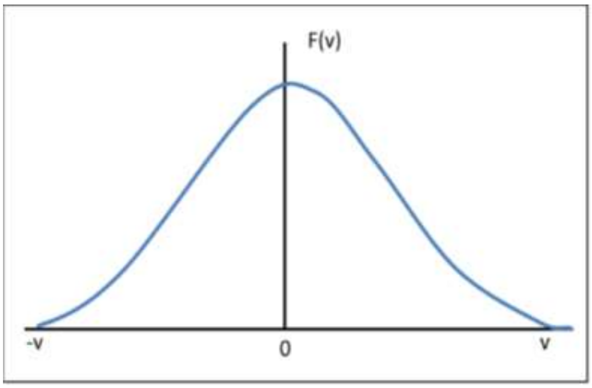

FIGURE 1: Schematic illustration of the Maxwellian electron velocity distribution.

MHD system description

The practical MHD conversion system was initially discovered by Michael Faraday and later extended by Ritchie [1], [2]. This system is a distinctive method used for the generation of electric power based on the principle of Faraday's Law of electromagnetism and fluid (plasma) dynamics. The basic principle of operation of MHD system starts when a plasma or ionized gas is injected from a combustion chamber and then flows through a convergent-divergent nozzle at high velocity before entering the MHD duct. Inside the MHD duct, the ionized fluid velocity is decelerated by a strong magnetic field, placed between two electrodes. The dc magnetic field also creates a retarding force that is perpendicular to the direction of the fluid. Subsequently, the positive and negative ions of the plasma are collected by electrodes placed at 90° to the induced magnetic field, thereby producing an electric current as demonstrated in Figure 2.

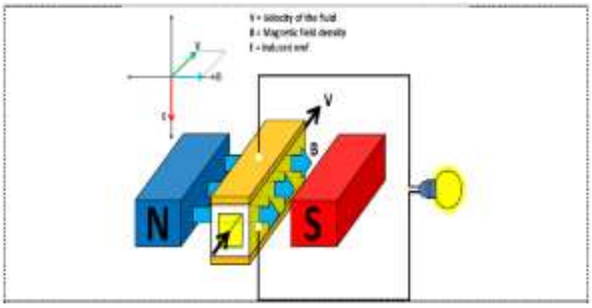

FIGURE 2: Principle of MHD system

Extraction of power from an MHD generator

To perform analysis on any categories of MHD system, the following conditions are often assumed: (i) the gas should be moving at constant velocity and pressure, (ii) the operating gas should be an ideal gas, (iii) the applied magnetic field must be uniform and (iv) there should not have any heat transfer to the surroundings.

When an ionized gas flows with high velocity along the MHD generator, the applied magnetic field creates an induced Electromagnetic Force (EMF) in the opposite direction to retard the flow of the gas particles. So, as the particles thermal energy penetrates the magnetic flux, an electrical energy is generated. The EMF and electric field, E, acting on the gas fluid is given by Lorentz force equation:

$$F = Q\ (E + v.B) \qquad (4)$$

In an open circuit MHD system, an electrical voltage V, can be obtained from the gas velocity v, the magnetic flux density Band the distance, l between the electrodes, as given by equation 5 [ ]:

$$V = vLB \qquad (5)$$

The maximum current I_{max} flowing inside the MHD generator is given by equation 6[ ]:

$$I_{max} = \frac{Bv A\sigma}{2} \qquad (6)$$

Where σ is the electrical conductivity of the fluid and A is the electrode surface area.

The maximum voltage V_{max} inside the MHD generator is given by equation 7 below:

$$V_{max} = vBl - I_{max}R \qquad (7)$$

Where internal resistance R of the is given by:

$$R = \frac{l}{\sigma A} \qquad (8)$$

The maximum power P_{max} that can be extracted from the open circuit MHD generator electrodes is obtained by using the equation (9):

$$P_{max} = I_{max}^2 R = \frac{B^2 V^2 A\sigma\, l}{4} \qquad (9)$$

Therefore, the dc output power that can be extracted from the MHD generator electrodes with external load resistor is given by equation 10 as given below:

$$P_{out} = B^2 v^2 A\sigma\, l * k(k-1) \qquad (10)$$

Here k is the electrical load factor given by:

$$k = \frac{R_L}{R_L + R_i} \qquad (11)$$

The MHD system conversion efficiency can be calculated by using the following equation [ ]:

$$\eta = \frac{V_{max}}{VB} \qquad (12)$$

Hall parameters [13]:

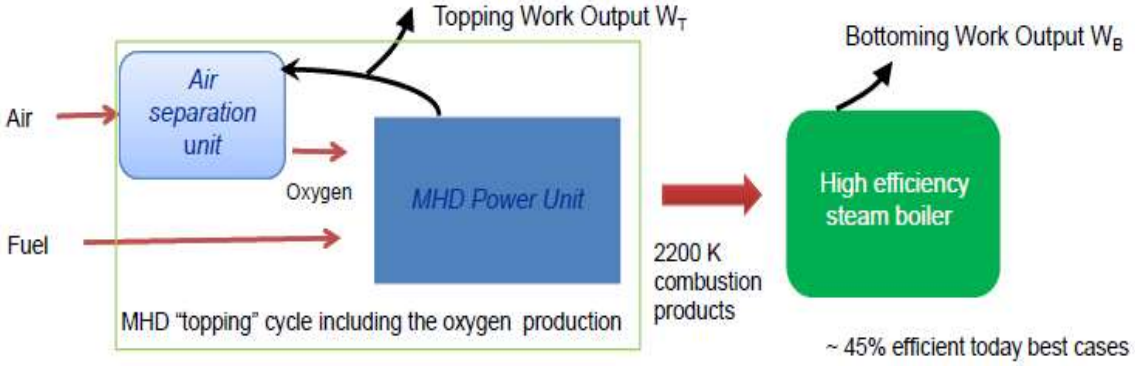

FIGURE 3: work output of MHD topping and bottoming plant

The ratio between electron gyro-frequency and electron-particle collision frequency is given by $\beta = \mu e\, B$ and for gas MHD we have $0.1 < \beta < 10$. The electrical mobility μe has in general a negative effect on power conversion, mainly because it spreads the charge carriers along the duct, reducing the induction effect. The fluid has to push through generator against a Lorentz force and produces the electrical power output. In that situation the factor β tilts the field and reduces current density output in the MHD generator [13].

Enthalpy into the top plant = Q
Work from the top plant is $W_T = \eta_T Q$
Enthalpy into the "bottom" = $Q - W_T = Q(1 - \eta_T)$
Work from the bottom: $W_B = \eta B$ (Enthalpy into the bottom) = $Q(\eta_B - \eta_T\eta_B)$
Combined cycle efficiency: $(W_T + W_B)/Q = \eta_T + \eta_B - \eta_T\eta_B$

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% by implementing the MHD generators which utilize the energy from the hot gas-plasma 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.
- The higher cost 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.

The convergent-divergent nozzle

Most MHD generators require high velocity gas and temperature; the fuel-air exhaust exiting the combustion chamber in a plant is forced to flow through a convergent and divergent nozzle as shown in Figure 4. The purpose of the nozzle is to accelerate the fluid velocity up to the required ratio of the velocity of the fluid to the velocity of sound in that fluid or Mach Number before entering the inlet of the MHD generator.

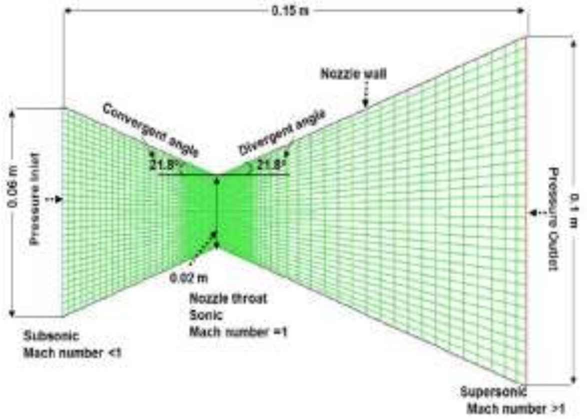

FIGURE 4: Nozzle mesh and geometry

The supersonic propelling nozzle uses the heat energy of the combustor exhaust to accelerate the fluid to a very high speed. The nozzle boundary conditions are set in such a way that when the fluid pressure increases at the inlet, their velocity should be very low (Subsonic). As the fluid flows through the nozzle throat, the pressure begins to decrease (Sonic) and the fluid velocity distribution increases toward the nozzle outlet (Supersonic).

Retrofitting of an MHD system to thermal generating plants

The generating efficiency of a typical open-cycle MHD power generation system has been extensively studied by many researchers and its efficiency has been reported to be 62 %. By integration of the MHD power generator to the conventional power plants, the overall efficiency of the combined system is increased from 40 % to about 60 %. A combined cycle power plant is shown in Figure 5 where carbon emission does not occur [14]. Additionally, greater efficiency of about 65 % to 70 % can be achieved if the MHD generator, the gas turbine and the steam turbine (triple cycle) are all coupled together [12]. The repowering of the existing combined cycle power plants is possible with a significant increase in the efficiency of the plant without environmental pollution. To this goal, two separate investigations are done to highlight the possibility of coupling an MHD system to the South African power stations, namely Ankerlig and Gourikwa (CCGST) [ ].

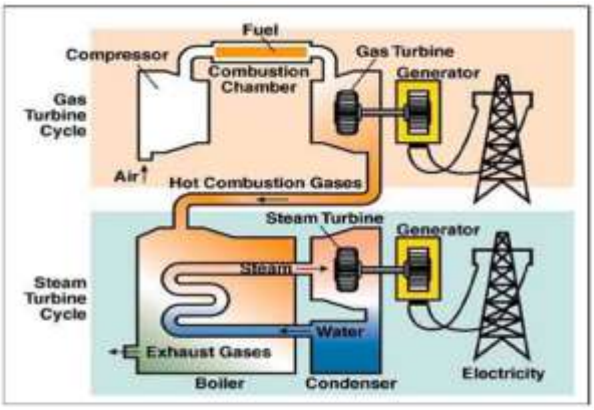

FIGURE 5: Combined-cycle gas-steam turbine system (Energy without carbon, 2015)

Many researchers around the world have been thinking of different ways through which the MHD system can be developed and be integrated into the existing conventional power plants as a topping unit [1-5], [6-7],[13]. In Figure 5 a combined cycle power plant has been shown where the topping plant is the MHD generator. The combined-cycle is generally referred to as the combination of a Brayton cycle (gas turbine) and a Rankine cycle (steam turbine). The theme of converting the Open Cycle Gas Turbine (OCGT) to a Closed Cycle Gas Turbine (CCGST) is to utilize the hot exhaust gas (about 8730 K) energy coming out from the gas turbine to create steam in a Heat Recovery Steam Generator (HRSG). This steam is utilized to drive the bottom unit steam turbine. The mechanical energy that is produced by the steam turbine is then converted to electrical energy using the generator. At the same time, a condenser converts the exhaust steam from the steam turbine back into the HRSG through a cooling process without carbon emission. Combined-cycle MHD gas-steam turbine system without load and with load resistance are shown in Figures 5 and 6 respectively.

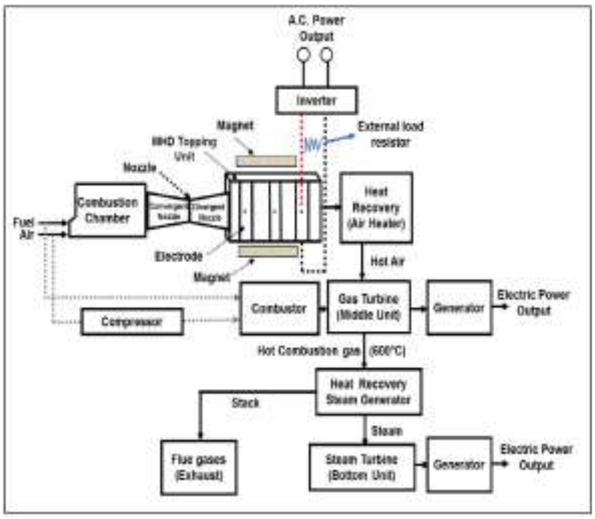

FIGURE 6: Combined-cycle MHD gas-steam turbine system

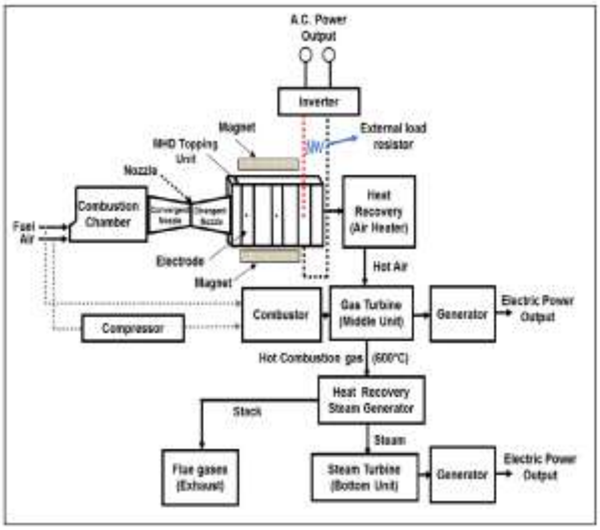

FIGURE 7: Combined-cycle MHD gas-steam turbine system with external load resistor

System studied [14]

In this study, the MHD system coupled to the South African Ankerlig and Gourikwa OCGT to improve their total nominal capacity is highlighted. In the Ankerlig power station, the electricity generating units are grouped into two phases, with phase one comprising of 4 units and phase two comprising of 5 units. Each unit consists of Gas Turbine (GT) 148.2 and 149.2 MW. The combined capacity of all the nine units is about 1338 MW (Phase-1: 149.2 MW x 4 units + Phase-2: 148.2 MW x 5 units). In the Gourikwa power station, there are five electricity generating units and each unit also consisting of a gas turbine. The combined capacity of all the five units is about 746 MW (149.2 MW x 5 units). Primary fuel like coals, natural gas and petroleum derivative (kerosene or diesel) are presently used in these stations. The operation of these two OCGT plants begins when an atmospheric air is compressed and mixed with the fuel inside a combustion chamber (1303⁰K – 1473⁰K. The fuel-air mixture is burnt, and the resulting high velocity gas is used to turn the turbine shaft connected to the generator rotor. As the rotor rotates inside the stator, electricity is generated and distributed via a high voltage transmission system. The Ankerlig and Gourikwa OCGT can also be converted into a more efficient Combined-Cycle Gas-Steam Turbines (CCGST), as shown in Figure 6.Table 1 illustrates the parameters of MHD models 1 and 2 These parameters are modeled theoretically using equations (9) and (10) to determine the optimum power that can be obtained from the CCMGST plant [14].

TABLE 1: MHD models 1 and 2 respectively

Parameters	Model 1	Model 2
Simulated exhaust velocity (V)	1088m/s	1088m/s
Magnetic field (B)	2 Tesla	2.5Tesla
Exhaust conductivity (σ)	15 mho/m	20 mho/m
Electrode surface area (A)	1 m²	1.6 m²
Distance between two electrodes (L)	1m	1.6 m

Model 1:

$I_{max}=\frac{Bv A\sigma}{2}= \frac{2*1088*1*15}{2}= 16320A$

$$R_i = \frac{L}{\sigma A} = \frac{1}{15*1} = 0.066\,\Omega$$

V=vlB = 1088*1*2= 2176 V

V_{max} =2176- 16320*0.066= 1088V

$P_{max} = I_{max}^2 R = \frac{B^2V^2A\sigma l}{4}$

$P_{max}=(16320)^2 * 0.066$ =17.76 MW

$\%\eta= \frac{V_{max}}{vB} * 100 = \frac{1088}{1088*2}$*100=50%

Model 2:

$I_{max}=\frac{Bv A\sigma}{2}=\frac{2.5*1088*1.6*20}{2}$=43520 A and

$R_i = \frac{L}{\sigma A} = \frac{1.6}{20*1.6} = 0.0.05\,\Omega$

V=vlB = 1088*1.6*2.5= 4352V

V_{max} =4352- 43520*0.05= 4352--2176=2176 V

$P_{max} = I_{max}^2 R_i=(43520)^2 * 0.05$ =94.70 MW

$\%\eta= \frac{V_{max}}{vB} * 100 = \frac{2176}{1088*2.5}$ *100= 80%

TABLE 2: Summary of the CCMGST output power calculations for models 1 and 2 [14].

	Model-1 parameters	Units	OCGT (MW)	OCGT to CCGST Increments (MW)	CCGST (OCGT+ Increment), (MW)	MHD (MW)	CCMGST Total Capacity (MW)
Anker link plant	Phase-1	4	597	320	917	71	988
	Phase-2	5	741	400	114	89	1230
	Gross output power (Phase 1+Phase 2)	9	1338	720	2058	160	2218
Gourikwa plant	Gross output power	5	746	400	1146	89	1235

TABLE 3: Summary of the CCMGST output power calculations for models 1 and 2.[14]

	Model-2 parameters	Units	OCGT (MW)	OCGT to CCGST Increments (MW)	CCGST (OCGT+ Increment), (MW)	MHD (MW)	CCMGST Total Capacity (MW)
Anker link plant	Phase-1	4	597	320	917	378.8	1295.8
	Phase-2	5	741	400	1141	473.5	1614.5
	Gross output power (Phase 1+Phase 2)	9	1338	720	2058	852.3	2910
Gourikwa plant	Gross output power	5	746	400	1146	473.5	1620

The results show that when models 1 and 2 parameters are applied to a single MHD generator unit as a topping unit the maximum output powers obtained are 17.76 MW and 94.7 MW, respectively.

From the conversion of OCGT to CCGST, the power capacity of Ankerlig station is increased from 1338 MW (Phase-1: 149.2 MW x 4 units + Phase-2: 148.2 MW x 5 units) to 2058 MW (80 MW x 9 units + 1338 MW), while in the Gourikwa station, the power capacity is increased from 746 MW (149.2 MW x 5 units) to 1146 MW (80 MW x 5 units + 746 MW) (Table 4.3). This conversion gives an overall generating cycle efficiency of about 65%.

The coupling of model 1 MHD unit to each of the nine-electricity generating unit in the Ankerlig CCGST station produces a total nominal capacity of approximately 2218 MW, for the CCMGST plant, as shown in Table 1. Likewise, the coupling of model 1 MHD unit to each of the five-electricity generating unit in the Gourikwa CCGST station produces a total nominal capacity of approximately 1235 MW, for the CCMGST plant.

The coupling of model 2 MHD unit to each of the nine-electricity generating unit in the Ankerlig CCGST station produces a total nominal capacity of approximately 2910 MW, for the CCMGST plant (Table 2). The coupling of model 2 MHD unit to each of the five-electricity generating units in the Gourikwa CCGST station produces a total nominal capacity of approximately 1620 MW, for the CCMGST plant. Thus, the overall generating efficiency of these power plants has increased significantly by retrofitting technique [14].

CONCLUSION

In the first study, two open circuit MHD models 1 and 2 are explored theoretically to the CCGST stations to form the Ankerlig and Gourikwa CCMGST stations. This is done in order to produce an output power with optimum generating efficiency. The results showed that when models 1 and 2 parameters are applied to a single MHD generator unit, the maximum output powers obtained are 17.76 MW and 94.7 MW, respectively. When model-1 MHD unit is incorporated into the CCMGST stations, the optimum powers obtained are 2218 MW and 1235 MW, respectively. When model-2 MHD unit is incorporated into the CCMGST stations, the optimum powers obtained are 2910 MW and 1620 MW, respectively. The repowering of the existing thermal power plants is possible with a remarkable increase in the efficiency of the plant.

REFERENCES

[1] Md. Shariful Islam M.S., Molla N. H., Quddus E., “Prospects of MHD Generation in Bangladesh”, Int. Journal of Engineering Research and Applications ISSN: 2248-9622, Vol. 3, Issue 6, Nov-Dec 2013, pp.745-748.

[2] Abubakar, M.A. Mohammad, A.A.H. & Bala, I.A. 2016. Thermal Plasma: A Technology for Efficient Treatment of Industrial and Wastewater Sludge. IOSR Journal of Environmental Science, Toxicology and Food Technology, 10(11): 63-75.

[3] Ahsan, M. Numerical analysis of friction factor for a fully developed turbulent flow using k-ε turbulence model with enhanced wall treatment. Beni-Suef University Journal of Basic and Applied Sciences, 3(4): 269-277., 2014.

[4] Ajith, K.R. and Jinshah, B.S. 2013. Magnetohydrodynamic Power Generation. International Journal of Scientific and Research Publications, 3(6): 1-11.

[5] Altintas, A. and Ozkol, I. 2015. Magneto-hydrodynamics flow of liquid-Metal in circular pipes for externally heated and non-heated cases. Journal of Applied Fluid Mechanics, 8(3): 507–514.

[6] Andreev, O., Kolesnikov, Y. and Thess, A. Corrected Article: Experimental study of liquid metal channel flow under the influence of a non-uniform magnetic field. Physics of Fluids, 19(3): 039902, 1-12, 2007.

[7] Anumaka, M.C. Explicit Technology of Magnetohydrodynamic (Mhd) Power Generation. International Journal of Innovative Technology and Research, 2(4): 1072-1077,2014.

[8] Aoki, L., G Maunsell, M. & Schulz, H. 2012. A magnetohydrodynamic study of behavior in an electrolyte fluid using numerical and experimental solutions. Engenharia Térmica (Thermal Engineering), 11(1-2): pp. 53–60.

[9] Louis J.F. and Holman R.R.; “A Nuclear-Powered Space based Disk MHD Power System Description and Performance Assessment”, Proc.25thSymp.Eng. Aspects MHD, pp.11.1.1-5, Nashville, Tennessee, U.S.A., June (1998).

[10] 10.Macheret, S. O., Shneider, M.N., and Candler, G.V., 2004, “Modelling of MHD Power Generation on Board Reentry Vehicles”, PaperNo.AIAA-2004-1024.

[11] Ajith Krishnan R. and Jinshah B.S., “Magnetohydodynamic Power Generation”, International Journal of Scientific and Research Publications ISSN: 2250-3153, Volume3, Issue6, June2013.

[12] Internet Article, Magnetohydrodynamic generator, http://www.thermopedia.com/content/934/, Accessed Date: Sept. 09, 2020.

[13] Tushar KantiBera, “A Magnetohydrodynamic (MHD) Power Generating System: A Technical Review”, IOP Conf. Ser., Mater. Sci. Eng. 955 012075. 2020.

[14] Ayokunle Oluwaseun Ayeleso, “An improved plasma energy conversion system for electric power generation”, Cape Peninsula University of Technology Bellville, June 2018.

[15] R Woodside, “Retrospective and prospective aspects of MHD power generation”, thermal science division, NETL ORD MHD Workshop, 2014.

[16] W. da Silva Fonseca, R. C. F. Araújo, M. d. O. e Silva and D. O. d. A. Cruz, "Analysis of Magnetohydrodynamic Behavior of the Flow of Conductive Fluid in Pipes for Industrial Applic

[17] ations,” 14th IEEE International Conference on Industry Applications (INDUSCON), pp. 1177-1183, 2021