Acta Polytechnica **58**(1):1–8, 2018
doi:10.14311/AP.2018.58.0001

available online at http://ojs.cvut.cz/ojs/index.php/ap

EXPERIMENTAL CHARACTERIZATION OF A MAGNETOHYDRODYNAMIC POWER GENERATOR UNDER DC ARC PLASMA

Ayokunle O. Ayeleso*, Mohamed T. E. Kahn

Electrical, Electronic & Computer Engineering, Cape Peninsula University of Technology, P.O.Box 1906, Bellville 7535, Cape Town, South Africa

* corresponding author: kulama2005@gmail.com

Abstract. The generation of electric power through the conventional systems (thermal and hydro-electric) is no longer sufficient to meet the increasing industrial and commercial usage. Therefore, an alternative energy conversion system is currently being sought. The aim of the presented study is to develop a direct energy conversion system (Magnetohydrodynamics, MHD generator) to generate electric power using plasma. Additionally, the generator electric response is investigated based on the Faraday's principle of electromagnetism and fluid dynamics. For this purpose, a rectangular MHD generator prototype with segmented electrodes was constructed and subjected to continuous plasma from a DC arc source at test facilities available in the Western Cape region (South Africa). Subsequently, the terminal voltages at the middle-electrodes were measured one after another across 1, 100 and 470 Ω load resistors. In all experiments, the absolute time-averages of the measured terminal voltage across each load resistor were similar, which indicates a generation of power. The maximum power of the order 0.203 mW was obtained when 1 Ω resistor was connected to the middle-electrodes. Conclusively, these results validate the measurement approach of the MHD generator with segmented electrodes and could be used to design a large MHD unit that can be incorporated to the existing conventional thermal plant to improve their cyclic thermal efficiency.

Keywords: magnetohydrodynamics; electric power; rectangular MHD generator; DC arc plasma; terminal voltages; middle electrodes; load resistors; conventional systems.

1. Introduction

For the past 50 years, the thermal energy from conventional conversion systems such as hydro and nuclear plants have been used to generate electric power. In these plants, the potential energy of the primary gas is first converted into mechanical energy before being converted into electrical energy, with an output efficiency of about 40–45 % [1–3]. However, due to the lack of fossil fuel and other resources in Africa, electric power generation through the conventional system can no longer meet the increasing demand and usage [2]. Moreover, the generation of electricity through this method is usually expensive and often raises several environmental concerns such as pollution. As a result, there is a need to discover new methods in which electricity can be produced efficiently. One of these methods is the use of a direct energy conversion system such as the Magnetohydrodynamics, MHD, system [4–7]. Section 2 of this paper presents the theoretical background of the research, including the concept of the MHD system. Section 3 describes the construction of the MHD generator prototype, and Section 4 elaborates on the setup of the DC arc plasma experiment. Section 5 describes the DC arc plasma setup for the MHD generator, and the outcomes and findings of the experiments are discussed in Section 6.

2. Theoretical background

This section reviews the literature supporting the research, with a focus on the concept and operation of the MHD system. The idea of the MHD was first discovered by Michael Faraday and was later developed by Ritchie in 1832 [8, 9]. For any type of a MHD conversion system, a high temperature fluid (plasma) can be directly converted into electric power without any mechanical rotating parts. This system consists of a combustor and an expansion nozzle, which injects a gas fluid into the MHD duct transversed by a strong magnetic field, B [10]. Inside the MHD generator, the electrodes are connected to an external load resistor, R_{L}, placed at a 90° angle to the induced magnetic field. The magnetic field creates a retarding force (Lorentz force, F), which opposes the fluid flow direction and decreases the fluid velocity by extracting energy from the flow. Subsequently, an electrical voltage and current can be measured across the electrodes [3, 9, 11–13].

The most practiced MHD generator designs are the Faraday, the Hull and the Disc systems. The Faraday design can be categorised into different groups: continuous, segmented and diagonally connected electrodes. These systems vary according to how electrodes are connected to the load. However, in the present study, the Faraday system with segmented electrodes is con-

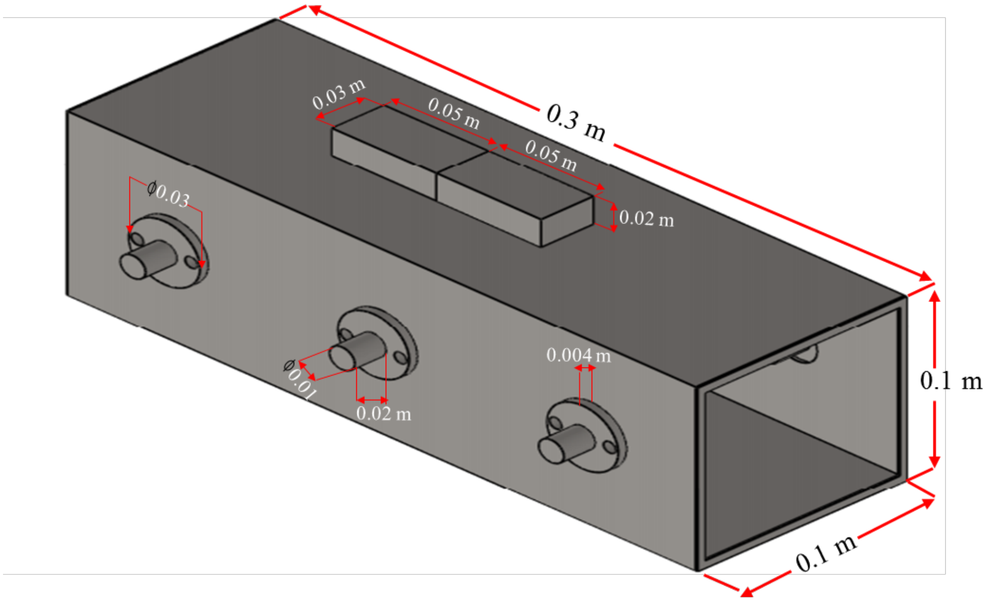

Figure 1. 3-D Representation of the MHD generator prototype.

sidered [3, 14]. The process involved in the development of all the different categories of the Faraday configuration has been discussed by reference [12].

3. MHD generator prototype

The prototype is made of a rectangular mild steel duct, round copper electrodes and neodymium N35 permanent magnets. The typical remanent flux density of these magnets are 1.17 T. The duct plane is located at the horizontal xy plane (plane $z = 0$). In addition, the neodymium magnets are positioned along the z-direction to produce external magnetic fields and the Lorentz force acting on the plasma gas. Copper is used for the construction of the electrodes due to its good work function and high conductivity. A 3-dimensional (3-D) representation and pictures of the MHD generator prototype are depicted in Figures 1 and 2.

As seen from Figure 2, the duct and the magnets are insulated from one another with ceramic materials while the round electrodes are insulated from the duct with tufnol materials. Additionally, the round segmented electrode is innovative and has been selected to minimize the experimental uncertainty that could arise from complex designs and structures. This configuration also helps to improve on the efficiency of the generator.

4. Setup of the DC arc plasma experiment

To enable this experiment, a commercial 40 A tradeweld plasma cutting device has been configured in a non-transferred arc mode to produce the actual plasma, which flows into the MHD generator. This device was selected because of its high temperature and it was the only available plasma source at the authors

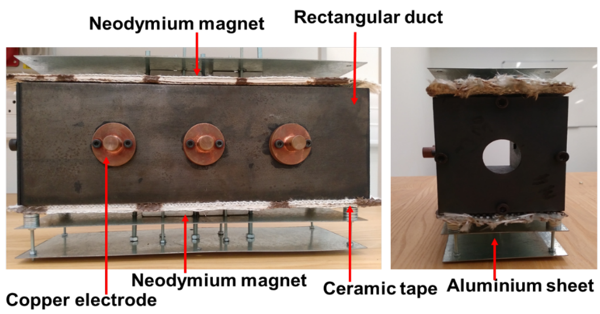

Figure 2. Photos of the MHD generator prototype.

disposal. Moreover, the plasma device torch uses ambient air as the primary gas and consists of special consumable components, namely a copper electrode, a shielding cup, a hafnium or zirconium copper nozzle and a retaining cup, as depicted in Figure 3 [15–17].

The structure of the DC arc plasma device consists of a power supply, an arc starting circuit, which ignites the torch and an air compressor, with a tank capacity of about 24 litres (Figure 4). In addition, the open circuit voltage of the power source of the plasma arc device is about 220 V. The main and pilot arcs of the DC plasma device are shown in Figure 4.

Before the start of the experiment, an atmospheric air is first compressed and filtered at a pressure of about 3.5–4 bar (50–58 psi) inside the plasma device. Thereafter, the device anode (aluminium workpiece) is positioned within few millimeters of the device torch (cathode) to produce a high temperature non-transferred arc plasma jet, which flows out of the torch nozzle into the MHD generator. Due to the thickness (15 mm) of the aluminium workpiece, an output current of about 25 A is used from the plasma device. After each experiment, to maintain the arc

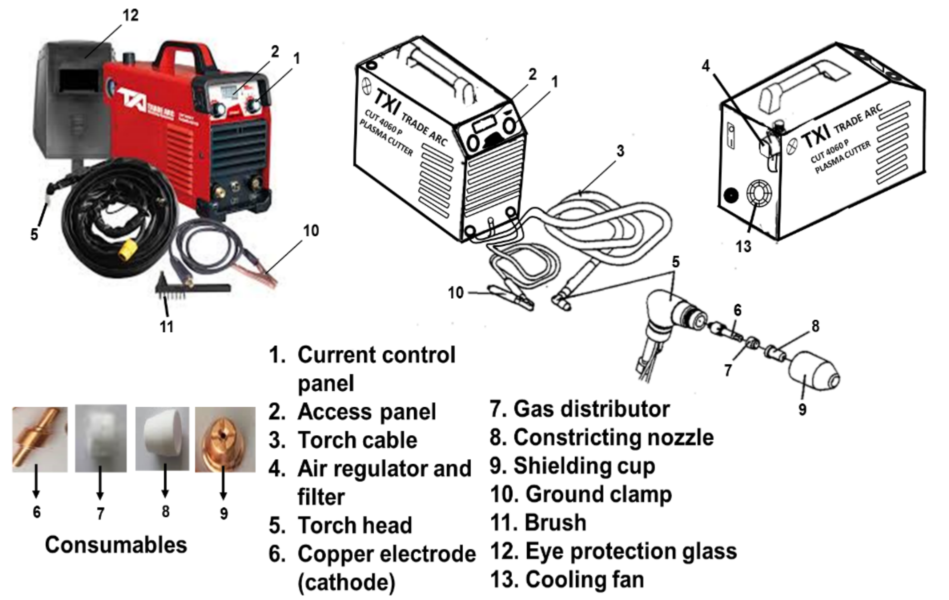

Figure 3. Components of the DC arc plasma device [16].

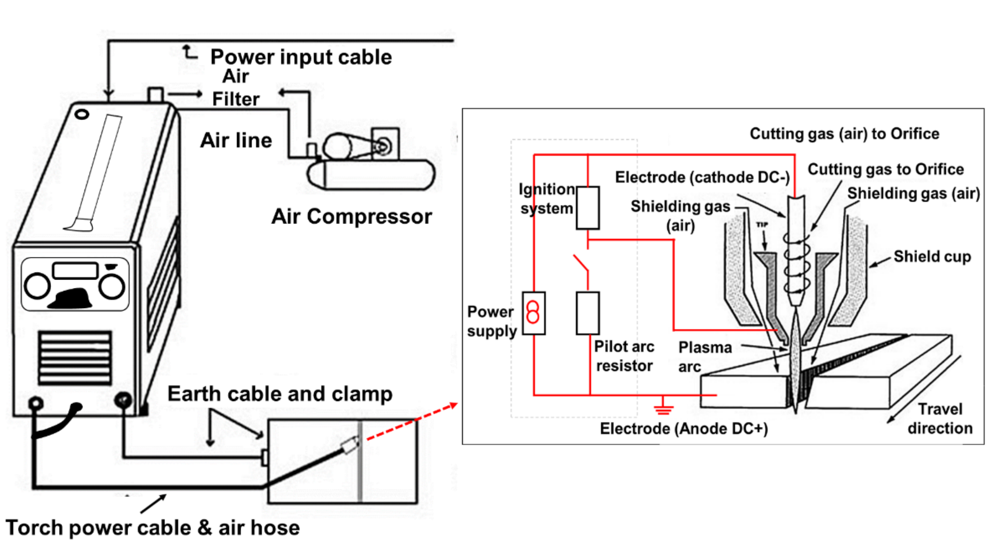

Figure 4. The main and pilot arc of the DC plasma device [17].

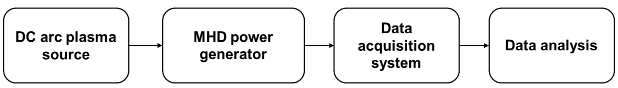

Figure 5. Flowchart of the experimental setup.

plasma for a long period of time, the torch nozzle is slightly shifted towards a smooth section of the anode. This process helps to produce a high ionization capability and strong plasma energy needed during the experiment. Subsequently, the output voltage data from the MHD generator is measured and recorded using a personal computer (PC) with National Instrument (NI) Labview and data acquisition (DAQ) software installed. The flowchart of the experimental setup is shown in Figure 5, while the pictures of the experimental setup are shown in Figure 6.

5. DC arc plasma setup for the MHD generator

This section describes the circuit model of the MHD generator used in the DC arc plasma experiment.

5.1. Description of the circuit model

The measurement setup implemented for the MHD generator under the exposure to the DC arc plasma is shown in Figure 7. In this setup, the middle-electrodes of the MHD generator are connected in the segmented mode (where the neodymium magnets are positioned). The load resistors (1, 100 and 470 Ω) are also connected to the middle-electrodes one after another. The aim of the experiment is to measure the generator terminal voltages across the electrodes when exposed to a plasma generated from the DC arc device.

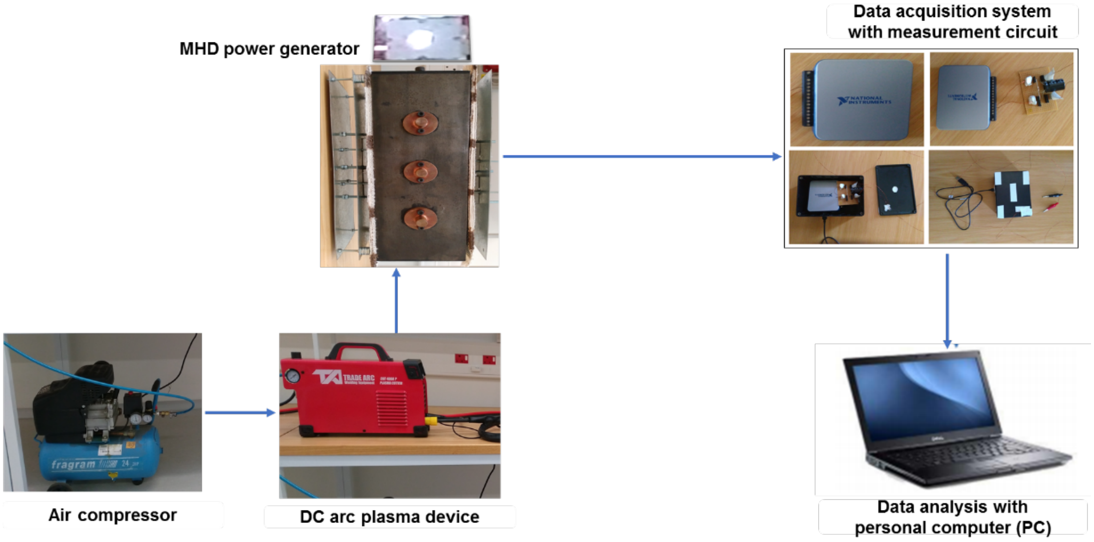

Figure 6. The setup of the DC arc plasma experiment.

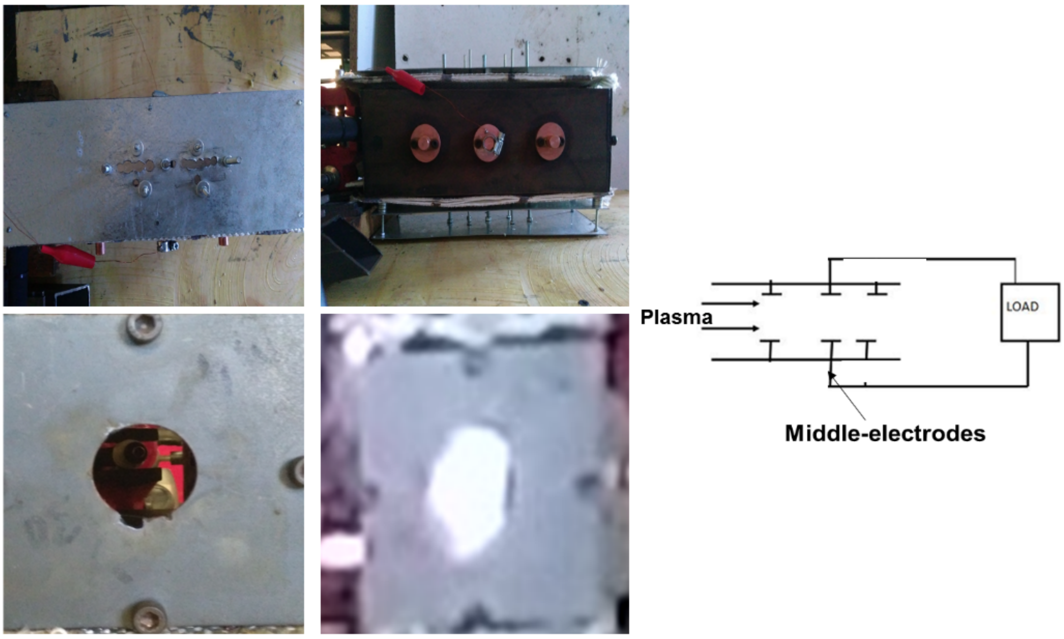

Figure 7. Photos of the DC arc plasma measurement setup with the MHD generator prototype.

The experiments are conducted at the Department of Electrical, Electronic and Computer Engineering, Cape Peninsula University of Technology, Cape Town (South Africa).

5.2. Analog signal acquisition using the NI USB-6002 DAQ device

To log and read the voltage data from the experiments, the NI USB-6002 DAQ device is configured in the differential measurement mode, as shown in Figure 8. In this mode, the voltage difference between the two analog signals (AI+, and AI−) across the external load resistor, R_L, is determined. Data samples are also taken at continuous time intervals, with 1000 samples over a period of about 0.5 ms.

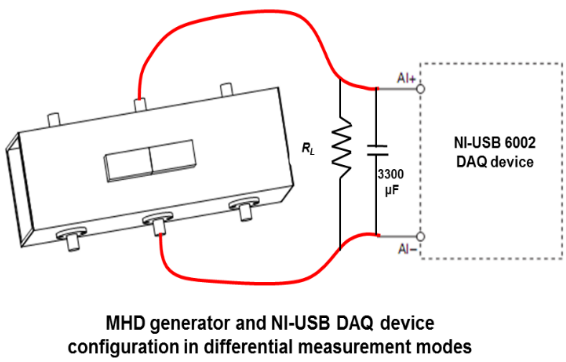

Figure 8. Measurement circuit with NI-USB 6002 DAQ device.

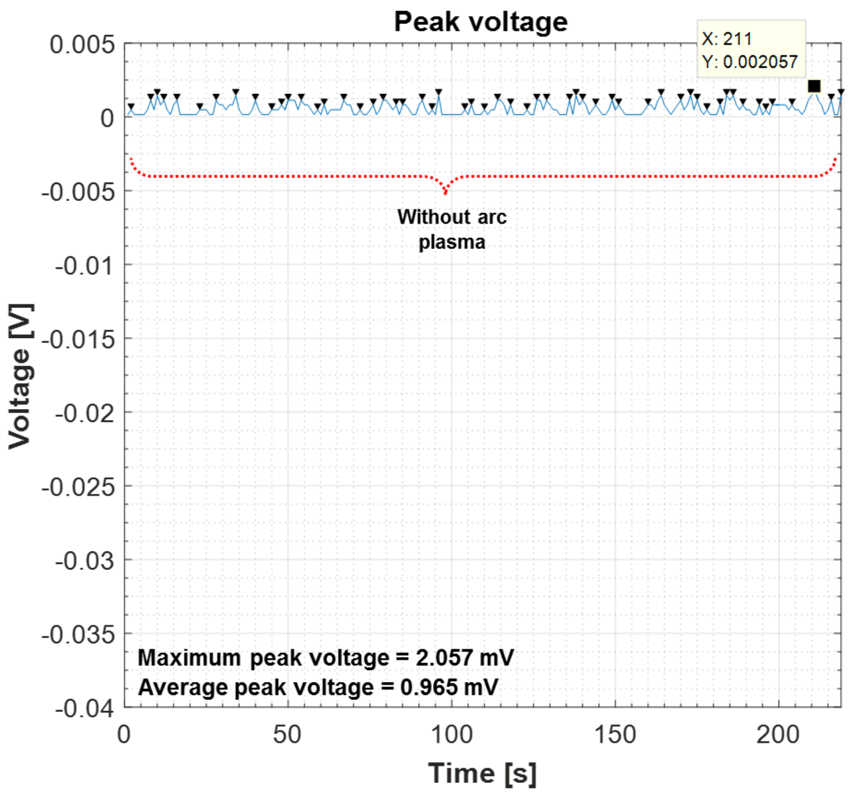

FIGURE 9. The systemic offset voltage measured without DC arc plasma.

From Figure 8, the circuit model is stabilized with a capacitor of about 3300 µF capacitance, and the measured voltage signal is further filtered with a Butterworth Filter for a greater accuracy and noise reduction. This is done because the signal leads (greater than 2 m) travel through a noisy environment.

6. Outcomes of the MHD generator under DC arc plasma

This section presents the measurement results of the DC arc plasma experiment. The apparatus used during the experimental setup includes a multimeter and the NI USB-6002 DAQ device. The current flowing from the middle-electrodes is determined through measuring the voltage, V, across 1, 100 and 470 Ω load resistors.

The first experiment (without the DC arc plasma) serves as the control experiment since there is no generation of electrons and ions. The voltage measured is assumed to be a systemic offset voltage (Figure 9). Moreover, the calculated absolute (average) offset voltage is 0.965 mV.

In the second experiment (arcing with plasma occurred), the absolute time-averages of the measured terminal voltage signals change significantly with respect to the applied load resistors. These terminal voltages are very low and consistent before the arc occurs. When the arc plasma is applied, the voltage signal amplitude increases and gradually decreases to lower levels when the arc plasma is not applied. Furthermore, the graphical representation of the acquired voltage signals helps to observe the overall signal magnitude and significant peaks. The increase in the voltage signal levels depicts the presence of the arc plasma, as shown in Figures 10, 11 and 12. In these figures, the horizontal axis signifies the time domain while the vertical axis represents the signal magnitude.

In all experiments, the actual voltage, V_{actual}, is the voltage measured across the 1, 100 and 470 Ω load resistors after subtracting the offset voltage from the average voltages in Figures 10, 11 and 12. The Faraday's current, I_{mhd}, and the optimum power from the MHD generator can also be determined from $I_{\mathrm{mhd}} = V_{\mathrm{actual}}/R_{\mathrm{L}}$, which is derived from the generating circuit in Figure 13.

The experimentation and the calculation results are summarized in Table 1. In this table, the maximum actual voltage (14.235 V) is obtained when 1 Ω load resistor is applied to the middle-electrodes. Therefore, based on the dimensions and size ($0.3 \times 0.1 \times 0.1$ m) of the MHD generator prototype used in the present study, the optimum power of about 0.203 mW is obtained from the middle-electrodes.

When comparing the results obtained in all the experiments, it can be clearly seen that the voltages measured are of the same order, that is, the flux of particles are similar. The voltage difference obtained

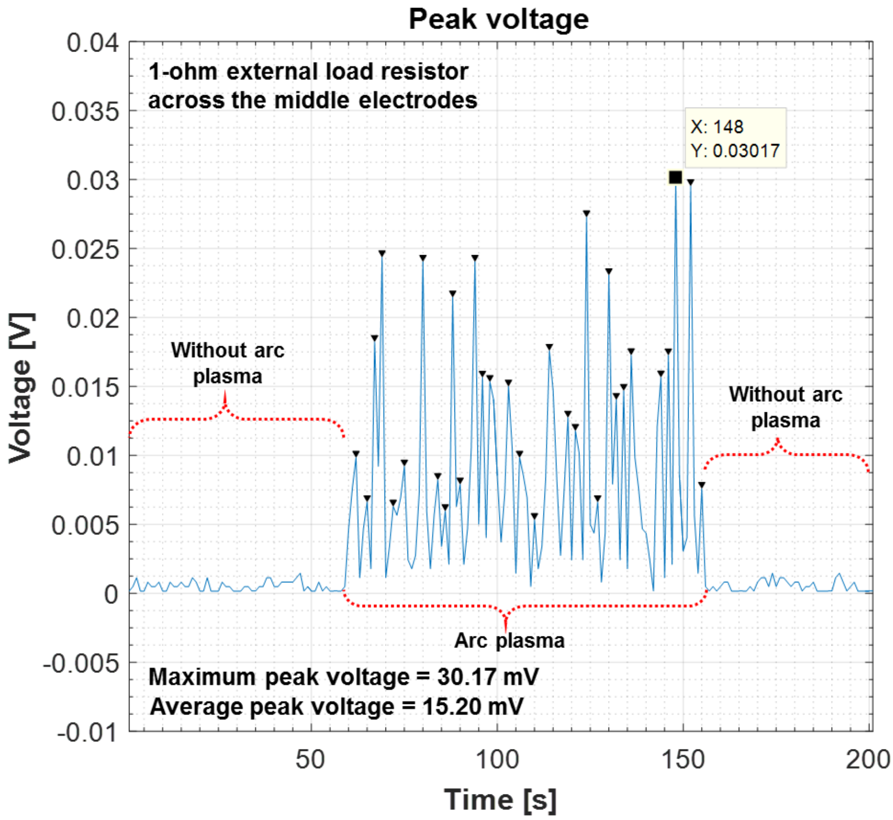

Figure 10. Average voltage measured across the middle-electrodes using $1\,\Omega$ resistor.

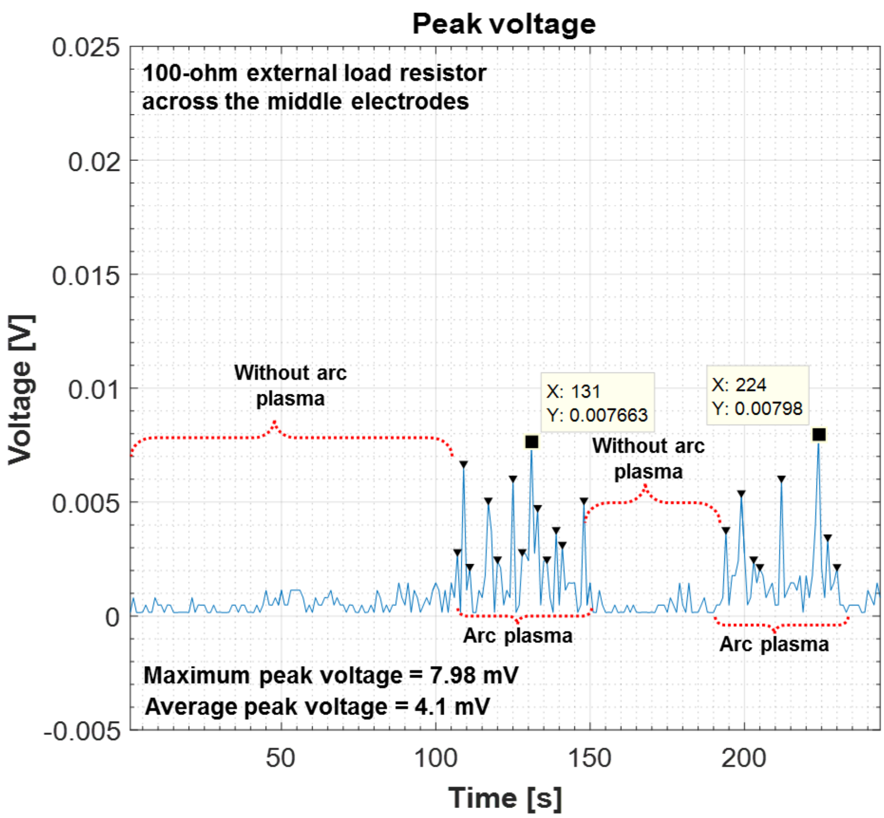

Figure 11. Average voltage measured across the middle-electrodes using $100\,\Omega$ resistor.

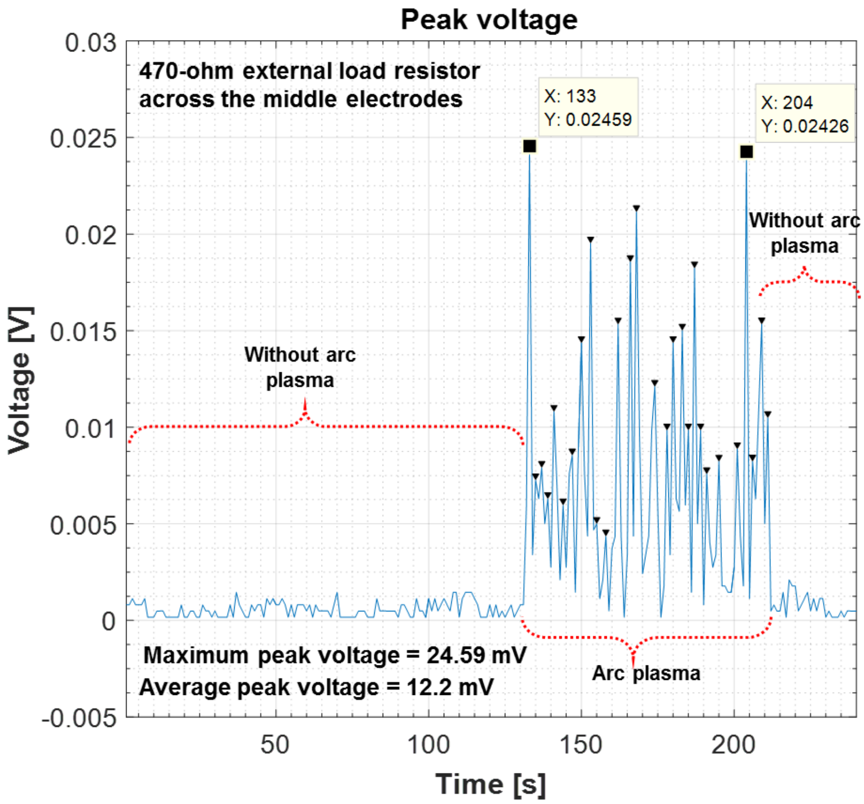

Figure 12. Average voltage measured across the middle-electrodes using 470 Ω resistor.

Measured parameters	Experiments with arc plasma		
External load resistor	1 Ω	100 Ω	470 Ω
Average voltage [mV]	15.2	4.1	12.2
Measurement offset voltage [mV]	0.965	0.965	0.965
V_{actual} — average minus offset voltage [mV]	14.235	3.135	11.235
Current, I_{mhd}, [mA]	14.235	0.031	0.024
MHD Generator Power [mW]	0.2026	0.0001	0.0003

Table 1. Measured power from the MHD generator under DC arc plasma experiment.

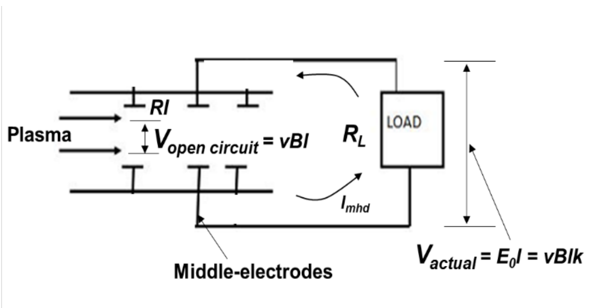

Figure 13. MHD power generating circuit.

when the 100 Ω resistor is applied may be due to low plasma levels inside the generator. Another reason for the difference between the power generated using 100 Ω and 470 Ω load resistors may be due to their resistance. Moreover, it is possible that some factors such as change of some consumable components shape due to heat and corrosion could, in long time, influence the plasma flow, which can cause fluctuations. For any possible future experiments, the authors recommend the use of a larger MHD generator and a higher velocity plasma source such as the ones used in large thermal plants.

7. Conclusion

This paper principally investigated the electric response of an MHD generator exposed to DC arc plasma conditions. For this purpose, a rectangular MHD duct prototype with segmented electrodes has been constructed. The round electrodes are recommended because it helped not only to simplify the experimental setup but also to minimize the experimental uncertainty that often arises from complex design and structures. From the DC arc plasma experiment, consistent time-average voltage measurements, which indicate a direct measurement of plasma and generation of power, were observed. These results also validate the measurement approach of the MHD generator with segmented electrodes and could be used to design a large MHD unit that can be incorporated to the existing conventional thermal plants.

Acknowledgements

The authors would like to thank the Cape Peninsula University of Technology (CPUT) and Council for Scientific and Industrial Research (CSIR) for providing financial support and the software used for the realization of this work.

References

[1] S.C. Kaushik, S.S. Verma, A. Chandra. Solar-Assisted Liquid Metal MHD Power Generation: A state of the Art Study. Heat Recovery Systems and CHP 15(7): 675-689, 1995. DOI:10.1016/0890-4332(95)90047-0

[2] B. Masood, M.H. Riaz, M. Yasir. Integration of magnetohydrodynamics (MHD) power generating technology with thermal power plants for efficiency improvement. World Applied Sciences Journal, 32(7): 1356-1363, 2014.

[3] A.O. Ayeleso, M.T.E. Kahn, A.K. Raji. Plasma Energy Conversion System for Electric Power Generation. In 12th International Conference on the Industrial and Commercial Use of Energy, (Cape Town, South Africa, 2015), P206-211. DOI:10.1109/ICUE.2015.7280270

[4] M. Ishikwa, M. Yuhara, T. Fujino. Three dimensional computational of Magnetohydrodynamics in a weekly ionized plasma with strong MHD interaction. Journal of Materials Processing Technology 181: 254-259, 2007. DOI:10.1016/j.jmatprotec.2006.03.032

[5] D.D. Vishal, S. Anand. The Future Power Generation with MHD Generators Magneto Hydrodynamics generation. International journal of electrical and electronics engineering 2(6): 2278-8948, 2013.

[6] N. Kandev. Numerical Study of a DC Electromagnetic Liquid Metal Pump: Limits of the Model. Proceeding of the Comsol conference, Hannover, 2012.

[7] S. Takeshita, C. Buttapeng, N. Harada. Characteristics of plasma produced by MHD technology and its application to propulsion systems. Vacuum 84: 685-688, 2010. DOI:10.1016/j.vacuum.2009.10.017

[8] L.P. Aoki, M.G. Maunsell, H.E. Schulz. A Magnetohydrodynamics study of behavior in an electrolyte fluid using numerical and experimental solutions. Thermical Engineering (Engenharia Termica) 11(1-2): 53-60, 2012.

[9] R.R. Parsodkar. Magneto Hydrodynamics Generator. International Journal of Advanced Research in Computer Science and Software Engineering 5(3): 541-546, 2015.

[10] W. Ritchie. Experimental Researches in a voltaic electricity and electromagnetism. Philosophical Transactions of the Royal Society of London 122: 279-298, 1932. DOI:10.1098/rstl.1832.0014

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

[12] P. Li, G. Barry, S. Castellanos, C. Chan, K. Do, C. Gamez, J. Kuhn, A. Leon. Power Generation Using Magnetohydrodynamic Generator with a Circulation Flow Driven by Solar-Heat-Induced Natural Convection. 2007. `http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.highlight/abstract/8630/report/F` [2018-02-01].

[13] C.A. Mgbachi. Design Analysis of Magnetohydrodynamic (MHD) Electrical Power Generation Technology. International Journal of Advancements in Research and Technology 4(10): 103-108, 2015.

[14] M. Anwari, S. Takahashi, N. Harada. Performance Study of a Magnetohydrodynamic Accelerator Using Air-Plasma as Working Gas. Energy Conversion and Management 46 (15-16): 2605-2613, 2005. DOI:10.1016/j.enconman.2004.12.003

[15] W. Xue, K. Kusumoto, K. Nezu. Relationship between Plasma Arc Cutting Acoustic and Cut Quality. Science and Technology of Welding and Joining 10: 44-49. 2005. DOI:10.1179/174329305X19376

[16] J. Grill. Guide to Plasma Arc Equipment. `http://weldguru.com/OLDSITE/plasma-arc-equipment.html` [2018-02-01].

[17] Robot Industrial Supplies. Plasma ARC Cutting. `http://www.robotindustrial.co.za/thermodyne16a` [2018-02-01].