



A simulation approach to a magneto-hydrodynamic-steam electrical power generation system
by Teodoro Canillas Robles

A thesis submitted in partial fulfillment of the requirements for the degree of DOCTOR OF
PHILOSOPHY in Electrical Engineering
Montana State University
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Abstract:

A mathematical model of a magneto-hydrodynamic-steam electrical power generation system was developed, incorporating the results of experimental and theoretical investigations conducted by various researchers, applicable to large power generation. A real gas at sub sonic condition (typical for large power generation) is used in the flow calculation. A quasi one-dimensional MHD generator model was used to explore the advantages of the model in the design of the control mechanisms for the system. The numerical techniques used in the simulation are described and the results of the simulation are presented. The behavior of the MHD generator in response to load changes are discussed. The dynamic model of the direct-current (DC) to alternating-current (AC) power converter is presented and the design parameters compatible with the MHD generator operation are discussed. The dynamic model of the steam plant and air heaters was developed and the results of the simulation of the model in response to changes in input conditions are shown. The design parameters of the steam plant for a 2000 megawatt (thermal input) MHD system are given.

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ELECTRICAL POWER GENERATION SYSTEM

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A thesis submitted in partial fulfillment
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DOCTOR OF PHILOSOPHY

in

Electrical Engineering

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August, 1975

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to the many people who have offered assistance during the course of his graduate work and thesis research. Special thanks are due to Professor Roy M. Johnson for his untiring guidance and encouragement. The helpful suggestions and constructive criticisms of Professor Robert F. Durnford and Professor Donald A. Pierre are greatly appreciated. The author is grateful to Professor James L. Knox for his effort in making it possible for the author to pursue graduate work at Montana State University.

The author is indebted to Dr. Paul E. Uhlrich and the Electrical Engineering department for the financial support and the use of the department's facilities during his stay at Montana State University. The scholarship grant sponsored by Mr. James C. Taylor is also gratefully acknowledged.

Finally, the author would like to thank his family and friends for their encouragement and support, especially his wife Angel for her patience, cooperation and encouragement during the course of the author's graduate study.

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LIST OF SYMBOLS

<u>Symbol</u>		<u>Page first Encountered</u>
a	electrode width, meter	38
	speed of sound, meters/sec	100
A	channel cross-sectional area, sq meter	28
b	electrode pitch, meter	38
b*	electrode pitch to electrode separation ratio	48
B	magnetic induction, webers/sq meter	3
c	speed of light, meters/sec	24
C _f	friction coefficient	65
c ₁	friction coefficient	31
C _h	convective heat transfer coefficient	32
C _g	specific heat of the gas, Joules/Kg-°K	66
C _p	specific heat of the gas at constant pressure	33
D	channel hydraulic diameter, meter	28
E	applied electric field, volts/meter	3
E _i	induced electric field, volts/meter	3
f	friction factor	31
F	force per unit volume	3
	friction force per unit volume	29
G	heat transfer per unit volume	29

<u>Symbol</u>		<u>Page first encountered</u>
g	local gravity, meters/sec ²	65
g _i	statistical weight of the ground state of the ion	35
g _o	statistical weight of the ground state of the neutral atom	35
h	specific enthalpy of the gas, Joules/Kg	23
	electrode separation, meters	38
I _L	load current, amperes	43
I*	dimensionless current	43
J	current density, amperes/ sq meter	3
K	loading parameter	3
k _x		
k _y	coefficients in equations 2.64-2.65	48
k		
L	channel length, meters	5
M	molecular weight of the working fluid, Kg	34
n _e	electron density	35
n _i	ion density	35
n _s	neutral seed atom concentration	35
p	pressure, Newtons/sq meter	5
P	Electrical power, Joules/sec	139
P _i	Electrical power input	5
P _o	Electrical power output	5

<u>Symbol</u>	<u>Page first encountered</u>
P_r Prandtl Number	32
q_c convective heat transfer to the wall, Joules/sec-meter	31
q_g convective heat transfer to the wall	65
q_r radiative heat transfer to the wall	31
q_s heat transfer to the fluid	65
R gas constant	23
recovery factor	32
Re Reynolds number	31
Rm magnetic Reynolds number	26
S Boltzman's constant, Joules/ $^{\circ}K$	34
t time	21
T temperature	32
T_{aw} adiabatic wall temperature	32
T_w wall temperature	32
u gas axial velocity	3
u, u' parameter from Dzung [116] in eq. 2.26-2.28	48
\bar{v} gas velocity	21
v, v' parameter from Dzung [116] in eq. 2.26-2.28	48
V electric potential	46
volume	67
w mass flow rate, Kg/sec	65

<u>Symbol</u>		<u>Page first Encountered</u>
W	mass, Kg	68
x,y,z	space coordinates	3
α	cross-connection parameter	42
β_e	Hall parameter, electron	27
β_i	Hall parameter, ion	27
δ	boundary layer thickness, meter	52
ϵ	permittivity, Farads/meter	24
ϵ_g	gas emissivity	34
ϵ_w	wall emissivity	34
κ	thermal conductivity , Joules- ^o K/sec-meter	22
μ	permeability, henry/meter	24
η	gas viscosity, poise	23
η_e	electrical (isentropic) efficiency	43
ω	angular frequency, radians/sec	25
ϕ	electrode voltage drop parameter	45
Φ	electric potential, volts	48
ρ	mass density , Kg/cu meter	21
ρ	charge density, Coulombs/cu meter	21
σ	electrical conductivity, mho/meter	3
τ	shear stress	21
	Hall angle	49

SymbolPage first
encountered

τ_w wall shear stress

31

Subscripts

d diffuser
 e economizer
 g gas
 h high pressure turbine
 i inlet
 l low pressure turbine
 o outlet
 p radiant section
 r reheater
 s primary superheater, steam
 w wall
 ac air compressor exit
 al low temperature air heater exit (air side)
 do diffuser exit (steam side)
 ei high temperature economizer inlet (steam side)
 eo high temperature economizer exit (steam side)
 em high temperature economizer metal
 ge high temperature economizer exit (gas side)

Subscript

gp	radiant section exit (gas side)
gr	reheater exit (gas side)
gs	primary superheater exit (gas side)
hi	high pressure turbine inlet (steam side)
ho	high pressure turbine exit (steam side)
li	low pressure turbine inlet (steam side)
lo	low pressure turbine exit (steam side)
pm	radiant section metal
rm	reheater metal
si	primary superheater inlet (steam side)
so	steady state or design value (steam side)
sm	primary superheater metal
gah	high temperature air heater exit (gas side)
gal	low temperature air heater exit (gas side)
alm	low temperature air heater metal

ABSTRACT

A mathematical model of a magnetohydrodynamic-steam electrical power generation system was developed, incorporating the results of experimental and theoretical investigations conducted by various researchers, applicable to large power generation. A real gas at subsonic condition (typical for large power generation) is used in the flow calculation. A quasi one-dimensional MHD generator model was used to explore the advantages of the model in the design of the control mechanisms for the system. The numerical techniques used in the simulation are described and the results of the simulation are presented. The behavior of the MHD generator in response to load changes are discussed. The dynamic model of the direct-current (DC) to alternating-current (AC) power converter is presented and the design parameters compatible with the MHD generator operation are discussed. The dynamic model of the steam plant and air heaters was developed and the results of the simulation of the model in response to changes in input conditions are shown. The design parameters of the steam plant for a 2000 megawatt (thermal input) MHD system are given.

Chapter I

INTRODUCTION

1.0 System Simulation

The goal of developing a large Magnetohydrodynamics (MHD) Electrical Power Generation System has created a need for the study of the system performance under normal and abnormal operating conditions. Simulation provides one means for investigating the behavior of the system and aids in predicting system performance under specified operating conditions. The system may be represented by a scaled, pilot or analytical (mathematical) model. After considering the advantages and the disadvantages of each model, such as flexibility, cost, time and responsiveness, the mathematical model was selected for this study.

The mathematical model consists of partial and ordinary differential equations which accurately define the system. Since the simulation is implemented by the use of a digital computer, numerical methods are utilized in solving the defining equations.

1.1 Open-cycle MHD-Steam Electrical Power Generation

Magnetohydrodynamics or more correctly magnetofluidmechanics is the science dealing with the interaction between an electrically

conducting fluid and a magnetic field. For a compressible fluid, part of the kinetic and thermal energy is converted directly into electricity. A simple MHD generator is shown in Figure 1.1. The generator consists of a channel of rectangular cross-section with one pair of electrically conducting electrodes and one pair of electrically insulating walls. The load is connected between the electrodes, and the magnetic field is perpendicular to the insulating wall.

In an open-cycle MHD generator, the fluid consists of the combustion gases from the burning of fossil fuels, seeded with an alkali metal to increase the electrical conductivity. A combustion temperature of 2500° Kelvin to 2800° Kelvin is necessary to provide enough electrical conductivity and thermal energy for an efficient energy conversion.

The fluid flow is accelerated through a nozzle and enters the MHD duct. The magnetic field acts to decelerate the charge carriers in the fluid stream. In the absence of energy transfer from the other particles, the electrons spin in a circular orbit about the transverse axis in the magnetic field. The fluid stream forces the electrons through the applied magnetic field. The net effect is a reduction in the kinetic energy of the fluid stream and an equivalent direct current electrical power is induced in the external load circuit. The coordinate system used to describe the phenomena taking

place in the generator is shown in Figure 1.2.

If a steady state condition is assumed, and one-dimensional flow approximations are used, the voltage induced by the interaction of the velocity field with the magnetic field is

$$E_i = uB \quad (1.1)$$

and the current density is

$$J = \sigma(uB - E) \quad (1.2)$$

where the notation is defined in the symbol reference list.

Following Rosa [1], a loading factor (K) may be defined as

$$K = E/uB \quad (1.3)$$

so that

$$J = \sigma(1 - K)uB \quad (1.4)$$

The power delivered to the load per unit volume is

$$P_o = JE = \sigma K(1 - K)u^2 B^2$$

The current interacts with the magnetic field to induce a force (F) opposed to the fluid motion. The force on a unit cube of the fluid is

$$F = JB = \sigma(1 - K)uB^2 \quad (1.5)$$

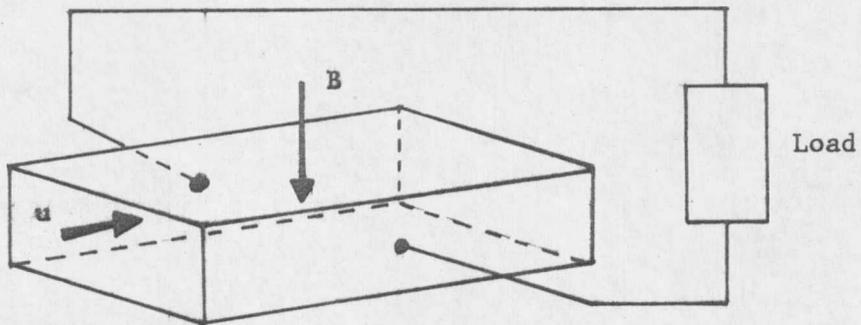


Figure 1.1. A Simple MHD Generator

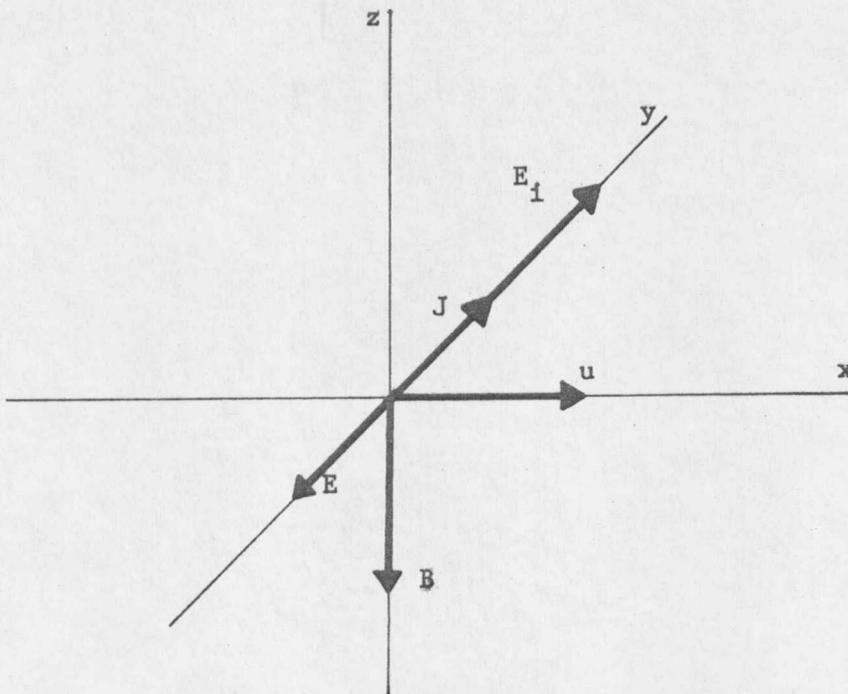


Figure 1.2. Coordinate System.

In order for the gas to move through the generator, a pressure difference between the entrance and the exit must exist and is given by (neglecting friction effects)

$$p = FL = \sigma(1 - K)uB^2L \quad (1.6)$$

where L is the generator length.

The work done by the gas in pushing itself through the magnetic field is

$$P_i = Fu = \sigma(1 - K)u^2B^2L \quad (1.7)$$

Thus the electrical efficiency is

$$\eta_e = P_o/P_i = K \quad (1.8)$$

Since the energy dissipation in this device occurs within the working fluid, it is not lost energy, and can still be recovered in a bottoming plant.

In the MHD generator, the electrical conductivity of the fluid decreases rapidly with the decreasing gas temperature, thus it becomes uneconomical to extract electrical power directly from the fluid by the MHD process below a fluid temperature of 2100°K . The thermal energy of the fluid leaving the MHD generator can be used for heating the air needed in the combustion process (to attain high combustion

temperature) and to produce steam for a steam turbine to generate more power (see Figure 1.3). The MHD generator thus operates as a topping plant for a steam-electric power plant making it possible to obtain higher thermal efficiency than existing conventional thermal electric power plants.

1.2 Historical Review

Magnetohydrodynamics Electrical Power Generation

Magnetohydrodynamics electrical power generation is based on the Faraday effect in which a voltage is induced in a circuit when a magnetic field linking the circuit is changed. This effect was first observed by Michael Faraday [2] in 1831, when he experimented with mercury flowing through a magnetic field. Industrial experiments with gaseous MHD were conducted by Karlovitz [3] in the period 1938 to 1944. The generator failed to operate because of the low conductivity of the working gas.

Extensive work started again in the late fifty's and early sixty's in the United States [4-8]. The first combustion experiment was performed at Westinghouse Electric Corp. [8] and followed by similar experiment [9]. The cycle analysis of the MHD electrical power generation system [10-17] showed that if a MHD generator is operated above 2500°K , and used as a topper for a steam plant, high thermal efficiencies can be obtained. Considerable work had been done

