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

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 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 dis cussed. 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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LIST OF SYMBOLS

Symbol		Page first Encountered
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-^oK	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

Symbol		Page first encountered
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, k	coefficients in equations 2.64-2.65	48
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

Symbol		Page first encountered
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/^{o}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

Symbol		Page first Encountered
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

Symbol		Page 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^{o} Kelvin to 2800^{o} 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

$$E_i = uB \tag{1.1}$$

and the current density is

$$J = \sigma(uB-E) \tag{1.2}$$

where the notation is defined in the symbol reference list.

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

$$K = E/uB \tag{1.3}$$

so that

$$J = \sigma(1 - K)uB \tag{1.4}$$

The power delivered to the load per unit volume is

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

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

$$F = JB = \sigma(1 - K)uB^2 \tag{1.5}$$

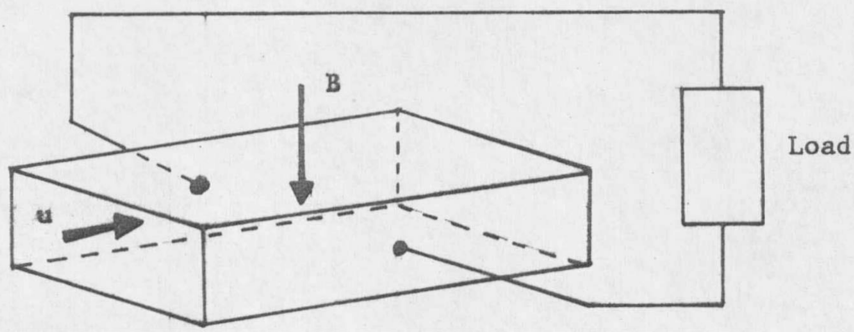

Figure 1.1. A Simple MHD Generator

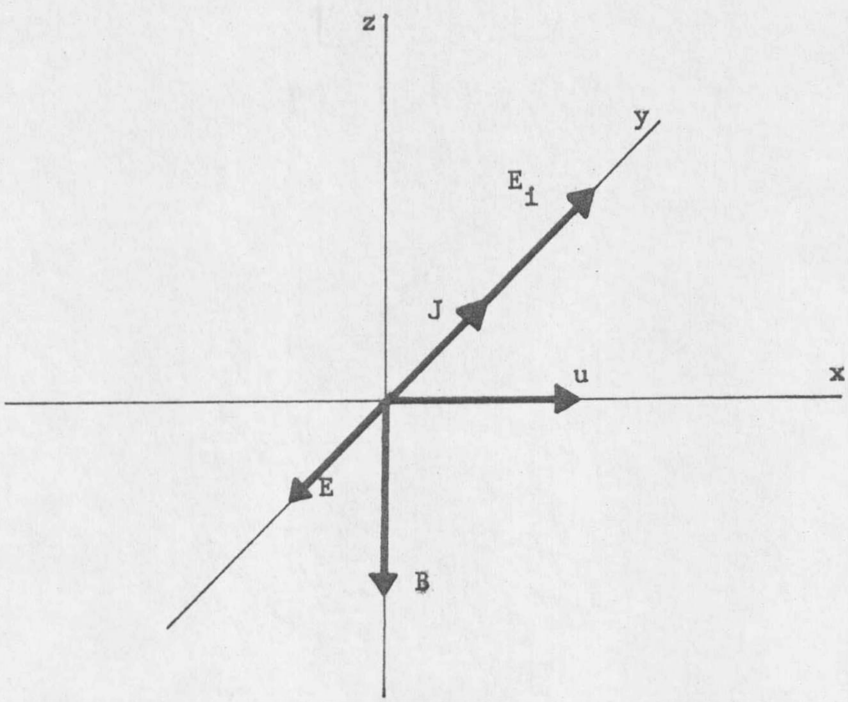

Figure 1.2. Coordinate System.

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)

$$p \simeq FL = \sigma(1 - K)uB^2L \tag{1.6}$$

where L is the generator length.

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

$$P_i = Fu = \sigma(1 - K)u^2B^2 \tag{1.7}$$

Thus the electrical efficiency is

$$\eta_e = P_o/P_i = K \tag{1.8}$$

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^oK. 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