EFFECTS OF INSTALLED SDR ON STABILITY OF MHD GENERATION SYSTEM

Nobuhiro HAYANOSE and Daisuke SEO
Department of Electrical Engineering, Kobe City College of Technology
Kobe City 651-2194, Japan, e-mail: hayanose@kobe-kosen.ac.jp
Yoshitaka INUI
Department of Electrical and Electronic Engineering, Toyohashi University of Technology, Toyohashi City 441-8580, Japan, e-mail: inui@eec.tut.ac.jp
Motoo ISHIKAWA
Institute of Engineering Mechanics and Systems, University of Tsukuba
Tsukuba City 305-8573, Japan, e-mail: misikawa@kz.tsukuba.ac.jp

ABSTRACT

Effects of installed SDR (System Dumping Resistors) on the stability of open-cycle disk MHD generator and synchronous generator system connected in parallel to power transmission lines are numerically studied. Usually the SDR is used to absorb the output energy of synchronous generator and to get stability of the power transmission system when faults occur in the A.C. power transmission lines.

In this paper, we propose to apply the SDR at the D.C. lines between the MHD generator and the primary side of connected line-commutated inverters for system stability. The MHD system includes MHD generator, synchronous generator, line-commutated inverter and transmission network. We show by a time dependent numerical analysis that the SDR is effective for the system stability when faults occur in the transmission line.

1. Introduction

This study is carried out as a part of the wide research on large-scale MHD generation systems. The MHD generation system consists of MHD generator as a topping cycle, of steam-turbine generator as a bottoming cycle and of power transmission network. Coal fired gas is used as the working fluid in this study. For the thermal input of 1,000MW the MHD generator produces power output of class of 200MW, the synchronous generator dose class of 300MW, and overall thermal efficiency is above 50%.(1) The D.C. output power of MHD generator should be converted into the three-phase A.C. power by the inverter system and should be supplied to the power transmission network.

Faults in the power transmission line give remarkable fluctuations to the MHD generator and to the electric power transmission network. Then, it is required to take countermeasures for stable operation of the generation system. Usually the fluctuations do not converge to a stable state after cutting off the faulted transmission lines because the commutation failure occurs in the inverter system after the line faults.

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It has been shown that line-faults give remarkable influences to the MHD generator and the transmission network and that the control of the inverter is required for the stable operation of the generation system\(^{(2,3)}\). The fluctuations do not converge to a stable state after cutting off the fault lines. It has been shown that the control of the inverter angle in addition to cutting off the faulted lines is effective to remove the fluctuations of the MHD system\(^{(4)}\).

Usually the SDR is installed at the AC primary grid of transmission line for the system stability. The SDR is used to absorb the output energy of synchronous generator and to get stability of the power transmission system when line faults occur in the transmission line.

In this paper, we propose to install SDR(System Dumping Resistor) circuits in the MHD generation system. The SDR circuits are installed at the D.C. lines between the MHD output terminal and the D.C. primary side of the inverter. We show by a time dependent numerical analysis that the SDR circuits are effective for the system stability.

2. Analyzed system

The analyzed model of power system is made for a large-scale disk type MHD generator where the thermal input for the system is 1300MW, the MHD generator output 235MW and the synchronous generator output 300MVA. The voltage and frequency of the transmission-line are 275kV and 60Hz, respectively.

Figure 1 depicts the schematic diagram of MHD generation system. The electrical system of the MHD generation consists of disk type MHD generator, synchronous generator and electrical power network. The power network system consists of two SDR circuits, two line-commutated inverters, four transformers, capacitive compensator, harmonic filters, and double circuit transmission lines. The infinite-bus is assumed in the secondary end of the transmission lines.

We propose a cascade connected line-commutated inversion system for the generator. Double circuit transmission lines are connected between the bus bar of power grid and the infinite bus. The power transmission system is designed to connect the disk type generator, which has two power-output-terminals for different values of power. Then, the harmonic filters of 5\(^{th}\), 7\(^{th}\), 11\(^{th}\), 13\(^{th}\) harmonics and high pass and the capacitive compensator for phase modification are also connected to the bus bar because the line-commutated inverter generates large reactive power. The SDR circuits and inverters are connected to the upstream and downstream output terminals of the generator channel.

The SDR circuits are installed in the DC primary side of the inverter system with the DC switch for system stability\(^{(4)}\). The SDR circuits are switched on by using the thyristor switches in addition to cutting off the faulted transmission lines when the faults occur in transmission lines. The inverter system is cut off after a short delay time. This procedure is effective to remove the fluctuations of the MHD generation system.

![Figure 1 Schematic diagram of MHD generation system](image)

The disk MHD generator shown in Fig. 2 is a subsonic inflow type and has two pairs of power output terminals. It has been reported in previous works that an open-cycle disk type generator is probably unstable\(^{(6,7)}\). It has been
also shown that large-scale disk MHD generator is operated stably with the conditions of subsonic inflow and two pairs of load at designed conditions by the linear stability analysis (4). The working fluid is the coal-fired combustion-gas, where the thermal input is 1300MW and the MHD generator output is about 235MW by two-pair loads.

![Figure 2 Schema of inflow disk type MHD generator.](image)

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![Figure 3 Schema of synchronous generator.](image)

Figure 3 Schema of synchronous generator.

Figure 3 depicts the three phase synchronous generator of two-pole revolving-field cylindrical rotor type. The generator is analyzed by the two-reaction model of d and q axis. The synchronous generator is described as a function of the rotor position by the voltage equations taking into account the magnetic coupling among three-phase armature windings, main field winding and two-axis damper winding, in addition to the swing equation(5).

The output power of the synchronous generator is 300MVA and the revolution is 3600rpm.

3. Basic Equations

3.1 Disk Type MHD Generator

The governing equations of the disk type generator in Fig. 2 are given by the gasdynamical conservation equations in the polar coordinates. The equations of the quasi-one-dimensional conservation equations are as follows:

\[
\frac{\partial V}{\partial t} = -\frac{\partial F}{\partial r} + H
\]  
(1)

\[
V = \begin{bmatrix}
\rho \\
m_r \\
m_a \\
\varepsilon
\end{bmatrix}, \quad F = \begin{bmatrix}
m_r \\
\frac{m_r^2}{\rho} + p \\
\frac{m_r m_a}{\rho} \\
\frac{m_a (\varepsilon + p)}{\rho}
\end{bmatrix}
\]

\[
H = \frac{-1}{A} \frac{\partial A}{\partial r} + \begin{bmatrix}
m_r \\
\frac{m_r^2}{\rho} \\
\frac{m_r m_a}{\rho} \\
\frac{m_a (\varepsilon + p)}{\rho}
\end{bmatrix}
\]  
(2)

\[
\begin{bmatrix}
0 \\
\frac{m_r^2}{\rho} \\
\frac{m_r m_a}{\rho} \\
\frac{m_a (\varepsilon + p)}{\rho}
\end{bmatrix} + \begin{bmatrix}
0 \\
J_a B \\
J_r B \\
J, E_r
\end{bmatrix}
\]

State of gas:

\[
p = \rho RT
\]

where \( A \) is the channel cross-section, \( B=(0,0,B) \) the applied magnetic flux density, \( E=(E_r, E_r, 0) \) the electric field, \( J=(J_r, J_r, 0) \) the current density, \( u=(u_r, u_r, 0) \) the gas velocity, \( \rho \) the mass density, \( p \) the pressure, \( T \) the temperature, \( \varepsilon \) the internal energy density, \( f \)
=(r, \cdot 0)$ the friction losses, $q$ the heat loss, $h$ the enthalpy, and $R$ the gas constant.

MacCormak's explicit predictor-corrector scheme\(^{(0)}\) is applied for the time-dependent calculation of the equations (1) and (2).

Electrical governing equations in MHD channel are given by Maxwell equations as follows:

Current continuity:

\[ J_r = \frac{1}{A} \]  \hspace{1cm} (4)

Electric field:

\[ E_\theta = 0 \]  \hspace{1cm} (5)

The generalized Ohm's law is as follows:

\[ J_r = -\frac{\sigma}{1 + \beta^2} \left( \beta_c (E_r + u_r B) - \beta_c (E_\theta - u_\theta B) \right) \]
\[ J_\theta = \frac{\sigma}{1 + \beta^2} \left( \beta_c (E_\theta + u_\theta B) - \beta_c (E_r - u_r B) \right) \]  \hspace{1cm} (6)

where $I$ is the output current of MHD generator. $\cdot$ and $\cdot$ are given as following equations.

\[ \sigma_r = \frac{\sigma}{G}, \quad \sigma_\theta = \frac{\beta}{G}, \quad G = 1.1 \]  \hspace{1cm} (7)

Working gas is a coal-fired gas seeded with the potassium of 1wt\% by $K_2CO_3$. $\cdot$ is the conductivity and $\cdot$ the Hall parameter. These are given by approximate functions of $p$ and $T$\(^{(0)}\).

### 3.2 Synchronous generator

The synchronous generator driven by the steam turbine is assumed as the two-pole cylindrical rotor type. The mathematical description for the synchronous generator in Fig. 3 is usually given by Park's transformation\(^{(8,10,11)}\). A simplified model which is often used for a stability analysis is the voltage behind transient inductance model. The governing equations for the d and q axes of the generator are as follows:

Governing equations:

\[ \frac{de_d}{dt} = \frac{1}{T_{d_0}} \left[ \frac{x_{d'} - x_{d'd}}{x_{d'} - x_{d''d}} e_d + \frac{x_{d'd} - x_{d''d}}{x_{d'} - x_{d''d}} e_{d''} \right] \]  \hspace{1cm} (8)

\[ \frac{de_q}{dt} = \frac{1}{T_{q_0}} \left[ \frac{x_{q'} - x_{q'd}}{x_{q'} - x_{q''d}} e_q + \frac{x_{q'd} - x_{q''d}}{x_{q'} - x_{q''d}} e_{q''} \right] \]

\[ \frac{de_d}{dt} = \frac{1}{T_{d_0}} e_d + \frac{x_{d'd}}{x_{d'} - x_{d''d}} \left( e_d'' - \frac{x_{d''d}}{x_{d'} - x_{d''d}} i_d \right) \]

\[ \frac{de_q}{dt} = \frac{1}{T_{q_0}} e_q + \frac{x_{q'd}}{x_{q'} - x_{q''d}} \left( e_q'' - \frac{x_{q''d}}{x_{q'} - x_{q''d}} i_q \right) \]

Swing equations:

\[ \frac{d\omega}{dt} = \omega - \omega_0 \]

\[ \frac{d\omega_0}{dt} = \frac{\omega_0}{2H} \left[ \frac{p_T - p_s - D}{\omega_0} (\omega - \omega_0) \right] \]  \hspace{1cm} (9)

Auxiliary equations:

\[ v_d = e_d' + x_{d'd} \omega_0 \]
\[ v_q = e_q' - x_{q'd} \omega_0 \]

where $e$ is e.m.f. voltage, $i$ current, $x$ reactance, $T$ time constant, $\cdot \cdot$ angular velocity, $H$ inertia constant, $D$ damper constant, $p_T$ mechanical input, $p_s$ electrical output. The subscripts $d$ and $q$ indicate the d and q axis, superscripts ' and " indicate transient and sub transient states, respectively.

The AVR and the governor are given by the block diagrams shown in Fig. 3 and 4, respectively, which are simple models of controller of a turbine and a synchronous generator.

The Runge-Kutta-Gill method is applied to solve the governing equations of synchronous generator (8) to (10) in addition to the equations of AVR and governor.

The two-phase voltages of $d$ and $q$ axis are converted to the three phase voltages of $a$, $b$ and $c$ by the Park's conversion.

![Figure 3 Broc diagram of AVR.](image-url)
3.3 Power Transmission Network

The power transmission network except for the MHD generator and the synchronous generator is simulated by using Bergeron's equivalent-circuits\(^{(10)}\). The network circuit consists of R-L-C impedance branches, and infinite voltage sources. Each impedance branch in the circuit is replaced to an equivalent resistance in parallel with equivalent current source, which are converted by integration with the trapezoidal rule. Numerical transient voltages and currents of the network circuits are solved by a nodal admittance matrix method.

\[ V_i - V_j = L \frac{di_{ij}}{dt} \]  \hspace{1cm} (11)

which must be integrated from \( t \rightarrow t + \Delta t \) to \( t \)

\[ i_{ij}(t) = i_{ij}(t - \Delta t) + \frac{1}{L} \int_{t-\Delta t}^{t} \left[ V_i(t) - V_j(t) \right] \, dt. \]  \hspace{1cm} (12)

Using the trapezoidal rule of integration, the branch current is given by

\[ i_{ij}(t) = \frac{1}{R_L} \left[ V_i(t) - V_j(t) \right] + I_{ij}(t - \Delta t) \]  \hspace{1cm} (13)

where the equivalent resistance \( R_L \) is

\[ R_L = \frac{2L}{\Delta t} \]  \hspace{1cm} (14)

and the equivalent current source \( I_{ij} \) is known from the past history

\[ I_{ij}(t - \Delta t) = i_{ij}(t - \Delta t) \]

\[ + \frac{1}{R_L} \left[ V_i(t - \Delta t) - V_j(t - \Delta t) \right]. \]  \hspace{1cm} (15)

The equivalent impedance for \( L \) is shown in Figure 5(b).

The impedance R-L of a branch i, j shown in Fig. 6(a) is given by

\[ V_i - V_j = L \frac{di_{ij}}{dt} + R_L i_{ij} \]  \hspace{1cm} (15)

The equation is integrated into

\[ i_{ij}(t) = \frac{1}{R + R_L} \left[ V_i(t) - V_j(t) \right] + I_{ij}(t - \Delta t) \]  \hspace{1cm} (16)

where \( R_L \) and \( I_{ij} \) are as follows:

\[ R_L = \frac{2L}{\Delta t} \]  \hspace{1cm} (17)

\[ I_{ij}(t - \Delta t) = \frac{R - R_L}{R + R_L} i_{ij}(t - \Delta t) \]

\[ + \frac{1}{R + R_L} \left[ V_i(t - \Delta t) - V_j(t - \Delta t) \right]. \]  \hspace{1cm} (18)

The equivalent circuit for R-L is shown in Figure 6(b). All branches of the network circuit as R-L-C are replaced to equivalent impedance branches by the same method\(^{(11)}\). It is very simple to establish the nodal equations for a complicated network circuit.
4. Numerical Conditions

The disk type generator is conceptually designed by rating conditions shown in Table 1, where the thermal input of the generator is 1300MW. Since reflection waves must be considered in subsonic channels, a nozzle of 0.2m and a diffuser of 0.4m are included in the disk generator of length of 2m.

Table 2 shows performances of the designed MHD generator. The total output of 235MW is a summation of 151MW at upstream and 84MW at downstream of MHD channel at the steady state. The e.m.f voltages of the upper- and down-stream are 30.0kV and 38.0kV, respectively.

Table 1. Rating condition of disk generator

| Thermal input | 1300MW |
| Inlet stagnation temperature | 2700K |
| Inlet stagnation pressure | 4.2atm |
| Inlet Mach number | 0.9 |
| Inlet radial flow velocity | 370m/s |
| Inlet swirl ratio | 2 |
| Applied B field | 8.5T |
| Channel length | 4m |
| Inlet radius | 6m |
| Outlet radius | 2m |
| Nozzle length | 0.2m |
| Diffuser length | 0.4m |

Table 2. Performance of two-pairs loading disk generator. (inlet r=6m → outlet r=2m)

| Stagnation temperature | 2700k → 2259K |
| Static temperature | 550K → 2195K |
| Stagnation pressure | 4.2atm → 1.0atm |
| Static pressure | 2.64atm → 0.84atm |
| Mach number | 0.90 → 0.54 |
| Swirl ratio | 2.0 → 0.77 |
| Electrical output | 234.7MW |
| Enthalpy efficiency | 18.1% |
| Output voltage | 15.3kV (4m~6m) |
| Heat output | 12.0kV (2m~4m) |
| Output current | 9.85kA(4m~6m) |
| | 7.00kA(2m~4m) |

Table 3 lists rating conditions of synchronous generator, AVR and governor main elements of the transmission circuit, where the power output of the synchronous generator is 300MVA, the power factor 0.85, the terminal voltage 13.75kV, and the frequency 60Hz.

Table 4 lists rating conditions of main elements of the transmission circuit, where the power transmission lines voltage is 275kV, and the frequency 60Hz.

Table 3. Rating conditions of synchronous generator, AVR and governor.

<table>
<thead>
<tr>
<th>Synchronous generator</th>
<th>AVR</th>
<th>Governor</th>
</tr>
</thead>
<tbody>
<tr>
<td>H = 4pu</td>
<td>D = 1pu</td>
<td></td>
</tr>
<tr>
<td>x_d = 1.7pu</td>
<td>x_q = 1</td>
<td></td>
</tr>
<tr>
<td>x' = 0pu</td>
<td>x_q = 1.2pu</td>
<td></td>
</tr>
<tr>
<td>T_d' = 6s</td>
<td>T_Q = 0.3s</td>
<td></td>
</tr>
<tr>
<td>T_e = 0.015s</td>
<td>T_e = 0.025s</td>
<td></td>
</tr>
<tr>
<td>K_A = 30</td>
<td>T_A = 0.1s</td>
<td></td>
</tr>
<tr>
<td>K_G = 20</td>
<td>T_G = 2s</td>
<td></td>
</tr>
</tbody>
</table>

5. Simulation Results

The behavior of the MHD generator, synchronous generator and network circuits are solved iteratively and combined each other through the voltages and currents at each
time steps.

In this study, we assume that the 3-phase short-circuit fault and single-phase grounding fault occur at a single-line in the double-circuit transmission-line when the MHD power system is operated at the steady state. The nominal operating condition is used as the initial condition for all simulation cases, where the inverter control angle is 140°. The calculations are carried out to confirm the stability of the MHD generation system controlled by the proposed method of the SDR circuit in the following 4 cases:

Case 1: The SDR circuits and the circuit breaker in the faulted line are not operated when the 3-phase short circuit fault occurs.

Case 2: The SDR circuits are not operated but the circuit breaker in the faulted line is operated when the fault occurs.

Case 3: The SDR circuits and the circuit breaker in the faulted line are operated but the inverter system is not re-operated when the fault occurs.

Case 4: The SDR circuits and the circuit breaker in the faulted line are operated when the fault occurs. After the removal of the fault the inverter system is re-operated and the faulted line is reconnected by the circuit breaker.

It is assumed that the line faults occur at t=40ms, the circuit breaker in the faulted line is operated at 123.4ms (5 cycles after the fault), and the SDR circuits are automatically operated when the MHD output currents increase more than 125% of the nominal values after the fault. The inverters are cut off at a short delay after the operation of SDR. The inverters are re-operated at 300ms (260ms after fault) and the faulted line is reconnected at 310ms (270ms after fault). The SDR circuits are cut off when the inverter system is re-connected to the MHD power system.

We only show results of the simulation for Case 1 and Case 3 because the simulation results of Case 1 and Case 3 are almost the same as those of the Case 2 and Case 4.

Figure 5 depicts for the Case 2, the time variations of the MHD output currents of upstream and downstream of MHD channel, the gas velocity in the MHD channel and the angular velocity of the synchronous generator. It is clear that large fluctuations occur in all values in Figure 5. The MHD output currents increase more than 2.5 times of the nominal values within 0.5sec. It is shown that the commutation failure occurs in the line-commutated inverter after the fault. Then the gas velocity and angular velocity are remarkably fluctuated. The MHD system becomes unstable and the fault currents can damage the electrodes of MHD generator and the thyristors in the inverters.

Figure 6 depicts for the Case 4, the time variations of the MHD output currents of upstream and downstream of MHD channel, the gas velocity in the MHD channel and the angular velocity of the synchronous generator. The maximum values of MHD currents are restricted about 125% of the nominal values. The operation of the case 4 is effective to makes small the fluctuations of the MHD currents and gas-velocity. The fluctuation of the angular velocity reduces with time. It is expected that all of the variations converge to the initial values with time.

Next are results of the one-line grounding for the Case 4. Figure 7 depicts the time variations of the MHD output currents of upstream and downstream of MHD channel, the gas velocity in the MHD channel and the angular velocity of the synchronous generator. The results show that fluctuations are to be almost the same as the case of Fig. 6 and are slightly small.

Figures 6 and 7 show clearly that the SDR circuits are effective to make stable the MHD generation system and to reduce the damages of the MHD generation system when the faults occur in the system.
(a) MHD output currents

(b) Gas velocity of r-direction in the MHD channel

(c) Angular velocity of synchronous generator

6. Conclusions

In this paper, the authors propose to install SDR circuits for stabilization of the MHD generation system connected to the power transmission system. The SDR circuits are installed in the DC primary side of the inverter system and the SDR circuits are operated when the faults occur in the power transmission system.
It has been shown that the faults give remarkable influences to the MHD generator system, but all values of the system become stable when the SDR circuits are operated after the fault. The SDR circuits are effective to reduce the damages of the MHD generator and the inverters and to make stable the MHD generation system when the faults occur in the system.

![Graph](image)

(a) Gas velocity of r-direction in the MHD channel

![Graph](image)

(b) Angular velocity of synchronous generator

Figure 7 Variations when the SDR and the circuit breaker in the faulted line are operated after the one-phase grounding fault. Then the inverter system is re-operated and the faulted line is re-connected.

(a) References


