Analysis of Transiently Stable Control of Commercial-Scale MHD Generator Connected to Power Network

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Abstract

Transiently stable control of MHD generators in the case of electric power line faults is an important subject for commercialization of MHD electric power stations that realize high efficiency and low environmental pollution. The authors propose and investigate a new improvement method of transient stability under the power line fault condition for the MHD generator through time-dependent numerical simulations of a total interconnecting system between the MHD generator and the electric power transmission network. The simulation model is assumed to consist of a commercial-scale open-cycle subsonic inflow disk type MHD generator with two pairs of the output electric power terminals, d.c. reactors, cascade-connected two line-commutated inverters, filters, double-circuit super-high-voltage transmission lines and infinite bus. The thermal input of the MHD generator is 1300 MW and the electrical power output is 235 MW with the channel length of 4 m using coal-fired combustion gas plasma as a working fluid and selecting the rated control angle of the inverter as 140.3 degrees. The rated effective line voltage and frequency are 275 kV and 60 Hz, respectively. The analysis is directed at the study of electrical and gas dynamical behavior under the condition of full interaction between the MHD generator and the electric power transmission network. The electric current flowing into the inverter at the transient state is closely related to the d.c. inductances between the MHD generator and the line-commutated inverter.

The authors propose and investigate an improvement method of the transient stability of the MHD generator, which only manipulates the control angle of inverter under the condition of the electric power line fault. To confirm the validity of this proposed control method, numerical simulations are performed in the cases the control angle of inverter is reduced to various levels between 90 and 140.3 degrees just after the fault occurs, and it is successfully found out that the stable operation of the MHD generator is realized after cutting off the fault in the cases the control angle of inverter is reduced to 125 degrees and below.

Numerical simulations are executed in the cases the control angle of inverter is at first reduced to 125 degrees and below just after occurring the fault, and next it is returned back to the rated inverter control angle of 140.3 degrees by applying the constant margin angle control of inverter after the transmission lines are restored to the double-circuit mode, and result that this control is very effective and can stably return the MHD generator back to its normal steady state within a few second.

It is made clear through the simulations of electric power line fault that the proposed control scheme of inverter is sufficiently effective to improve the transient stability of the MHD generator.

1. Introduction

Since large-scale open-cycle MHD generators for commercial use tend to be unstable, many stability analyses of the generators were performed [1-4], and it has already been made clear that subsonic inflow disk generators with multi-loads are stable under usual operating conditions [5]. Electric power line faults, however, give remarkable fluctuation to the generator and make it fairly unstable. After the fault is removed, therefore, the generator usually does not return back to its stable steady state before the fault. This means that some control scheme that can maintain transient stability of the generator against electric power line faults is required.

The authors, therefore, have been investigating improvement methods of transient stability under
electric power line fault condition for commercial-scale subsonic open-cycle disk MHD generators connected to power system, and proposed to utilize system dumping resistor circuit in the previous paper [6]. This circuit is very effective to maintain the transient stability, because it suppresses fluctuation induced by power line faults and assists the generator in returning back to the stable steady state after the fault is removed. This method, however, needs to install an additional device of system dumping resistor circuit.

Several simulations [7-10] have revealed that the output electric current of the MHD generator becomes very large during the fault and after cutting off the faulted line. When this output current is too large, it brings bad influence upon the performance and durability of the inverter in the transient state. The output electric current of the MHD generator is closely related with the direct current reactor (d.c. reactor) between the MHD generator and inverter. The d.c. reactor is playing an important role to restrict the input electric current of inverter. As the direct current inductance (d.c. inductance) gets larger, the maximum input electric current of inverter after cutting off the faulted line gradually decreases. The required period of the transient stable control, however, gets long as the d.c. inductance becomes large.

Considering the above-mentioned facts, the authors propose a new improvement method of transient stability for the generator under power line fault condition, which adopts the most suitable d.c. inductances and investigate its performance through time-dependent numerical simulations of a total interconnecting system between the MHD generator and the electric power transmission network system. The control method needs no additional device, and uses only the inverter control angle as a manipulated variable to return rapidly back the MHD generator to its previous stable steady state.

2. Simulation model

Fig. 1 illustrates the schematic diagram of the simulation model of an interconnecting system between the MHD generator and the power system used in the present study. The model is assumed to consist of a commercial-scale open-cycle subsonic inflow disk MHD generator with two pairs of power output terminals, d.c. reactors, cascade-connected two line-commutated inverter bridges, two inverter transformers, filters, a shunt capacitor connected through a transformer, double-circuit transmission lines and an infinite bus. In this section, brief explanation is given for each component of the model system.
2.1. MHD generator

The authors have already succeeded in designing a commercial-scale open-cycle MHD generator that is stable under usual operating conditions [5,6] and, therefore, the designed generator is adopted in the present simulation model. It is subsonic inflow disk type with two pairs of power output terminals, using coal-fired combustion gas with 1% (weight) potassium seed. Fig. 2 shows the schematic diagram of the generator. The radiiuses of the anode, 1st cathode and 2nd cathode are 6, 4 and 2 m, respectively, and two loads of the upstream and the downstream sides are connected between the anode andances cathode and between the 1st cathode and the 2nd cathode, respectively. The thermal input is 1300 MW and the electrical output is 234.7 MW, which is the sum total of 150.7 MW on the upstream side and 84.0 MW on the downstream side. Table 1 lists the size and the rated conditions of the generator.

<table>
<thead>
<tr>
<th>thermal input</th>
<th>1300 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>inlet stagnation temperature</td>
<td>2700 K</td>
</tr>
<tr>
<td>inlet stagnation pressure</td>
<td>4.2</td>
</tr>
<tr>
<td>inlet mach number</td>
<td>0.90</td>
</tr>
<tr>
<td>radial flow velocity</td>
<td>-370 m/s</td>
</tr>
<tr>
<td>inlet swirl ratio</td>
<td>2.00</td>
</tr>
<tr>
<td>applied B field</td>
<td>8.5 T</td>
</tr>
<tr>
<td>channel length</td>
<td>4.0 m</td>
</tr>
<tr>
<td>nozzle (analyzed length)</td>
<td>0.2 m</td>
</tr>
<tr>
<td>diffuser (analyzed length)</td>
<td>0.4 m</td>
</tr>
<tr>
<td>stagnation temperature</td>
<td>2700K — 2259 K</td>
</tr>
<tr>
<td>static temperature</td>
<td>2550K — 2195 K</td>
</tr>
<tr>
<td>stagnation pressure</td>
<td>4.2 — 1.0 atm</td>
</tr>
<tr>
<td>static pressure</td>
<td>2.64 — 0.84 atm</td>
</tr>
<tr>
<td>mach number</td>
<td>0.90 — 0.54</td>
</tr>
<tr>
<td>electrical output</td>
<td>235.3 MW</td>
</tr>
<tr>
<td>enthalpy efficiency</td>
<td>18.1 %</td>
</tr>
<tr>
<td>output voltage (upstream side)</td>
<td>11.9kV</td>
</tr>
<tr>
<td>(downstream side)</td>
<td>15.5kV</td>
</tr>
<tr>
<td>output current (upstream side)</td>
<td>9740A</td>
</tr>
<tr>
<td>(downstream side)</td>
<td>7140A</td>
</tr>
</tbody>
</table>

2.2. Power network

To simplify the simulation system and make the calculations easy, the power system is treated as double-circuit transmission lines and a three-phase infinite bus connected at the end of the lines. The rated effective line voltage and frequency are 275 kV and 60 Hz, respectively, and the total inductance of the transmission lines is selected as 0.01 + j0.1 pu on the basic capacity of 250 MVA.

2.3. Inversion system

Some inversion system is needed to supply d.c. output of the MHD generator to a.c. power system and, therefore, cascade-connected two line-commutated inverter bridges are equipped in the system. Each bridge is connected to the generator through a d.c. reactor and inverts the output current of the generator upstream or downstream side. The inductance of the d.c. reactor between the MHD generator and the line-commutated inverter should be decided by considering both the maximum value of allowable electric current of inverter and the target of the control time that is required to stably return back the quantities of the generation system to their steady state after cutting off the faulted line. It is decided from numerical calculations that the most suitable d.c. inductance of the upstream side and that of the downstream side are 500 mH and 650 mH, respectively.

An inverter transformer is connected with each bridge. The rated capacity, voltage and impedance of the upstream side transformer are 200 MVA, 13/275 kV and 0.007+j0.15 pu, respectively, and those of the downstream side one 110 MVA, 10/275 kV and 0.007+j0.15 pu, respectively. The rated control angle of the inverter is selected as 140.3 degrees, because the total output power of the generator coincides with its designed value under this condition.

The line-commutated inverter generates large amount of harmonics and reactive power. The 5th, 7th, 9th, 11th single-tuned type (the quality factor Q=50) and the high-pass type (24th, Q=3) filters are equipped to absorb the harmonics, and each capacity is selected as 15, 10, 15, 10 and 25 MVA, respectively. The shunt capacitor with capacity of 50 MVA is also equipped to absorb the reactive power, and it is connected through a transformer with rated capacity, voltage and impedance of 50 MVA, 275/77 kV and 0.007+j0.1 pu, respectively.

3. Simulation method

3.1. MHD generator

The calculations of time-dependent behavior of the disk MHD generator are performed by using the quasi-one-dimensional time-dependent simulation code developed by the authors.
In the code, the cylindrical coordinate system shown in Fig. 2 is used, and the following quasi-one-dimensional time-dependent equations of the plasma flow in the generator are taken into account as the basic equations of the calculations:

**Mass conservation:**
\[
\frac{\partial}{\partial t} (\rho A) + \frac{\partial}{\partial r} (\rho u_r A) = 0
\]  
Equation (1)

**Momentum conservation:**
\[
\rho \frac{\partial u_r}{\partial t} + \rho u_r \frac{\partial}{\partial r} \left( \frac{u_r^2}{r} \right) = -\rho \frac{u_r^2}{r} - \frac{\partial p}{\partial r} + J_\theta B - f_r
\]  
Equation (2)
\[
\rho \frac{\partial u_\theta}{\partial t} + \rho u_r \frac{\partial u_\theta}{\partial r} - \rho u_r u_\theta = -J_\theta B - f_\theta
\]  
Equation (3)

**Energy conservation:**
\[
\rho \frac{\partial}{\partial t} \left( h + \frac{u_r^2 + u_\theta^2}{2} \right) + \rho u_r \frac{\partial}{\partial r} \left( h + \frac{u_r^2 + u_\theta^2}{2} \right)
\]
\[
= \frac{\partial p}{\partial r} + J_r E_r + J_\theta E_\theta - q
\]  
Equation (4)

**State of gas:**
\[
p = \rho R_g T
\]  
Equation (5)

**Current continuous:**
\[
J_r A = I_L
\]  
Equation (6)

**Electric field:**
\[
E_\theta = 0
\]  
Equation (7)

**Generalized Ohm’s law:**
\[
J_r = \frac{\sigma_{\text{eff}}}{1 + \beta_{\text{eff}}} \left[ \left( E_r + u_\theta B \right) - \beta_{\text{eff}} \left( E_\theta - u_\theta B \right) \right]
\]  
Equation (8)
\[
J_\theta = \frac{\sigma_{\text{eff}}}{1 + \beta_{\text{eff}}} \left[ \beta_{\text{eff}} \left( E_r + u_\theta B \right) - \left( E_\theta - u_\theta B \right) \right]
\]  
Equation (9)

where, \( A \) is the channel cross-section, \( B = (0,0,B) \) the applied magnetic flux density, \( E = (E_r,E_\theta,0) \) the electric field, \( J = (J_r,J_\theta,0) \) the current density, \( u = (u_r,u_\theta,0) \) the gas velocity, \( \rho \) the mass density, \( p \) the pressure, \( T \) the temperature, \( f = (f_r,f_\theta,0) \) the friction losses, \( q \) the heat loss, \( R_g \) the gas constant and \( h \) the enthalpy, \( I_L \) the output current of MHD generator.

\( \sigma_{\text{eff}} \) and \( \beta_{\text{eff}} \) are the effective conductivity and the effective Hall parameter, as following equations:
\[
\sigma_{\text{eff}} = \frac{\sigma}{G}, \quad \beta_{\text{eff}} = \frac{\beta}{G}, \quad G = 1.1
\]  
Equation (10)

The basic equations of gas dynamical quantities (1)-(4) are solved by adopting the MacCormack predictor-corrector method [11].

Adopting the MacCormack predictor-corrector method solves the basic equations of gas dynamical quantities (1)-(4).

In addition to the generation channel, the nozzle and the diffuser (0.2 and 0.4 m long, respectively) are also included in the analytical region, and gas dynamical and electrical quantity distributions in the extent between the nozzle inlet (the radius \( r = 6.2 \) m) and the diffuser outlet (\( r = 1.6 \) m) are calculated. Concerning the boundary conditions of gas dynamical quantities, the stagnation temperature and the stagnation pressure are fixed at the inlet boundary, and the stagnation pressure is fixed at the outlet boundary, because the gas flow is subsonic and these conditions are most suitable for this flow.

### 3.2. Power circuit

Time-dependent analyses of power circuits are usually performed on their simplified equivalent single-phase circuits because transient response time of usual power machinery and apparatus is much longer than one cycle of a.c. The transient response time of the MHD generator is, however, very short and the influence of detailed switching operation of the inverter upon the time-dependent behavior of the generator can not be neglected. Considering the above facts, the simulations are carried out on the detailed three-phase circuit of the model, not on the simplified equivalent single-phase circuit. In the calculations, thyristors in the inverter bridges are simulated as ideal switches which are turned on by the gate signal under forward voltage condition and are turned off at the timing of zero current, and the circuit breakers equipped at both ends of the transmission lines are also simulated as ideal switches which break the circuit at the timing of the first zero current condition after their operation of current interruption. The node voltages are selected as unknown quantities and the Bergeron method, which is the same scheme as EMTP [12], is adopted as the analytical scheme.

### 4. Investigation on improvement method of transient stability

#### 4.1. Stabilization of MHD generator

To propose and investigate a new improvement method of transient stability for the MHD generator, which only manipulates the control angle of inverter, under condition of electric power line fault, numerical simulations are performed in the case a three-phase ground fault occurs at the center of one of the double-circuit electric power transmission lines.
The stable steady state of the nominal operating condition, in which the rated value of 140.3 degrees is used as the inverter control angle, is selected as the initial condition. In the calculation sequence, the fault is assumed to continue for 5 cycles (83.3 ms) and be cleared by disconnecting the faulted line through operation of the circuit breakers located at both ends of the line. After that, the operation continues using only another transmission line for 18 cycles (300 ms), and finally the removed line is reconnected and the circuit returns back to the normal connection, because usual grounding spontaneously disappears by this time.

Numerical simulations are performed in the cases the control angle is reduced to various levels between 90 degrees and 140.3 degrees just after the fault occurs, because the most suitable d.c. inductances have already selected as 500 mH for the upstream side one and as 650 mH for the downstream side one by considering both the maximum value of allowable electric current of inverter and the target of the control time.

Figures 3 and 4 show the numerically obtained time variations of the output currents of the MHD generator and the radial gas velocity distributions in the MHD generator, respectively. In the case the control angle of the inverter is reduced to 130 degrees, as shown in Figure 3 and Figure 4 (a), the commutation failure does not disappear due to the difficulty of keeping the inverter margin angle even after the fault is cleared. It is successfully found out from these figures that stable operation of the MHD generator is realized after cutting off the faulted line in the cases the control angle of inverter is reduced to 125 degrees and below. The control angle of 125 degrees is, therefore, considered to be the critical control angle of inverter. It can be confirmed that the commutation failure induced by the fault disappears after the fault is cleared and the generator converges in a new stable steady state corresponding to the new control angle of 125 degrees and below.

The above results indicate that the proposed control method, reduction of the control angle of inverter just after the fault occurs, is effective in stabilization of the MHD generator, though there exists a possibility that the highest critical control angle changes depending on sort and duration time of the fault.

4.2. Restorative operation to normal steady state

The MHD generator is successfully stabilized, whereas its operating state is quite different from its normal operation, because it converges in different steady state corresponding to the new control angle.

(a) Currents of upstream side.

(b) Currents of downstream side.

a: steady state period
b: fault period
c: period of cutting off the fault
d: double-circuit lines period

Figure 3 Time variations of output currents of MHD generator.
The output electric current of the upstream side of the MHD generator reaches about twice as large as one's normal value and the radial gas velocity in the MHD generator is in an accelerated state, as seen in Figures 3 and 4. The inverter control angle, therefore, should be returned back to its rated value.

Considering the above discussion, the authors propose the following new control scheme to improve the transient stability under condition of electric power line fault for the MHD generator:

Step 1: Reduce the control angle of inverter to the critical control angle and below just after the fault occurs.

Step 2: Increase the control angle of inverter to its rated control angle by using the control method of constant inverter margin angle after the removed line is reconnected.

To reveal the behavior of the generator when the proposed control scheme is implemented, numerical simulations are performed in the cases that the control angle of inverter is at first reduced to its critical value of 125 degrees and below just after the fault occurs and next it is returned back to its rated value of 140.3 degrees by using the control method of constant inverter margin angle after the faulted line is reconnected.

The minimum margin angle is selected as 15 degrees, and increase of the control angle is stopped in the case the margin angle falls below 15 degrees.

Figures 5 and 6 illustrate the numerically obtained time variations of the radial gas velocity distributions in the MHD generator, the inverter margin angles, the output currents of the MHD generator and the active power provided to the electric power transmission network in the cases the control angle of the inverter is 125 and 120 degrees, respectively. It can be confirmed from these figures that the MHD generator, which at once fluctuates by the fault, stably converges in its normal operation within a few seconds by applying the control method. The margin angle of inverter, as shown in Figures 5 (b) and 6 (b), finally reaches about 23 degrees, which is the value under its normal steady state operation, though the increase of the control angle is stopped a few times before arriving at the rated control angle of 140.3 degrees. The maximum value of the output electric current of the MHD generator, as seen in Figure 5 (c), becomes about 13000 A, and consequently this response is very good for inverter operation because the transient
current after the fault is cleared is effectively suppressed.

The results of these simulations indicate that the proposed control scheme of the inverter can stably returns the MHD generator back to its normal steady state operation and, therefore, is very effective to improve the transient stability of the MHD generator.

5. Conclusions

In this paper, the authors propose and investigate a new improvement method of transient stability under condition of electric power line fault for commercial-scale open-cycle subsonic inflow disk MHD generators connected to electric power transmission network system through time-dependent numerical simulations of a total interconnecting system. The simulation model is assumed to consist of the MHD generator with two pairs of power output terminals, direct current reactors, cascade-connected two line-commutated inverter bridges, two inverter transformers, filters, a shunt capacitor connected through a transformer, double-circuit transmission lines and an infinite bus.

The control method of constant margin angle needs no additional device and only manipulates the control angle of inverter when the most suitable direct current reactors are adopted.

It is made clear through the simulations under the condition of electric power line fault that the proposed control method is very effective to improve the transient stability of the MHD generator by reducing the inverter control angle to or below its critical angle and can stably return the MHD generator back to its normal steady state within a few seconds.

Acknowledgment

The super computers in the Data Processing Center, Kyoto University, Japan, carried out the numerical computations.

References

Figure 5  Time dependent performances of various quantities with control method. ( inverter control angle = from 125 to 140.3 degrees )
(a) Radial gas velocity distribution

(b) Inverter margin angle

(c) Output currents of MHD generator

(d) Active electric power

Figure 6 Time dependent performances of various quantities with control method. ( inverter control angle = from 120 to 140.3 degrees )