Investigation on the transient stability of hydro generator working with power grid

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Abstract. Huge hydro-generator is the inevitable development trend of hydro-generator for utilization of water resources. It is very necessary to research the technical issues for 1000MW hydro-generator. Whether the short-circuit faults locate at the generator terminal or the end of transmission line, the transient stability of hydro-generator is calculated and analyzed based on the field-circuit coupling model. Short-circuit fault must be cleared immediately in order that the power system and generator can maintain stable operation, in this paper, fault clearing time limit under different conditions is obtained by mass of simulation. The results obtained in this paper can provide valuable reference for the actual operation of 1000MW hydro-generator, and it is also useful and valuable for the design of protection devices, the dispatching of power grid and the debugging of generator when be connected to power grid.

1. Introduction

There are many rivers in China, which are rich in water resources and have great development potential. Among all kinds of power generation resources, hydraulic resources have low cost, clean, pollution-free, sustainable use and electricity generation with low costs. It will get more and more attention with its related projects can also improve the area's transportation and economy advantages. Stable operation of large synchronous generator is the guarantee of reliable operation of power system.

Many problems about hydro-generator has been studies for the last ten years, the principle of NSET modeling method for nonlinear state estimation was summarized [1]. In Reference [2], the nonlinear load characteristics for a certain 1000 MW hydro generator within considering saturation were studied based on theoretical analysis. The Reference [3] conducts a detailed analysis of the cause of a failure at its large hydro-generator terminal because of a short-circuit fault. In Reference [4], the problem with unbalanced magnetic pull (UMP) in large hydro generators was analyzed, the static and the dynamic eccentricity impact on the air-gap length is described through an original mathematical model. Reference [5] presents the field-circuit coupled time-stepping finite-element model of huge hydro-generator based on the unit-machine. Reference [6] proposes a contact-less excitation systems for hydroelectric power plants. Measurements of circulating currents in a downsized hydro generator on a test bench were given in Reference [7]. Reference [8] explains the talented impact of utilizing the Adaptive Neuro Fuzzy Inference System (ANFIS) technique on enhancing the performance of the generator Loss-of-Excitation (LOE) protection. In Reference [9], based on MATALB, a mathematical
model of hydro-generator under loss of excitation LOE condition is constructed to analyze the dynamic performance. In Reference [10], it is investigated that the mechanism of inter-bar currents and their impact on the axial distribution of damper bar currents under unbalanced load. Reference [11] analyzed the available core loss model to compute the electromagnetic core losses in large hydro electrical machine during no-load and short-circuit modes. Reference [12] presents an overview of the main objectives to be met by electricity producers in Romania. Reference [13] presents both a theoretical MMF analysis of the stator tooth harmonics and the space harmonics and a finite elements analysis of the rotor bar currents. Reference [14] presents both a theoretical MMF analysis of the stator tooth harmonics and the space harmonics and a finite elements analysis of the rotor bar currents. Reference [15] describes measurements of sudden three-phase short-circuit currents of hydro generators. In Reference [16], a full three dimensional (3D) finite element model and method of the coupled eddy current and temperature fields in the end region of a large hydro-generator are developed and studied. Reference [17] proposed a time frequency compression stochastic resonance method (FCSR) to detect rotor fault signals in the early stage.

This paper established the field-circuit coupling model for grid-connected operation a hydro-generator, which is simulated and analyzed from the perspective of field-path coupling, the fault clearing time limit under different conditions will be obtained by mass of simulation.

2. Establishment of coupling model of hydro-generator

2.1. Two-dimensional finite-element model of hydro-generator

The size of 1000MW hydro-generator is huge. The main structural parameters of 1000MW hydro-generator for a planning large-scale hydro-power station are shown in Table 1, and the main rated parameters are shown in Table 2 [18].

| Parameter                      | Size         | Parameter                      | Size         |
|--------------------------------|--------------|--------------------------------|--------------|
| Stator Outer Diameter $D_o$   | 18000mm      | Rotor Outer Diameter $D_o$     | 16728mm      |
| Stator Inner Diameter $D_i$   | 16800mm      | Rotor Inner Diameter $D_i$     | 14218mm      |
| Effective Core Length         | 2965mm       | Pole-core Width                | 540mm        |
| Slot Depth                    | 255mm        | Pole Height                    | 280mm        |
| Nominal-air-gap Width $\delta$| 36mm         | Pole-pairs $p$                 | 28           |
| Stator Yoke Height / l        | 329mm        | Rotor Length                   | 3600mm       |
| Iron Core Fan Blade Number    | 84           | Width of Pole Shoe             | 700mm        |
| Slot Number Z                 | 672          | Pole shoe height               | 75mm         |
| Slots Per Pole Per Phase      | 4            | Number of Exciting winding     | 16.5         |
| Parallel Branch               | 7            | Each Pole of Damper Adapter    | 9            |

| Parameter                      | Rating        | Parameter                      | Rating        |
|--------------------------------|--------------|--------------------------------|--------------|
| Apparent Power $S_N$           | 1111MVA      | Voltage $U_N$                  | 26kV         |
| Power Factor                   | 0.9          | Current $I_N$                  | 24670A       |
| Active Power $P_N$             | 999900kV     | Frequency $f_N$                | 50Hz         |
| Speed $\Omega$                 | 107.1r/min   | Pole Height                    | 280mm        |
| Excitation Voltage $U_F$       | 484V         | No-load Excitation Current     | 2074.4A      |
| Load Excitation Current        | 3767.6A      | Efficiency                     | 98.97%       |

Table 1. Main structure parameter of 1000MW hydro-generator.

Table 2. Main rated parameter of 1000MW hydro-generator.
During the establishment and solution of the two-dimensional finite element model, considering the large capacity and size of 1000MW hydro-generator, the following reasonable assumptions were made to reduce the operation time [19]:

1. The vector magnetic potential in the motor does not change along the axial direction, the magnetic field is treated as a two-dimensional field;
2. Considering the symmetry of the structure and the periodicity of the magnetic field, take one of its magnetic poles as the solution region;
3. The displacement current is ignored, in other words, the electromagnetic field in the solution area is considered as quasi-stable field;
4. The material is isotropic, that is to say, the hysteresis effect of ferromagnetic material is ignored;

Figure 1 is the finite element solution domain of 1000MW hydro-generator.

When using the finite element method to analyze the distribution of electromagnetic field in the generator, and then analyzing operation performance, the two-dimensional electromagnetic field problem expressed by vector magnetic potential $A_z$ satisfies the two-dimensional Poisson equation in the solution region [20]:

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu} \frac{\partial A_z(t)}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\mu} \frac{\partial A_z(t)}{\partial y}\right) = -J_z(t)$$

In Equation (1), $A_z(t)$ is the z-axis component of the vector magnetic potential at time $t$; $J_z(t)$ is the source current density at time $t$; $\mu$ is the magnetic permeability of the material.

2.2. Coupling model of hydro-generator

To unite the 2-d Poisson equation of the electromagnetic field inside the generator, stator and rotor winding loop, the circuit equation of the rotor damping winding, it's easy to conclude the time-step finite element equation of the field-path coupling form of the generator as follows:

$$\begin{pmatrix}
K & -C_z & -C_u & 0 & A & D_z & 0 & 0 & 0 \\
0 & -R_z & 0 & 0 & I_z & -J_z C_z & -L_z & 0 & 0 \\
0 & 0 & R_z & 0 & I_z & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & C_z & M_z & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & M_z & R_z & I_z & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & L_z & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & I_z & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 
\end{pmatrix} \begin{pmatrix} A \\ I_z \\ I_z \\ M_z \\ R_z \\ I_z \\ I_z \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ I_z \\ I_z \\ C_z I_z \\ M_z I_z \\ R_z I_z \\ I_z \\ 0 \end{pmatrix}$$

The specific elements of each incidence matrix are introduced details in literature, $K$ is the stiffness matrix, $C_z$ and $D_z$ are the coefficient matrix of the effect of current on the magnetic field in the rotor damping bar.

On the basis of obtaining the time-step finite element equation of the field-path coupling form, the post-difference Euler method, which is used to solve the finite element equation discretely.

2.3. Simulation model of hydro-generator

On the premise of the mathematical basis of outlet coupling model, the simulation model of 1000MW hydro-generator field coupling is established, through the 500kV transmission line and 150km double-loop overhead transmission line, the finite element model of 1000MW hydro-generator is interconnected with infinite bus. In the simulation model, the parameters of the 500kV booster
transformer refer to the parameters of the 500kV booster transformer produced by BAODING TIANWEI BAODIAN ELECTRIC CO., LTD which is matched with the 1000MW turbo-generator [21], the parameters of the 500kV transmission line refer to Henan electric power test and Research Institute has conducted tests on part of 500kV transmission lines in Henan [21], and the relevant data has the practical engineering value.

Detailed simulation model is shown in Figure 2, field-circuit coupling simulation model can be implemented in the excitation adjustment and engine power automatic adjustment, the specific method of adjustment is shown in Figure 3 below, by monitoring the dynamic changes of the voltage of the generator that feedback to the control module, in order to realize the continuous adjustment of the voltage of the generator. The mechanical power output by the prime mover is also adjusted according to the fluctuation of the active power output by adjusting the opening of the water gate of the hydro-generator in real time to adjust the output mechanical power, so as to maintain or close to the synchronous speed during the operation and ensure the stable operation of the synchronous generator without losing step [22].

![Figure 2. Field-circuit coupled model of hydro-generator with power grid.](image1)

![Figure 3. Realization of automatic speed and voltage regulators.](image2)

**Figure 2.** Field-circuit coupled model of hydro-generator with power grid.

**Figure 3.** Realization of automatic speed and voltage regulators.

**3. Transient stability in case of three-phase short circuit fault**

Transient stability refers to whether a power system or a generator set can achieve a new stable operation state through transient transition after being suddenly disturbed by a large disturbance in a certain operating condition. Under the requirement of comprehensive consideration of calculation amount and calculation accuracy, the simulation step size is 0.0005s. Grounding resistance is 0.001Ω, the generator suddenly occurred during the operation of three phase short circuit in several situations for simulation analysis.
3.1. Transient stability in case of terminal failure of transmission line without regulation

It is assumed that a three-phase short-circuit fault occurs at the end of the transmission line during the rated operation of 1000MW hydro-generator at 3s, and the two situations of the fault removal after the fault lasts 0.4245s or 0.4250s are simulated respectively, then the load angle can be got, the fault is removed at 3.4245s or 3.4250s, and the response curve of power angle and electric angular velocity is shown in Figure 4.

![Waveform for three-phase short circuit when it locates at the end of transmission line.](image1)

(a) The load angle was cut for 0.4245s  
(b) The load angle was cut for 0.4250s  
(c) Continue cutting speed for 0.4245s  
(d) Continue cutting speed for 0.4250s

**Figure 4.** Waveform for three-phase short circuit when it locates at the end of transmission line.

![Waveform for three-phase short-circuit when it locates at the terminal of generator.](image2)

(a) The load angle was cut for 0.390s  
(b) The load angle was removed for 0.3905s  
(c) The removal speed continued for 0.390s  
(d) The removal speed continued for 0.3905s

**Figure 5.** Waveform for three-phase short-circuit when it locates at the terminal of generator.

Through the analysis of the above simulation results, it can be seen that when the simulation step is 0.0005s, three-phase short-circuit fault occurs at the end of the transmission line and the automatic adjustment of the unit is not considered, the allowable fault limit cutting time is 0.4245s.

3.2. Transient stability in case of terminal failure of generator without regulation action

It is assumed that a three-phase short-circuit fault occurred suddenly at the generator end during the rated operation of 1000MW hydro-generator at 3s, and the two situations of fault removal after the
fault lasted 0.3900s or 0.3905s were respectively simulated, the fault-clearing time is at 3.3900s or
3.3905s, and the corresponding power Angle and speed were shown in Figure 5.
Through the analysis of the above simulation results, it can be seen that when the simulation step
size is 0.0005s, the 3-phase short-circuit fault occurs at the machine end and the automatic adjustment
of the unit is not considered, the allowable fault limit cutting time is 0.3900s.

3.3. The end fault of adjustable power transmission line of transient stability
Assumption that 1000 MW hydro-generator is working with three-phase short circuit fault on the end
of transmission line at 2.5s during the normal operation, after the failure lasted for 0.4555s and
0.4560s of simulation, in other words, the faults were cut out at 2.9555s and 2.9560s, the load angle
and speed is shown in Figure 6.

(a) The load angle was cut for 0.4555s
(b) The load angle was cut for 0.4560s
(c) The removal speed continued for 0.4555s
(d) The removal speed continued for 0.4560s

Figure 6. Results with three-phase short circuit fault when it locates at the end of transmission line.

(a) The load angle was cut for 0.4160s
(b) The load angle was cut for 0.4165s
(c) The removal speed continued for 0.4160s
(d) The removal speed continued for 0.4165s

Figure 7. Simulation results with three-phase short-circuit when it locates at the terminal of generator.
Through the analysis of the above simulation results, it can be seen that when the simulation step size is 0.0005s, when the three-phase short circuit fault on the end of transmission, the allowable fault limit cutting time is 0.4555s.

3.4. The fault of generator ends adjustable transmission of transient stability

It is assumed that a three-phase short-circuit fault occurred suddenly at the generator end during the rated operation of 1000MW hydro-generator at 2.5s, and the two situations of fault removal after the fault lasted 0.4160s or 0.4165s were respectively simulated, the fault-clearing time is at 2.916s or 2.9165s, and the corresponding load angle and speed were shown in Figure 7.

In Figure 7, it can be seen that when the simulation step size is 0.0005s, when the three-phase short circuit fault on the end of power transmission line, the allowable fault limit cutting time is 0.4160s.

4. Transient stability in case of other short circuit faults

The same method is adopted to simulation analysis when the other types of short-circuit faults occur. Through a lot of simulation analysis, the fault limit cutting time for different faults is in Table 3.

| Fault Type | Adjusting or not | with regulating effect(s) | no regulating effect(s) |
|------------|------------------|--------------------------|-------------------------|
| one-phase ground at the end of generator | ≥12.5 | ≥12 |
| phase fault at the end of generator | ≥12.5 | 3.9≥Tc≥3.8 |
| two phase ground at the end of generator | ≥12.5 | 0.8145 |
| one-phase ground at the end of the line | ≥12.5 | ≥12 |
| phase fault at the end of the line | ≥12.5 | 10.2≥Tc≥10.1 |
| two phase ground at the end of the line | ≥12.5 | 2.9860 |

It can be seen from the Table 3, when several short-circuit conditions occur, the unit speed oscillates continuously for a long time without losing step. The reasons are as follows:

1. During the fault duration, although the power oscillates greatly, the giant hydro-generator has a large rotational inertia, and the speed changes relatively slowly. In addition, during the power oscillation, the average power still maintains near the rated output power point, so the generator will not lose step immediately.

2. On account of the established giant hydro-generator simulation model is integrated into the infinite power grid, most of the fault power consumed at the fault point is provided by the infinite power grid, which is consistent with the objective fact that even if the protection device fails to clear the fault at a certain point in the power system without all the generators running out of synchronization in fact.

3. In the established model, consider fully the excitation regulation and speed regulation, in other word, when the fault occurs, because of the excitation generator terminal voltage to reduce the excitation system of force excitation, in addition that, according to the variation of generator active power output with automatic adjustment, therefore, it improves the stability of the system in a certain extent.

5. Conclusions

Combining established the field-circuit coupling model for grid-connected operation of hydro-generator, using time-domain simulation method, for generator terminal and the end of transmission lines in different type of faults, start with both sides, one side is never considerate the unit automatic excitation regulation and the speed regulation, the other side consider the automatic adjustment,
simulated analyze the transient stability of the hydro-generator in grid-connected operation, the unit was allowed to take the limit of fault running time in different conditions, analyze the unit takes a long time without losing step for several cases, justify it reasonable.

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