THE RESEARCH ABOUT INFLUENCE OF WET STEAM ON OVERSPEED FOR NUCLEAR STEAM TURBINE

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ABSTRACT
The overspeed results is one of the most important technical specifications for the safety design of nuclear steam turbine. Because of the low parameter and high humidity of steam in Nuclear Steam Turbine, it should pay more attention to wet steam influence for nuclear units compared to fossil units in overspeed calculation, but it usually be ignored in a lot of overspeed calculation. In order to enhance the attention to influence of wet steam on overspeed calculation for nuclear turbine, to explore how to lower the wet steam influence of nuclear turbine in technical aspect, to lower the overspeed results, and to improve the safety and reliability for nuclear unit, this paper analysis and research the wet steam influence on overspeed of Nuclear Steam Turbine, summary overspeed calculation method of Nuclear Steam Turbine considering wet steam influence, and get the increment about the results of overspeed calculation considering the influence of wet steam by means of example calculation. Meanwhile, this paper also give a brief description and calculation about the other Influencing Factors that play an important role in overspeed for Nuclear Steam Turbine.

2. PRINCIPLE FOR OVERSPEED
High pressure steam, generated by the nuclear island (boiler), enters the turbine through the throttle and governing valves. The turbine blading uses the energy of this expanding steam to generate power. If there is an electrical problem on the grid, the breaker is opened, and the restraining torque on the rotor is lost. The steam energy which previously was directed toward producing electricity now accelerates the rotor, the result may produce an overspeed condition. There are two protective functions built into modern steam turbine controls, the explanation is as follows.

1) If the turbine load is above 30% and the generator’s breaker is open, a portion of the overspeed protective controller(OPC) system initiates an action called Load Drop Anticipator(LDA). This then causes the rapid closure of the governor and intercept valves.

2) If the LDA fails to arrest the speed before it reaches 110%, a mechanical trip is activated, which results in the rapid closing of all steam valves.

There are different types of overspeed protective system in the different turbine-generator unit design, but the fundamental is consistent between different overspeed protective systems. Basically, when the turbine in load rejection condition, at first it activate the signal of the rapid closure of the control(governor and intercept) valves, if after a load rejection the control valves fail to close or for other reasons that make the overspeed reaching 110% rated speed, then the overspeed protection trips the turbine and starts to
close all the stop valves. Finally to prevent the speed of the turbine-generator train from surpassing design limitations of 120 percent of rated speed.

According to the overspeed calculation principle by American Society of Mechanical Engineers (ASME), the overspeed energy mainly include the rotor initial kinetic energy, entrapped steam energy in the turbine, energy added due to delays in trips and valve closing and the capability of including the energy of flashing water has been added (ASME PTC 20.2, 1965).

3. INFLUENCE OF WET STEAM ON OVERSPEED CALCULATION

3.1 THE ENERGY OF WET STEAM IN NUCLEAR UNIT

According to ASME overspeed calculated method, the energy of flashing water in zone is a part of all overspeed energy. When turbine in rejection condition, there is a greater pressure drop in the zone, according to the steam properties and thermal process, the saturated water in the zone will convert to the steam and expand. And the steam with a certain temperature and pressure would expand to generate power to cause the overspeed. To the fossil units, because of the high steam parameter which could usually reach subcritical, supercritical and ultra-supercritical, there is few wet steam zone in the turbine, so the flashing water energy is very low, we can use estimated value in simplified calculation. But to the nuclear units, the steam parameter is low, the HP (High Pressure) admission is saturated steam with a certain humidity. Here we list the conventional island HP admission parameter for several popular reactors, see the Table 1. The admission humidity is 0.4% ~ 0.5%, and humidity is increasing after the steam enter into the blading in HP casing to create power, the HP exhaust humidity can reach up to 12% to 15%. The LP (Low Pressure) inlet steam is superheated steam which is from HP exhaust and through the Moisture Separator and Reheater (MSR) to reheat and dehumidify. There is a gradual decline in the steam parameter when it enter into LP casing because of the steam expand to generate power, and then the superheated steam gradually convert to wet steam. The LP exhaust humidity can reach up to 12% to 14%.

Table 1 Advanced nuclear reactor parameter

<table>
<thead>
<tr>
<th>Reactor type</th>
<th>Steam temperature (℃)</th>
<th>Steam pressure (MPa)</th>
<th>Steam flow rate(t/h)</th>
<th>humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>M310</td>
<td>268.1</td>
<td>5.34</td>
<td>2016</td>
<td>0.5%</td>
</tr>
<tr>
<td>CPR1000</td>
<td>280.1</td>
<td>6.43</td>
<td>5808</td>
<td>0.47%</td>
</tr>
<tr>
<td>HPR1000</td>
<td>280.9</td>
<td>6.5</td>
<td>6125</td>
<td>0.5%</td>
</tr>
<tr>
<td>AP1000</td>
<td>268.6</td>
<td>5.38</td>
<td>6795</td>
<td>0.45%</td>
</tr>
<tr>
<td>CAP1700</td>
<td>270.3</td>
<td>5.53</td>
<td>10260</td>
<td>0.36%</td>
</tr>
</tbody>
</table>

3.2 DIFFERENT FORM OF FLASHING WATER

The accumulative water could present in several form in turbine zone, a part of that is the water in the steam, existing as a vaporific or granular form in the steam, another part is the drainage which haven’t been removed from the casing. Besides, the wet steam could be accumulated to form water film with a certain thickness on the inside wall of inner casing and on the surface of the stationary and rotating blades, the part of water film also have flashing energy when the pressure drop in the zone during the rejection condition. Except for all above, the flashing water energy in extraction piping and feed water heaters should be taken into account for the last two stage extraction steam pipes which have no non-return valve, and the other extraction steam pipes also have the similar calculated methods under the failure condition of non-return valves (Wang et al., 2003; Wu et al., 2015).

3.3 THE EFFECTIVE DEHUMIDIFICATION METHODS

Take the PWR (pressurized water reactor) 1000MW unit for example, all the steam in turbine is almost in the wet steam environment except for the less of stage. Because of the high humidity in nuclear turbine, the wet steam have great effect on result of overspeed, so it is necessary to take measures to lower the steam humidity to avoid overspeed.

Almost all the nuclear units have effective dehumidification structure, including the dehumidification grooves, drainage holes and other dehumidification systems. These structures could greatly reduce the water in the turbine. Except for what have mentioned above, last stage hollow stationary blade and heating last stage diagraph to dehumidify are the advance dehumidification methods at present, the explanation is as follows.

1) Hollow stationary blade to dehumidify: in the design of the hollow stationary blade, the stationary blade is welded to a hollow structure, and some thin slots which connect to the hollow structure are machined in the blades at appropriate area, because of negative pressure in the hollow structure, any water passing on the surface of the blades may be drawn into the thin slots to the hollow structure and finally drain into the condenser. Hollow stationary blade work well for dehumidification, the shape of the hollow blade is the same as the normal blade, so it won’t reduce the turbine efficiency.

2) Heating last stage diagraph to dehumidify: in this design, the last stage diagraph is designed as a special hollow structure, it could be equivalent to heat exchanger. Inside the diagraph, it is the high parameter steam from one of HP extractions, and outside is the mainstream wet steam, so the inside steam parameter determine the evaporation capacity (heat exchange capacity) (Sun, 2017).

3.4 OVERSPEED CALCULATION ADDED THE ENERGY OF FLASHING WATER

3.4.1 THEORY ENERGY CALCULATION METHOD

According to overspeed calculation specification of Westinghouse Corporation in early stage, the method of calculating the additional energy added by flashing water have a simplified method is based on the concept that after the heater has been evacuated of all of its available energy, the state point of the remaining water will be at the saturated conditions at the pressure level in the zone to which this steam expanded. The amount of energy available from this steam can be estimated from the following equation:

$$E = \frac{h_f - h_{fg}}{\rho}$$


\[ Ef = 1.056 - 3*(W_2 - W_1) \times (h_{g2} - h_{iso}) \times eff / 2 \]

\( W_2 \) is the remaining weight of water (lbs).
\( W_1 \) is the initial weight of water (lbs).
\( h_{g2} \) is the enthalpy of saturated steam at the zone pressure (BTU/lb).
\( h_{iso} \) is the enthalpy of the steam after an isentropic pressure drop from the zone pressure to the pressure at which the steam will expand (from steam tables) (BTU/lb).
\( eff \) is the assumed blading efficiency, 0.80.

The factor of 2 at the end of the equation is because the energy added must be integrated between the beginning and end of the process. The value at the end is zero, so the process is assumed linear, dividing the initial energy by two is equivalent to the integration.

\( W_2 \), the amount of water that remains is found from the following equation:

\[ W_2 = W_1 \times (h_{gavg} - Uf_1) / (h_{gavg} - Uf_2) \]

\( W_1 \) is the initial weight of water (lbs).
\( h_{gavg} \) is the average latent energy throughout the process (BTU/lb). To be found by averaging the saturated latent energy at the initial zone pressure and the saturated latent energy at the pressure in the zone to which this steam will expand (from steam tables).

\( Uf_1 \) is the initial energy (BTU/lb). To be calculated from the equation: \( u = h - 0.185*p*v \), Where \( u \) (BTU/lb), \( h \) (BTU/lb), \( p \) (psia) and \( v \) (ft^3/lb) are found in the steam tables at the saturated liquid conditions at the initial zone pressure.

\( Uf_2 \) is the final internal energy (calculated as above) at the pressure in the zone to which this steam will expand (from steam tables).

The difference between the initial water and final water is the amount of steam that will expand through the turbine.

### 3.4.2 Calculating Example

According to ASME overspeed calculated method, the input for overspeed calculation mainly included the whole closure time of valves, volume and parameters of the steam in the zones, weight moment of inertia for the turbine rotor and generator rotor, energy loss, rated speed and calculation power etc. The rated calculated load or the maximum calculated load (about 103–105% rated load for nuclear units, this is usually maximum guaranteed load) is one of the calculated initial condition, we could obtain the data from heat balance diagrams. And the end condition is the zero load or house load (about 5–8% rated condition). There is the maximal overspeed result in the condition of maximum calculated load rejection to zero load.

We take a 1000MW nuclear unit for the example of overspeed calculation. Figure 1 is the simulation model of the unit. The unit is a half speed (1500 r/min), single shaft, three casings with four exhausts, reheat, condensing nuclear turbine, the steam turbine consists of one High Pressure (HP) and two Low Pressure (LP) casings. The exhaust from HP casing enter the Moisture Separator and Reheater (MSR), and then enter into LP casing. The steam turbine and the generator are arranged in one line.

**Figure 1: The simulation model of a 1000MW nuclear unit.**

The parameters and volume in the zones of steam turbine and flashing water quality in wet steam zone are listed in the table 2, which are the key input information for calculation. Because of the drainage and dehumidification measure in nuclear units, so there are relatively less water in the zone, the flashing water mainly is water film on the inside wall of inner casing and on the surface of the stationary and rotating blades. According to the energy calculation method of flashing water which have been mentioned in the chapter 3.4.1 of this paper, the main input information to calculate the energy of flashing water is the initial weight of water \( W_1 \). Thickness for the water film have an experienced calculation value. To calculate the quality of the flashing water, so except for the thickness of the water film, superficial area of all parts which in the wet steam circumstance is needed.

**Table 2: The parameters in the zones of 1000MW nuclear steam turbine.**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Volume of steam (m³)</th>
<th>Pressure (MPa)</th>
<th>Enthalpy (KJ/Kg)</th>
<th>Flash water (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP Zone 1</td>
<td>22</td>
<td>6.45</td>
<td>2772</td>
<td>35</td>
</tr>
<tr>
<td>HP Zone 2</td>
<td>2.5</td>
<td>6.02</td>
<td>2753</td>
<td>9</td>
</tr>
<tr>
<td>HP Zone 3</td>
<td>36</td>
<td>3.04</td>
<td>2654</td>
<td>164</td>
</tr>
<tr>
<td>HP exhaust</td>
<td>-</td>
<td>1.07</td>
<td>2497</td>
<td></td>
</tr>
<tr>
<td>LP Zone 1</td>
<td>135</td>
<td>1.02</td>
<td>2983</td>
<td></td>
</tr>
<tr>
<td>LP Zone 2</td>
<td>112</td>
<td>0.985</td>
<td>2962</td>
<td></td>
</tr>
<tr>
<td>LP Zone 3</td>
<td>370</td>
<td>0.185</td>
<td>2668</td>
<td>2880</td>
</tr>
<tr>
<td>Condenser</td>
<td>-</td>
<td>0.0058</td>
<td>2497</td>
<td></td>
</tr>
</tbody>
</table>

Some other parametric boundaries are as follows. Rated power: 10000MW, Rated speed: 1500 r/min, Delay time: 0.135 s, Valve closing time: 0.5 s etc.

According to the calculation, we get the LDA and Emergency overspeed calculation results for different rejected load conditions in different effective of flashing water (table 3 and table 4). The results showed that the overspeed rises 0.5%-0.6% if the wet steam energy is considered for 1000MW nuclear unit, so the energy for flashing water in nuclear unit could not be ignored.

**Table 3: LDA overspeed results comparison for considering wet steam or not.**

<table>
<thead>
<tr>
<th>Load rejection</th>
<th>Not Including</th>
<th>Including</th>
<th>increment</th>
</tr>
</thead>
</table>

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![Image](image-url)
LDA overspeed: This is peak overspeed assuming an LDA action, which closes governor and interceptor, given in RPM and in percent of rated speed.

Emergency overspeed: This is the peak overspeed after mechanical trip set point has been exceeded. Values are given in RPM and in percent of rated speed.

4 OTHER INFLUENCING FACTORS ON OVERSPEED CALCULATION

4.1 VALVE DELAY AND CLOSING TIME

The main steam valve are arranged in front of the HP admission, connecting to the island main steam to adjust admission steam and protective turbine. The reheate valves are arranged on the hot reheat pipes between the MSR and LP casing to cut off the LP inlet steam flow when necessary. At the beginning of unit rejection, the main steam valve cut off the steam flow from island, and the reheate valve cut off the steam flow from MSR to protect turbine to avoid overspeed. According the energy principle of overspeed calculation, the delayed closing time would bring additional high parameter steam into the HP and LP casing, and the extra steam energy will accelerate the rotor’s speed. (Tang, 2015) So choosing the valve with short closure time is better to control the overspeed value. Take the 1000MW nuclear unit for example, when the closure time of reheate valve decrease to 0.5s from 1s, the average overspeed value can decrease over 1%.

4.2 ALLOCATION OF EXTRACTION CHECK VALVES

According to the requirement of overspeed protection and water prevention to turbine, it’s need to arrange extraction check valves on the extraction pipes to keep the steam which is from heater or deaerator out of turbine at rejection and trip condition.

When overspeed occurred at the rejection condition, once one of the non-return valve break down, steam in the extraction pipe and heater will flow backward to the turbine due to differential pressure. The portion of steam with energy get into turbine to generate mechanical energy, and accelerate the rotor’s speed. According to the energy calculation, overspeed value will increase nearly 0.2% at non-return valve of one extraction line failure for 1000MW class nuclear unit. So to the unit with high overspeed protective requirement, especially to nuclear unit, the “1+1” extraction check valve allocation is recommended, namely, there are one extraction check valve with actuator and one extraction check valve without actuator in every extraction line and be arranged in one line, it can be seen in figure 2.

Table 4 Emergency overspeed results comparison for considering wet steam or not

<table>
<thead>
<tr>
<th>load rejection condition</th>
<th>not including flashing water</th>
<th>including flashing water</th>
<th>increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% load to 0% load</td>
<td>1729.4 r/min</td>
<td>1737.6 r/min</td>
<td>8.2 r/min</td>
</tr>
<tr>
<td>103% load to 0% load</td>
<td>1730.9 r/min</td>
<td>1739.1 r/min</td>
<td>8.2 r/min</td>
</tr>
<tr>
<td>0% load to 0% load</td>
<td>(115.29) (115.94%)</td>
<td>(115.94%) (116.4%)</td>
<td>(0.49%)</td>
</tr>
<tr>
<td>100% load to 0% load</td>
<td>1703.0 r/min</td>
<td>1710.3 r/min</td>
<td>7.3 r/min</td>
</tr>
<tr>
<td>103% load to 0% load</td>
<td>(113.53%) (114.02%)</td>
<td>(114.02%) (114.52%)</td>
<td>(0.49%)</td>
</tr>
</tbody>
</table>

Figure 2 The “1+1” extraction check valves allocation diagram

4.3 MOMENT OF INERTIA ON ROTOR

We can consider moment of inertia on rotor as inertance of rotor. The amount of moment of inertia on rotor have a large effective on overspeed result. Also take the 1000MW nuclear unit for example, every 15% increase in moment of inertia on rotor, the overspeed result would decrease about 1%. So it’s beneficial to decrease overspeed result through enhancing the moment of inertia on rotor. So in the phase of structure design, we could optimize the rotor structure in reasonable range to enhance the moment of inertia on rotor to decrease overspeed level in a certain extent.

5 CONCLUSION

This paper analysis and research the wet steam influence on overspeed of nuclear steam turbine, including energy and form of flashing water in wet steam zone. And summary overspeed calculation method of nuclear steam turbine considering wet steam influence, and get the increment about the results of overspeed calculation considering the influence of wet steam by means of example calculation. Furthermore, this paper explore how to lower the wet steam influence of nuclear turbine in technical aspect, such as the drainage and dehumidification measure to lower the overspeed to improve the safety and reliability for nuclear unit. Besides, other Influencing Factors that play an important role in overspeed also be summarized in this paper, such as the valve delay and closing time, allocation of extraction check valves, moment of inertia on rotor. These results could also provide reference for overspeed calculation and on-site data analysis for other nuclear units.

NOMENCLATURE

Abbreviations:
HP   high pressure
LP   low pressure
MSR  Moisture Separator and Reheater
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