Study on Minimum Inertia Demand of System Considering Frequency Stability of MIDC Power Grid

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Abstract. The increase of UHVDC feed capacity and the grid-connected capacity of distributed new energy lead to increasingly prominent frequency stability problem of MIDC (Multi-infeed DC) grid. Based on the simplified frequency analysis model, it theoretically analyses the influence of system inertia reduction on frequency stability under high power disturbance fault. A method for estimating the system synchronous inertia demand that meets the requirements of safe and stable operation of the system is proposed. The correctness and reliability of the proposed method are verified based on the time domain simulation data of the East China Power Grid.

1. Introduction
With the continuous increase of UHVDC capacity and distributed new energy grid-connected capacity, the risk of large capacity power shortage fault increases, and the inertia and primary frequency regulation capability of the system continuously reduces at the same time, resulting in the risk of MIDC grid frequency instability growing gradually [1-3]. Therefore, it is imperative to accurately grasp the frequency stability characteristics of MIDC power grid [4-5].

Wind power and photovoltaic are different from conventional unit. The equivalent rotational inertia is small and lacking relevant frequency adjustment function. Literature [6-8] proposed virtual inertia control in which new energy participates in primary frequency regulation, but this control method requires enough spare capacity in normal operation mode to work.

Aiming at non-inertia DC and large capacity of new energy access in East China Power Grid, this paper analyses the influence of inertia reduction on system frequency stability, and proposes a method to estimate the system synchronous inertia demand that meets the requirements of system safety and stability. The reliability of the proposed method is verified by time domain simulation data of East China Power Grid.

2. Influence of inertia reduction on frequency response characteristics

2.1. System equivalent inertia with the scale access of new energy
The inertia reflects the buffering capacity of the unit to the frequency change, ensuring that the generator has sufficient time to adjust the active power when the load disturbance is relatively large.
For conventional units, define the inertia time constant $H = (T_J/2)$ as the ratio for the generator rotor energy storage $E_{mr} = J\omega_s^2/2$ to the rated motor capacity $S_N$ at synchronous angular velocity $\omega_s$.

The standardized equation for the rotor motion based on Newton's law of motion in a multi-machine system is the following equations.

$$2H \frac{d\omega}{dt} = P_m^* - P_e^*$$

(1)

Among them, $S_i$ expresses the capacity of the $i$-th unit, $H_i$ indicates the time constant of the $i$-th unit. Take $S_r = \sum_{i=1}^{n} S_i$ as the reference capacity of all the conventional units. Multiply the left and right sides of the equations above by $S_r/S_i$ and add them together to get

$$2H \frac{d\omega}{dt} = \sum P_m^* - \sum P_e^*$$

(2)

In the equation, $H = \sum_{i=1}^{n} (H_i S_i)/S_r$ is the equivalent inertia time constant of all conventional units.

On this basis, assuming that grid-connected capacity of the new energy of the system is $S_W$, and define new energy penetration rate as

$$\eta = \frac{S_W}{S_W + S_r} = \frac{S_W}{S_S}$$

(3)

Further, the equivalent inertia time constant of the system is

$$H' = (1-\eta)H_e$$

(4)

2.2. Frequency response characteristics of the system

Assuming that the grid contains $n$ generator sets, the power-frequency static characteristic coefficient of the $i$-th unit is $K_{Gi}$ [9-10], the time constant of the speed regulation system is $T_{Gi}$, and the capacity of the $i$-th unit is $S_{Gi}$. Assuming that the time constants of the governors of all units are consistent, the equivalent power-frequency static characteristic coefficient of the total system is

$$K_{Geq} = \sum_{i=1}^{n} (K_{Gi} S_{Gi}) / \sum_{i=1}^{n} S_{Gi}$$

(5)

For systems with new energy penetration rate $\eta$, if all new energy units do not participate in primary frequency regulation, the equivalent inertia time constant of the system is further obtained as follows

$$K_{Geq}^* = (1-\eta)K_G$$

(6)

In a multi-machine system, if the distance relationship between generators is neglected, that is, regardless of the difference in time and spatial distribution of frequency in the system, and the average frequency of system is taken as the frequency of the entire grid, then the frequency response model of the system can be simplified to a stand-alone system model [11], as shown in figure 1.
\[
\frac{\Delta \omega}{\Delta \omega} = \frac{(1 - \eta) K_G}{(1 + \eta) K_L} - \frac{1}{2(1 - \eta) H_G}
\]

\[
\frac{\Delta P_m}{\Delta P_m} = \frac{(1 - \eta) K_G}{(1 + \eta) K_L} - \frac{1}{2(1 - \eta) H_G}
\]

\[
\Delta P_e \Delta P_e - + \frac{1}{2(1 - \eta) H_G}
\]

\[\frac{(1 - \eta) K_G}{(1 + \eta) K_L} - \frac{1}{2(1 - \eta) H_G}\]

**Figure 1.** System frequency response stand-alone model considering new energy access

In the figure, \(K_I\) is the load comprehensive adjustment effect coefficient, \(\Delta P_e\) is the active power difference, \(\Delta \omega\) is the generator speed deviation.

The stand-alone equivalent model takes the inertial response of the generator unit, the governor action, and the frequency characteristics of the load into account.

For a certain active power deficiency, assuming \(\Delta P_e = K_I s\), then the time domain expression of \(\Delta \omega\) is

\[
\Delta f(t) = \frac{60K}{K_L + (1 - \eta) K_G} \left(1 - \sqrt{1 + \left(\frac{a + c}{b}\right)^2 \cos(bt + \tan^{-1}\frac{a + c}{b})e^{-at}}\right)
\]

(7)

In the equation:

\[
a = \frac{K_I T_G + 2(1 - \eta) H_G}{4(1 - \eta) H_G T_G}; b = \frac{K_I T_G + (1 - \eta) K_G}{2(1 - \eta) H_G T_G} - \frac{1}{4} \left(\frac{K_G}{2(1 - \eta) H_G} + \frac{1}{T_G}\right); c = \frac{K_G}{2H_G T_G}
\]

(8)

In general, the boundary conditions for system frequency stability include slip (frequency change rate), maximum frequency deviation, and steady-state frequency. The influence of system inertia on each parameter is specifically analyzed as follows.

(1) Slip. Once a significant imbalance between power supply and demand occurs, the frequency of the power system responds immediately to change [12]. The initial frequency change rate determines how long the generator can fully perform the primary frequency regulation action before the system frequency begins to deteriorate. Initial frequency change rate is

\[
\frac{df}{dt} = \frac{-\Delta P_e f_0}{2(1 - \eta) H_m S_i}
\]

(9)

In the power system, when a certain amount of active power deficiency occurs, if the capacity of the new energy unit accounts for \(\eta\) of the total capacity of the system, the initial frequency drop rate of the system will increase by \(1/(1 - \eta)\) times.

(2) Lowest frequency point. The lowest point of grid frequency drop can describe the worst degree of frequency dynamic change, and is also an important reference for the under frequency load shedding scheme setting based on starting frequency and action delay. After the new energy is highly permeable and connected to the grid, the lowest point of the grid frequency drop can be calculated by the following method.

Derive the frequency expression, and let \(d \Delta f / dt = 0\), it can be seen that \(t_{\text{max}}\) which makes \(\Delta f(t)\) take the maximum \(\Delta f(t)_{\text{max}}\) should satisfy the following formula.

\[
\tan(bt + \tan^{-1}\frac{a + c}{b}) = -\frac{a}{b}
\]

(10)

Substituting the corresponding time \(t\) into the expression of the frequency, \(\Delta f_{\text{max}}\) can be further solved.
(3) Steady frequency. Considering that within a dozen seconds, after the system completes the primary frequency regulation, the frequency of the system gradually stabilizes. The steady frequency of the system is

$$\lim_{s \to 0} s\Delta\omega(s) = \frac{K}{K_c + (1-\eta)K_G}$$  \hfill (11)

It can be seen that the steady frequency of the system is independent to the inertia but is related to the primary frequency regulation capability of the system.

3. System frequency response under different DC fault disturbances

For the MIDC receiving grid, the frequency disturbance caused by DC fault mainly includes DC block fault and DC continuous commutation failure fault. The frequency response characteristics of the system after disturbance are analyzed as follows.

3.1. DC block fault

The DC block fault is a permanent active power disturbance fault. It is assumed that the system has sufficient reactive power dynamic adjustment capability. During the rapid frequency drop, the system voltage can keep substantially constant, and the influence of voltage is ignored when analyzing the frequency stability. Regardless of the emergency control, the above model can be further simplified under the high power disturbance fault, and the output of the primary frequency response of the conventional unit in the system is combined into a first order inertial response link, that is

$$\Delta P_m = \frac{K}{s(1+ sT)}$$  \hfill (12)

In the formula, $T$ is the system integrated time constant of the primary frequency regulation, $K$ is the maximum adjusted power of the primary frequency regulation. Then, the expression of the system generators speed deviation $\Delta\omega$ can be simplified as shown in the following equation.

$$\Delta\omega = \frac{(-PLT + KM + PM)e^{-LT/M} + (P + K(1-e^{-sT}))LT - M(K + P)}{L(-M + LT)}$$  \hfill (13)

Where $P$ is the amount of power disturbance and $L$ is the combination of the system damping and load regulation factors.

3.2. DC commutation failure

For the DC commutation failure, especially under the fault disturbance of continuous commutation failure, the frequency deviation is mainly related to the system inertia due to the short fault impact time, large fault disturbance, and the system primary frequency regulation is too late to respond. The replacement of new energy units greatly reduces the inertia of the system and the instantaneous power shock in a short period of time can cause severe system frequency deviation.

During the continuous commutation failure of DC, the relationship between the maximum frequency deviation of the system and the inertia, DC power $\Delta P$, and commutation failure duration $\Delta t$ of the system is as follows.

$$\frac{df}{dt}_{\text{max}} = \frac{f_{0}}{2} \frac{\Delta P}{E_{\text{MWS}}} \cdot \Delta f_{\text{max}} = \frac{f_{0}}{2} \frac{\Delta P}{E_{\text{MWS}}} \Delta t$$  \hfill (14)
4. Demand analysis of system minimum inertia considering frequency stability

4.1. Theoretical derivation
Take the certain mode of the East China Power Grid in a certain year as an example. The total load of the system is 160 million kilowatts, the total power of the DC floor is 72 million kilowatts, and the maximum floor power of a single DC is 11 million kilowatts. The total kinetic energy of the conventional start-up unit is 588564MW.s. Among them, the frequency adjustment factor of system load is 2.1, the unit primary frequency regulation upper limit is 3.1% of the rated capacity, and the average response time is 5 seconds. Assume that the system has sufficient dynamic reactive power adjustment capability and there is no voltage offset problem.

The boundary of frequency stability of East China Power Grid mainly includes slip and minimum frequency: the restraint of slip is mainly the slip block of the under frequency load shedding device, which is 5.0Hz/s, the maximum frequency deviation of the system considers the frequency protection setting of the distributed PV off-grid and the protection setting is 49.5 Hz. The under frequency load shedding action is fixed at 49.0 Hz. Based on the calculation formula of the previous section, the theoretical minimum inertia requirements of the system under different boundary conditions can be obtained as shown in the following table 1.

| Fault types                                  | Restraints                    | Inertia requirements    |
|----------------------------------------------|-------------------------------|-------------------------|
| DC monopole block (550MW)                    | Lowest frequency 49.5Hz      | 919580 MW.s             |
|                                              | Lowest frequency 49.0Hz      | 476900 MW.s             |
| All DC simultaneous commutation failures     | Slip 5Hz/s                   | 360000 MW.s             |
| (duration 0.2 seconds)                       |                               |                         |

4.2. Time domain simulation verification
The frequency response characteristics of East China Power Grid are simulated and analyzed based on time domain simulation. The frequency response characteristics of different inertia levels are studied by adjusting the starting capacity of conventional units or the access ratio of new energy. Through time domain simulation analysis, in the initial mode, the lowest frequency of the system after DC monopole block of 11 million kilowatts is 49.2 Hz, and the initial slip of the system reaches 3.0 Hz/s after all DC commutate fail simultaneously.

4.2.1. Frequency response analysis under DC block fault. After the maximum floor power DC monopole block of East China Power Grid, the system power shortage is 5.5 million kilowatts. The frequency response curve of the system under different inertia is shown in the figure 2.

![Figure 2. System frequency curve after DC block](image)

It can be seen that by increasing the starting capacity of the conventional unit, when the system inertia is increased to 879,840 MW.s, the lowest frequency of the system after the fault is 49.5 Hz, by increasing the grid-connected capacity of the new energy, when the system inertia is reduced to
446,180 MW.s, after the fault, the lowest frequency of the system is 49.0 Hz, and the corresponding new energy penetration rate at this time is 14.3%.

4.2.2. Frequency response analysis of DC continuous commutation failure. Under the severe fault of the main grid, there may be a risk of multi-DC continuous commutation failure. It is assumed that all DC of the system simultaneous commutation failure. The frequency response curve of the system at different inertia levels is shown in the figure 3.

![Figure 3. System frequency curve after DC commutation failure](image)

The simulation curve shows that when the new energy access ratio reaches 22.7%, that is, the system inertia decreases to 357800 MW.s, the average rate of change within the initial 10 milliseconds after the fault reaches 5 Hz/s.

Under the above two kinds of faults, the minimum inertia demand obtained by the simulation is slightly larger than the theoretical estimation value. This is because the system damping and the frequency regulation characteristics of the load will slow down the rapid drop of the frequency to a certain extent, which is beneficial to the frequency stability of the system, leading to the theoretically calculated inertia demand may be slightly conservative relative to the actual situation.

5. Summary

With the continuous increase of UHVDC capacity and distributed new energy grid-connected capacity, the risk of frequency instability of MIDC power grid gradually increases. Through the impact on the system inertia after the large scale access of new energy, the relationship between system frequency stability and new energy penetration rate is analyzed. Based on the MIDC grid of East China, the minimum inertia requirement corresponding to the maximum slip and minimum frequency meeting frequency stability under different DC disturbances is analyzed, and the rationality and accuracy of the theoretical derivation method are verified by simulation. The method can be widely used in the UHV DC receiving power grid and the new energy scale to access the power grid. Through the estimation of the minimum inertia required by the system, the grid operation mode arrangement and grid dispatching are effectively guided, and the frequency stability of the power grid is improved.

Acknowledgments

This work was supported by State Grid Jiangsu Electric Power Co., Ltd. (The Science and Technology Project of “Study on Influence of Inertia Reduction on Safety and Stability of Jiangsu Power Grid and System Inertia Demand”).

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