Analysis on the Influence of Wind Power Participating in Frequency Modulation on Low-frequency Oscillation in Yunnan Power Grid

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Abstract: Low-frequency oscillation in Yunnan power grid with a high proportion of hydropower units is prominent. With the continuous access of large-scale new energy sources, it poses a serious threat to the frequency stability of the power grid. Based on the simulation model of Yunnan power grid in 2020, this paper studies the effect of wind power participating in frequency modulation on the damping of Yunnan power grid. Several low-frequency oscillation modes in Yunnan power grid are given through the analysis of two typical operation modes of Xia Da and Chun Xiao. This paper also analyzes the effect of the fan on the low-frequency oscillation mode of Yunnan power grid after adding primary frequency modulation and inertial control. The results show that both inertia control of fan and excessive primary FM sag coefficients will reduce the damping of the system. After wind power is involved in frequency modulation, a favorable effect on the damping of the low-frequency oscillation mode of Yunnan power grid can be produced by setting the control parameters appropriately.

1. Introduction

According to the requirements of China’s 14th Five-Year Plan for power development, the installed wind power capacity is expected to reach 540 million kilowatts in 2025. As of the beginning of 2020, the total installed wind power capacity of Yunnan Power Grid has reached 8854.85MW, accounting for 11.21% of the total installed capacity. The Yunnan power grid is sent out via ten-cycle DC, and after asynchronous interconnections with the Southern Power Grid, the power system of a high percentage of hydropower units is highly susceptible to weak damping or negative damping oscillations, and the problem of frequency stability are salient. The newly promulgated "Guidelines for the Safety and Stability of Power Systems", which took effect on July 1 this year, has added the requirement that new energy sources such as grid-connected wind farms should have primary frequency modulation capability. In this context, it is of great significance to study the influence of FM control parameters on the low-frequency oscillation of the system in combination with the actual engineering of Yunnan Power Grid, to meet the needs of the development of wind power in Yunnan Power Grid and to promote the energy transformation of Yunnan Power Grid.

Literature [1] proposed a method for modeling hydropower units, and the results show that if the sensitivity of governor is set high, coupled with the water hammer effect of the turbine itself, the frequency stability of the power system can be seriously affected. The Literature [2] established a
linearized model of doubly-fed fan based on the concept of amplitude-phase motion equation, studied the influence of inertia control parameters on the low-frequency oscillation mode of synchronous machine, and revealed the dynamic interaction mechanism between fan and synchronous machine. Literature [3] established a DFIG small signal model with PLL phase-locked loop and virtual inertia control to study how the PI parameters of the phase-locked loop is essential to the virtual inertia of fan, which in return led to the change of the damping ratio of system.

Based on the simulation model of Yunnan power grid after wind power participating in FM, this paper summarizes the existing oscillation patterns of Yunnan power grid under typical operation modes. Also, it analyzes the influence of the primary FM capability of wind farms on the damping ratio of the system, sums up the relevant rules, and provides guidance for the selection of fan control parameters in actual projects.

2. Low-frequency oscillation mechanism

Power oscillations sometimes occur between power system operating units, with low frequency oscillation frequencies ranging from 0.2 to 3 Hz. It is generally believed that the mechanism of low-frequency oscillation is due to the negative damping provided by the system under certain circumstances to offset the positive damping of the system motor, excitation winding, machinery and other aspects, so that the total damping of the system is small or negative.

The negative damping mechanism was proposed by F.P. Demello in 1969 [4]. Weakly damped or negatively damped low-frequency oscillations may occur when the currents of large-scale long-distance transmission lines are heavy. If the generator excitation system moves faster, the problem of negative damping will be more serious. In particular, for the Yunnan power grid with a high proportion of hydropower units, a more sensitive turbine governor parameters may easily cause instability in the dynamic processes of the system. When the damping of the system is low, the low-frequency oscillation amplitude will diverge and eventually lead to the system destabilization.

3. Research objects and methods

3.1 Double-fed fan control model
As shown in Figure 1, the control block diagram of the double-fed fan includes the control of the fast time scale of AC current, the medium speed time scale of DC voltage and the slow time scale of rotor speed.
The output voltage vector of the fan is synchronized with the voltage vector $V_t$ of the grid side through PLL phase lock. The control objective of the AC current time scale is to enable the rotor winding current $i_{rd}$, $i_{rq}$ and grid-side filter inductor current $i_{gd}$, $i_{gq}$ track the current reference value given by the external loop controller. The control objective of DC voltage time scale is to stabilize DC bus capacitor voltage $V_{dc}$. The control objective of the rotor speed time scale is to achieve maximum power tracking and to avoid rotor overspeed by adjusting the rotor speed $\omega_r$. The energy storage size of the control object varies from scale to scale, so the control dynamics of the three scales are fast and slow. Generally speaking, the control bandwidth of AC current time scale is 10 milliseconds, DC voltage time scale is 100 milliseconds and rotor speed time scale is seconds.

3.2 The Internal Potential Equation for the Electromechanical Time Scale of Doubly-fed Fan

In AC systems, synchronous machines or wind turbines and other nodes of equipment can be equivalent to internal potential and impedance in series based on Davenan's theorem, and the active and reactive power balance can be achieved by adjusting the phase amplitude of the potential within the node to ensure the stability of the grid voltage frequency and amplitude.

Assuming that the stator current out of the motor for the positive direction, and the rotor current into the motor for the positive direction, the steady-state standard unitary mathematical equation of the doubly-fed induction generator expressed in the form of complex vector in the synchronously rotating $dq$ coordinate system:

\[
\begin{align*}
V_s &= -R_s I_s + j\omega \psi_s \\
V_r &= -R_r I_r + j\omega_{dip} \psi_r
\end{align*}
\]
\[
\begin{align*}
\psi_s &= L_m I_r - L_s I_s \\
\psi_r &= L_s I_r - L_m I_s
\end{align*}
\tag{2}
\]

In the formula, \(V_s\), \(V_r\), \(\Psi_s\), \(\Psi_r\), \(I_s\), \(I_r\) represents the stator voltage vector, rotor voltage vector, stator flux vector, rotor flux vector, stator current vector and rotor current vector respectively. \(\omega_1\) is the synchronous speed, and \(\omega_{\text{slip}}\) is Slip, \(R_s\), \(R_r\) is the stator and rotor resistances, and \(L_m\), \(L_s\), and \(L_r\) are mutual inductance, stator inductance, and rotor inductance, respectively.

After ignoring the electromagnetic dynamic process of rotor-side current control, bringing Eq. (2) into Eq. (1) and neglecting the effect of internal resistance, one obtains:

\[
\begin{align*}
V_i &= j \omega_1 L_m I_r - j \omega_1 L_s I_s = E_s - j \omega_1 L_s I_s \\
E_s &= j \omega_1 L_m I_r, \quad X_s = \omega_1 L_s
\end{align*}
\tag{3}
\]

\(E_s\) is defined as the internal potential of the doubly-fed fan. The excitation current of the rotor winding of the doubly-fed fan first establishes a rotor magnetic field. After the magnetic field passes through mutual inductance, the AC voltage induced in the stator winding is the electric potential within the electromechanical time scale of the doubly-fed fan.

According to formula (3), the expressions of internal potential amplitude \(E_s\) and internal potential phase \(\theta_s\), active power \(P_s\) and reactive power \(Q_s\) can be obtained

\[
\begin{align*}
E_s &= \omega_1 L_m \sqrt{i_{\text{id}}^{\text{PLL}} + i_{\text{iq}}^{\text{PLL}}} \\
\theta_s &= \theta_{\text{PLL}} + \pi/2 + \arctan\left(\frac{i_{\text{iq}}^{\text{PLL}}}{i_{\text{id}}^{\text{PLL}}}\right)
\end{align*}
\tag{4}
\]

In the formula, \(i_{\text{id}}^{\text{PLL}}\) and \(i_{\text{iq}}^{\text{PLL}}\) are the active and reactive currents in the PLL coordinate system respectively, and \(\theta_{\text{PLL}}\) represents the phase of the PLL relative to the stationary coordinate system.

\[
\begin{align*}
P_s &= \frac{E_s V_i}{X_s} \sin(\theta_s - \theta_i) \\
Q_s &= \frac{E_s}{X_s} - \frac{E_s V_i}{X_s} \cos(\theta_s - \theta_i)
\end{align*}
\tag{5}
\]

Similar to the synchronous machine, when the value of \(\theta_s-\theta_t\) is disturbed, it will cause the active power output of the fan to oscillate or diverge. The internal potential phase of the doubly-fed fan is determined by its internal control. Therefore, the internal potential phase of the doubly-fed fan can be changed by changing the primary frequency modulation and inertia control parameters of the doubly-fed fan, thus affecting the damping of the system.

### 3.3. Research method

The 2020 grid model of Yunnan Power Grid is adopted, and two typical operation modes of Xia Da and Chun Xiao are mainly considered in the calculation. The generator models of the main units mostly adopt the sub-transient model with damping winding. The fan model is a three-generation model with a primary FM card and an inertia control card. The load model used in the calculation is a pure static load model.

Currently, the methods used for the analysis of low-frequency oscillations in power systems can be divided into two main categories: model-based analysis methods and analysis methods based on measured data. According to different research objects and applications, different research methods are selected to carry out low-frequency oscillation research. Among them, the implicit restart Arnoldi algorithm belongs to the eigenvalue analysis method among the model-based analysis methods, which...
has been applied in the practical analysis of large-scale power systems, and integrated in the small disturbance stability analysis program (PSD-SSAP). This article will use this method for research.

4. Simulation Results and Analysis of Yunnan Power Grid

4.1 Major oscillation modes in Xia Da mode

In the Xia Da operation mode, 52,703 MW of power was generated with a load of 25,490 MW. In this way, large hydropower stations in the main network are as full as possible while all fans are fully generated. New energy output accounts for about 15% of the total grid power generation. Using the small disturbance stability analysis program (PSD-SSAP) to implicitly restart the Arnoldi algorithm, there are seven major interval oscillation modes in Yunnan Power Grid.

| Mode | Real  | Imaginary | Oscillation frequency/Hz | Damping ratio | Oscillation area |
|------|-------|-----------|--------------------------|---------------|-----------------|
| 1    | -0.566| 5.584     | 0.889                    | 0.101         | Lincang - Lijiang |
| 2    | -0.679| 5.806     | 0.924                    | 0.116         | Lincang - Lijiang |
| 3    | -0.706| 5.426     | 0.864                    | 0.129         | Dehong, Lincang - Pu'er, Banna |
| 4    | -0.807| 5.556     | 0.884                    | 0.144         | Nujiang - Lincang |
| 5    | -0.801| 3.642     | 0.582                    | 0.215         | Pu'er, Banna - Zhaotong |
| 6    | -1.09 | 3.938     | 0.627                    | 0.267         | Zhaotong - Lijiang |
| 7    | -0.807| 5.556     | 0.884                    | 0.144         | Nujiang - Lincang |

The following studies the influence of inertia parameters, respectively compare $K_{wi}=10$, $T_{womi}=5.5$; $K_{wi}=50$, $T_{womi}=5.5$; The change of eigenvalues of the system under three conditions of inertia control ($K_{wi}$ is the inertia control proportional coefficient, $T_{womi}$ is the inertia control differential Time constant). According to the implicit restart Arnoldi algorithm, the inter-regional oscillation modes within the oscillation frequency of 0.1-2 Hz are selected for comparison, and the modes with a damping ratio change greater than 0.01% are recorded. After comparison, only two groups of interval modes, that is, the above-mentioned No5, No6 modes are influenced. And the damping ratio changes of all other modes are less than or equal to 0.01%. The comparison results of frequency and damping ratio under different inertia control are shown in Table 2.

| Mode | Inertia control parameters | Frequency/Hz | Damping ratio | Damping ratio change |
|------|----------------------------|--------------|---------------|----------------------|
| 5    | K_{wi}=10                  | 0.5797       | 0.2147        | -0.04%               |
|      | K_{wi}=50                  | 0.5818       | 0.2136        | -0.15%               |
| 6    | K_{wi}=10                  | 0.6267       | 0.2668        | -0.06%               |
|      | K_{wi}=50                  | 0.6289       | 0.2646        | -0.28%               |

Modes 5 and 6 mainly involve the Xiluodu to Nuozhadu and Xiluodu to Aha and Liyuan power plants. When the fan is added to the inertia control, there is a slight decrease in the damping ratio corresponding to these two modes. when the inertia control ratio parameter increases from 10 to 50, the negative effect will correspondingly increase.

Similarly, the influence of primary FM gain parameters is studied below. To simplify the analysis, the primary FM sag coefficients of positive/negative frequency deviation are the identical, and the system characteristic values are compared when the sag coefficients Kdroop are 10, 50 and 250 respectively (in this case, the inertia parameters are selected as $K_{wi}=10$ and $T_{womi}=5.5$). The modes with large change in damping ratio were recorded, and after comparison there are three groups of interval mode, namely, mode 5, 6, 7. The comparison results of frequency and damping ratio under
different primary FM parameters are shown in Table 3.

When the fan changes the FM droop control parameter once, it has obvious influence on the damping ratio of these three modes; Specifically, increasing the droop control parameter of the primary frequency modulation will cause the damping ratio to increase. When this parameter increases from 10 to 250, the system damping is stronger.

| Mode | Primary frequency modulation parameters | Frequency/Hz | Damping ratio | Damping ratio change |
|------|----------------------------------------|--------------|---------------|---------------------|
| 5    | 10                                     | 0.5803       | 0.1981        | -                   |
|      | 50                                     | 0.5797       | 0.2147        | 1.66%               |
|      | 250                                    | 0.5975       | 0.2323        | 3.42%               |
| 6    | 10                                     | 0.6249       | 0.2487        | -                   |
|      | 50                                     | 0.6267       | 0.2668        | 1.81%               |
|      | 250                                    | 0.6492       | 0.2813        | 3.26%               |
| 7    | 10                                     | 0.8838       | 0.1421        | -                   |
|      | 50                                     | 0.8842       | 0.1437        | 0.16%               |
|      | 250                                    | 0.8887       | 0.1463        | 0.42%               |

### 4.2 Major oscillation modes in Chun Xiao mode

In the Chunxiao operation mode, 13,778MW of power was generated with a load of 9,002MW, while the output of hydropower generating units was not high, but the proportion of new energy sources was high, which could reach 40% of the total output of the grid. Due to the low output of hydropower generating units, the number of oscillation modes in the system is reduced, and there are four major interval oscillation modes in Yunnan Grid.

| Mode | Real Part | Imaginary part | Oscillation frequency/Hz | Damping ratio | Oscillation area       |
|------|-----------|----------------|--------------------------|---------------|------------------------|
| 1    | -0.519    | 8.624          | 1.373                    | 0.06          | Qujing - Zhaotong      |
| 2    | -0.578    | 8.583          | 1.366                    | 0.067         | Zhaotong - Qujing      |
| 3    | -0.556    | 6.394          | 1.018                    | 0.087         | Dehong, Lincang - Pu'er |
| 4    | -0.601    | 4.856          | 0.773                    | 0.123         | Pu'er - Lincang        |

The following studies the influence of the inertia parameters, respectively comparing \( K_wi=10, T_{womi}=5.5 \); \( K_wi=50, T_{womi}=5.5 \). The change of eigenvalues of the system is controlled under three conditions without inertia. The oscillation frequency of 0.1~2Hz in all oscillation modes were selected for comparison, and the mode with damping ratio change greater than 0.01% was recorded. After comparison, it only has an impact on one set of interval modes, that is, Pu 'er-Lincang mode No. 4. And the damping ratio changes of all other modes are less than or equal to 0.01%. The results of the frequency and damping ratio in this mode are shown in Table 5.

| Mode | Inertia control parameters | Frequency/Hz | Damping ratio | Damping ratio change |
|------|---------------------------|--------------|---------------|---------------------|
| 4    | No inertia control        | 0.7726       | 0.1234        | -                   |
|      | Kw_i=10                   | 0.7728       | 0.1228        | -0.06%              |
|      | Kw_i=50                   | 0.7737       | 0.1206        | -0.28%              |

From Table 5, it can be seen that with the addition of inertia control (reference parameter \( Kw_i=10, T_{womi}=5.5 \)), the damping ratio of relative inertia-free control is reduced by 0.06%, while the proportional coefficient of inertia control is increased by 5 times and the damping ratio is further reduced, which is 0.28% lower than that without inertia control. Adding inertia control has a weak
negative effect on damping ratio of the mode in this area, and the degree of influence increases with the increase of inertia ratio coefficient. The results are similar to those under the operation of Xia Da mode.

Similarly, the influence of primary FM gain parameters is studied below. To simplify the analysis, the primary FM sag coefficients with positive/negative frequency deviation are identical, and the system characteristic values with sag coefficients Kdroop of 10, 30, 50, 100, 150 and 250 are compared respectively (in this case, the inertia parameters are selected as \( K_{\text{wi}}=10 \), \( T_{\text{wowi}}=5.5 \)). Recoding the modes with large changes in damping ratio. After comparison, there is a group of interval modes, namely mode No.4, Pu'er's oscillation to Lincang, the comparison results of frequency and damping ratio changes are shown in Table 6.

| Mode | Primary frequency modulation parameters | Frequency/Hz | Damping ratio | Damping ratio change |
|------|----------------------------------------|--------------|---------------|---------------------|
| 10   | \( K_{\text{droop}} = 10 \)           | 0.7646       | 0.1145        | -                   |
| 30   | \( K_{\text{droop}} = 30 \)           | 0.7681       | 0.1201        | 0.56%              |
| 50   | \( K_{\text{droop}} = 50 \)           | 0.7728       | 0.1228        | 0.83%              |
| 100  | \( K_{\text{droop}} = 100 \)          | 0.7829       | 0.1209        | 0.64%              |
| 150  | \( K_{\text{droop}} = 150 \)          | 0.7882       | 0.116         | 0.15%              |
| 250  | \( K_{\text{droop}} = 250 \)          | 0.7920       | 0.1089        | -0.56%             |

When changing the wind turbine primary FM sag control parameters, there is a clear impact on the damping ratio of the mode; with the increase in primary FM gain, the oscillation frequency will be slightly increased, the system damping ratio first increases and then decreases.

5. Conclusions

Based on the simulation model of Yunnan power grid in 2020, this paper studies the influence of wind power participation in frequency modulation on low-frequency oscillation of Yunnan power grid, and the following conclusions are obtained.

- Under the same regulation capacity limit of the fan, the characteristics of the network determine the intensity of the fan on each region, and thus the damping ratio of the oscillation pattern between regions varies when the fan participates in frequency modulation. Therefore, Considering the maximum improvement of system damping, different fan control parameters can be set according to the oscillation modes in different regions of Yunnan power grid.

- In different operating modes, the proportion of fan output determines the strength of the fan's participation in the inter-regional oscillation mode. When the proportion of fan output is high, an excessive frequency adjustment parameter will reduce the system damping ratio. Therefore, the primary frequency adjustment parameters of the wind turbine should be set appropriately to adapt to the different operating modes of Yunnan power grid.

- When the fan is added to the inertia control, the damping of the system decreases and the adverse effect on the system increases with the growing inertia proportional coefficient.

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