Self-adaption Dynamic Virtual Inertia Control Strategy of Doubly fed Variable Speed Pumped Storage Unit

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Abstract. The power decoupling control characteristic of doubly fed variable speed pumped storage unit (VSPS) makes the rotor of VSPS unable to respond to the change of grid frequency and reduces the inertia of power system. In this paper, a self-adaption dynamic virtual inertia control strategy for VSPS is proposed. The strategy introduces correction factor to change the coefficient of control by detecting the change of $\Delta f/dt$ and automatically control the active power output of VSPS to provide dynamic frequency support for power grid. Simulation results demonstrate that by dynamically compensating the reference power of doubly fed converter, the strategy can effectively increase the frequency stability of power grid.

1. Introduction
The intermittent and fluctuating characteristics of renewable energy would reduce the frequency stability of power system. The doubly fed induction generator (DFIG) based variable speed pumped storage unit (VSPS) has the advantages of flexible control and rapid power response [1], and becomes one of the most economical and effective means to ensure the safe and stable operation of power system.

However, the power decoupling control characteristic of doubly fed converter makes the rotor of DFIG in VSPS unable to respond to the grid frequency change thus VSPS contributes no inertia to the whole inertia of power system [2]. The direct consequence of this is that the frequency stability of the system decreases. In order to improve overall inertia and therefore improve frequency stability of power system, applying virtual inertia control to VSPS is therefore needed [3].

In the existing literatures, proportional differential (PD) controller is most commonly adopted by the virtual inertia control loop of doubly fed converter for DFIG based wind turbine generator. In Reference [4] control loop of $df/dt$ is replaced by $\Delta f/dt$ to compensate for the negative damping of VSPS that is introduced by traditional inertial control. In Reference [5] the variable droop coefficient strategy is used to change the distribution of active power output of generation units in the system, which successfully improves the lowest frequency of the system.

However, despite the fact that virtual inertia control of DFIG based variable wind turbine generator have been extensively investigated in vast literatures, there is a serious shortage of research in the area of virtual inertia control of VSPS. Besides, the existing control strategy of VSPS are generally adopt fixed control coefficients, the advantages of large adjustable range of unit speed are neglected [6], and the potential of enhancing frequency stability of power system by fully tapping the real-time available capacity of unit is neglected.
In this paper, a self-adaption dynamic (SAD) virtual inertia control strategy for VSPS is proposed. The strategy introduces correction factor to change the coefficient of control by detecting d∆P/dt and automatically control the active output of VSPS to provide dynamic frequency support for power grid. Simulation results demonstrate that compared with droop control and fixed coefficient virtual inertia control, VSPS with SAD virtual inertia control has better frequency response capability and stronger inertial support capability for power system, which verifies the feasibility of the proposed strategy.

2. Modeling of VSPS

2.1. Overall structure of VSPS

VSPS is a new type of hydraulic power generation system, which consists of reversible pump turbine unit, speed governor, doubly fed converter and so on. The stator of DFIG is connected to grid, and the three-phase symmetrically distributed excitation windings are used on rotor where variable frequency power supply device provides symmetrical AC excitation to it. The magnitude, frequency, phase and sequence of excitation voltage can be controlled according to the requirements, so that the magnitude and position of excitation magnetic field relative to rotor and the speed of DFIG can be controlled. Strong controllability makes DFIG have high operation stability, variable speed and constant frequency power generation capacity and independent active and reactive power regulation capacity [7]. The system diagram of VSPS is shown in figure 1. The optimal speed reference of VSPS is calculated according to the nonlinear characteristic of pump turbine and reference power \( P^* \) of VSPS and net head \( H^* \) of water reservoir. The speed control of VSPS is realized by adjusting the guide vane opening through speed governor. Stator flux orientation control is adopted by double fed converter to control the electromagnetic power of DFIG according to the power instruction. In the diagram, \( P_{ref} \) is rotor side active power reference command and \( \Delta \dot{P} \) is additional power command by control strategy.

2.2. Model for rotor side control of DFIG converter

On the premise of applying stator flux orientation control for DFIG and decoupling control for double fed converter, the active and reactive power of DFIG are regulated by stator current \( i_{ds} \) and \( i_{qs} \) respectively. For the sake that \( i_{ds} \) and \( i_{qs} \) are directly controlled by the rotor side converter of doubly fed converter, and the main control purpose of the grid side converter is to maintain the DC-side capacitor voltage stability, only the control block of rotor side is given, as is shown in figure 2. In the diagram of rotor side control, double closed-loop control structure is adopted where the outer loop is power control loop, which is mainly responsible for controlling the active and reactive power of DFIG, and the inner loop is current control loop, which is mainly responsible for controlling the \( d \) and \( q \) axis currents for DFIG, respectively.
3. Virtual inertia control of VSPS

3.1. Virtual inertia control of VSPS
By adding $\Delta P$ to the reference value of active power for the rotor side converter of VSPS and releasing the kinetic energy stored in the rotor to actively respond to the frequency change of power system, the frequency response characteristic of conventional generator can be simulated and the inertia of the system can be increased. Power of VSPS in transient state is affected by coefficient of differential link. The additional active power $\Delta P$ of virtual inertia control is expressed as follows:

$$\Delta P = (K_p \Delta f + K_d \frac{d \Delta f}{dt})$$  \hspace{1cm} (1)

Where $\Delta f$ is system frequency deviation, and $K_p$ and $K_d$ are coefficients of proportional and differential control, respectively.

3.2 Relationship between virtual inertia control and frequency stability of power system
Frequency stability of power system is directly affected by system inertia and damping [3]. The greater the inertia is, the lower the frequency offset and the initial frequency change rate are, but the adjustment time of frequency stabilization increases. With the increase of system damping, the frequency offset decreases, but the speed of frequency reaching peak value accelerates and the initial frequency change rate increases. The rotor motion equation of VSPS is as follows:

$$(2H_s + K_p)\frac{d \Delta f}{dt} = P_m - P_e - (D + K_p)\Delta f$$  \hspace{1cm} (2)

Where $H_s$ is inherent inertia constant of VSPS, $D$ is damping coefficient, $P_m$ is mechanical power of prime mover and $P_e$ is electromagnetic power of VSPS.

$K_p$ and $K_d$ directly determine the damping and inertia of virtual inertia control introduced into the system by VSPS, and jointly determine the frequency response characteristics of the system [8]. $K_p$ produce system damping, while $K_d$ produce a similar rotational inertia as synchronous generator. With the increase of $K_p$, the frequency nadir (FN) and recovery speed of the system increase, the short-term power of VSPS decreases, and the steady-state rotation speed of VSPS decreases. $K_d$ determines the inertial response characteristics of the system. The larger the $K_d$, the slower the system frequency descends, the longer the time to reach FN and the oscillation time, the higher the short-term power of VSPS, while the steady-state rotation speed of VSPS remains unchanged.

4. Self-adaption dynamic (SAD) virtual inertia control
When load disturbance occurs in the system, the frequency will change from the original stable value to the new stable value, and the frequency oscillation will occur at the moment of the disturbance. The typical frequency change curve can be divided into three stages. The characteristics of frequency variation and the required virtual inertia are different in each stage.

In stage 1, the load suddenly increases, the frequency drops rapidly to reach FN, $d\Delta f/dt$ suddenly increases from 0 to the maximum value, and falls back in a very short time, and decreases to 0 in FN. At this stage, $\Delta f<0$ and $d\Delta f/dt<0$, it is necessary to increase the inertia of VSPS and power system by increasing the power reference value of rotor side converter of VSPS, so that the rotor can release kinetic energy quickly, restrain the speed of the system frequency drop and improve FN.

In stage 2, $\Delta f$ begins to decrease slowly, and $d\Delta f/dt$ crosses zero first and then reverses. At this stage, $\Delta f<0$ and $d\Delta f/dt>0$, at the same time, the rotor of VSPS enters the acceleration stage. In this stage the value of virtual inertia should be appropriately reduced to speed up frequency recovery.

In stage 3, the frequency tends to be stable and the value of virtual inertia should be stable.

To meet the requirements, the additional power provided by the virtual inertia control of VSPS, i.e. the virtual inertia of VSPS, is automatically and dynamically adjusted by the correction factor $\alpha$. The relationship between $\alpha$ and $\Delta f$ and $d\Delta f/dt$ is as follows.

\[ \alpha = \frac{\Delta f}{d\Delta f/dt} \]
\[
\begin{cases}
\alpha = 1, & \left| \frac{d\Delta f}{dt} \right| < K_1 \\
\alpha = 1 + k \frac{d\Delta f}{dt}, & K_1 \leq \left| \frac{d\Delta f}{dt} \right| \leq K_2 \\
\alpha = 1 + k K_2, & \left| \frac{d\Delta f}{dt} \right| > K_2
\end{cases}
\]

(3)

Where \( k \) is the proportionality coefficient, \( K_1 \) and \( K_2 \) are the interval separating values of \( \frac{d\Delta f}{dt} \). \( K_1 \) can avoid the coefficient oscillation caused by measurement error and ensure the stability of the system in steady state. \( K_2 \) can limit the over-response of unit caused by excessive \( \frac{d\Delta f}{dt} \), thus avoiding unit power oscillation.

After introducing the correction factor, the additional active power reference value \( \Delta P \) provided by SAD virtual inertia control is as follows.

\[
\Delta P = \alpha K_d \Delta f + K_p \frac{d\Delta f}{dt} + \frac{d\alpha}{dt} + k \Delta f \frac{d\Delta f}{dt} = \Delta P_d + \Delta P_f + \Delta P_ad
\]

(4)

In addition to the proportional part \( \Delta P_p \) and differential part \( \Delta P_d \) provided by traditional virtual inertia control, the additional power \( \Delta P_ad \) is added in \( \Delta P \) by SAD virtual inertia control. In the initial phase of frequency drop, the sign of \( \Delta f \) and \( \frac{d\Delta f}{dt} \) are identical, \( \Delta P_ad \) is positive, and the power reference value of VSPS increases correspondingly. The SAD control has a larger electromagnetic power increment than traditional virtual inertia control of the same control parameter, which can more effectively suppress the frequency drop and provide greater inertial support. On the contrary, in the stage where the frequency starts to recover, the sign of \( \Delta f \) and \( \frac{d\Delta f}{dt} \) are different, therefore \( \Delta P_ad \) is negative. The power reference value is consequently becomes smaller, and the active power output of VSPS is reduced appropriately, which avoids the severe power oscillation of the unit.

5. Simulation analysis

To verify the effectiveness of SAD virtual inertia control, an isolated power system including 100 MW wind farm \( G_1 \), 10 MW diesel engine \( G_2 \), two 100 MW VSPSs \( G_3 \) and \( G_4 \), and loads \( L_1 \) and \( L_2 \) is built. Under initial condition, load is 100 MW, wind speed keeps 10 m/s unchanged, and the system operates in steady state. At 1s, 20 MW impulse load is put into operation. Under the same simulation conditions, VSPS is controlled by traditional droop control, traditional virtual inertia control and SAD virtual inertia control, and the results are compared.

(a) Power of VSPS. 
(b) Frequency of power system.

Figure 3. Frequency and power response of VSPS.

5.1. Comparison of different inertia control strategies

The frequency and power response curve of VSPS is shown in figure 3. The coefficient of droop is \( 1/0.05 \), \( K_p =1/0.05 \), and \( K_d =15 \). When applying traditional droop control, FN is 49.52Hz, the maximum output of the unit is 29.2MW, and the adjustment time is 7s. When applying traditional virtual inertia control, FN is 49.75Hz, the maximum output of the unit is 44.4MW, and the adjustment time is 4s. Compared with traditional droop control, FN of traditional virtual inertia control increased by 0.25Hz and the adjustment time is 42.8% faster. It is obvious that, by using virtual inertia control strategy, falling speed of the system frequency slows down and the frequency oscillation is restrained.
The frequency and power response curves of fixed coefficient virtual inertia control and SAD virtual inertia control are shown in figure 4. In all cases, $K_p = 1/0.05$, however, $K_{d1} = 15$ for small inertia control, $K_{d2} = 30$ for large inertia control, and $K_{d3} = 15$ for SAD control.

![Frequency and power response curves](image)

**Figure 4.** Frequency and power response of virtual inertial control.

In the phase of frequency drop, the maximum power output of VSPS in the case of small inertia control is 29.5 MW, in the case of large inertia control is 34.5 MW, and in the case of SAD control is 34 MW. Compared with the small inertia control with the same control coefficient, the maximum instantaneous power output of VSPS by SAD control increased by 15.25%. The effect of suppressing frequency drop by SAD control is more obvious, and the effect of inertia response is close to that of large inertia control. In the phase of frequency recovery from FN to stable value, FN of large inertia control is 49.73Hz, and adjusting time is 7s; FN of SAD control increased to 49.76Hz, and adjusting time is 5s. By dynamically reducing the inertia of VSPS, SAD control avoids the oscillation caused by over-response of the unit, and the frequency adjustment time becomes shorter, which speeds up the frequency recovery of the system.

![Correction factor by SAD control](image)

**Figure 5.** Correction factor by SAD control.

Correction factor $\alpha$ by SAD control is shown in figure 5. $\alpha$ undergoes a dynamic process from rapid increase to gradual decay to steady state. During the phase of frequency drop, $d\Delta f/dt$ increases rapidly and SAD virtual inertia control responds quickly correspondingly. The power reference of VSPS is adjusted by increasing $\alpha$, and then the virtual inertia of the system is increased. After the frequency drops to FN, it enters the frequency stabilization stage, $d\Delta f/dt$ is quite small. The frequency is stabilized quickly by reducing the equivalent inertia through decreasing $\alpha$. In the stable stage, $d\Delta f/dt$ approaches 0, $\alpha$ approaches 1, and the response process of SAD virtual inertia control ends.

![Comparison of $H_{vi}$](image)

**Figure 6.** Comparison of $H_{vi}$.

5.2 Comparison of equivalent virtual inertia time constants
The equivalent inertia time constant $H_{vi}$ of VSPS with different frequency regulation strategies is shown in figure 6. The value of $H_{vi}$ is calculated according to $\Delta \omega_{v}/\Delta \omega_{v_k}$ in the process of inertia response by VSPS [8]. It can be seen that $H_{vi}$ experienced a dynamic process from initial oscillation to gradual attenuation to steady-state value, with a three-stage variation characteristic.

In the phase of fast response: the frequency begins to fall. The inertia control makes the speed of unit decrease rapidly and releases the kinetic energy. The rotor speed decreases faster than the system frequency decreases, which increases $\Delta \omega_{v}/\Delta \omega_{v_k}$ and increases $H_{vi}$. Compared with traditional droop
control and traditional inertia control, SAD virtual inertia control has the fastest response speed, and $H_{vi}$ quickly reaches the maximum value.

In the phase of speed recovery: the speed starts to rise, which makes $\Delta \omega_r/\Delta \omega_s$ decreases and $H_{vi}$ begins to decrease. Compared with traditional droop control and traditional inertia control, by SAD virtual inertia control, the absolute value of speed change is larger, $H_{vi}$ drops more obviously. In additional to that, $H_{vi}$ has obvious oscillation process in traditional droop control.

In the phase of stable: as the system frequency tends to stabilize and the speed of VSPS returns to the rated value, $H_{vi}$ gradually approaches the steady state value, and the process of inertial response gradually ends.

6. Conclusion
In order to achieve better dynamic performance of frequency response for power system, a self-adaption dynamic virtual inertia control strategy for VSPS is proposed. A correction factor is introduced to change the coefficient of control and automatically control the active power output of VSPS to provide dynamic frequency support for power grid. By dynamically changing the virtual inertia at different stages the frequency response characteristics of VSPS can be better improved. By using this method, VSPS has better inertia support ability to the power grid, and can effectively enhance the frequency stability of power system.

7. References
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