Virtual inertia control strategy of doubly-fed induction generator with additional inertia and damping torque

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Abstract. Doubly-fed induction generator (DFIG) with dual Pulse-Width Modulation (PWM) converter cannot maintain the active power balance or voltage stability of the power grid self-synchronously because of lacking mechanical inertia and mechanical damping. The virtual synchronous generator (VSG) technology can help solve this problem through simulating the mechanical equation and electromagnetic equation of synchronous generator to control the grid-connected converter. However, under the common first-order virtual inertia link used in the VSG control scheme, while DFIG providing active power support, there exists second frequency dip and the rotor speed recovers slowly, which is not conducive for DFIG to provide continuous and effective virtual inertia support. In order to overcome the drawbacks as well as avoid second frequency dip, this paper puts forward a virtual inertia control strategy of DFIG with additional inertia and damping torque. The additional torque is achieved by proportional-derivative (PD) controller with rotor slip as an input signal. Simulation results on DIgSILENT/powerfactory platform show that the proposed control strategy is effective to reduce frequency deviation and recover the rotor speed faster without second frequency dip phenomenon.

1. Introduction

The sustained increasing of wind power penetration in the power grid leads to less proportion of conventional synchronous generators [1,2]. As the most widely used type of generators, modern doubly-fed induction generators (DFIG), integrated into power grid through converters, frequency and voltage support for power grids which used to be provided by synchronous generators cannot be provided any more by DFIG because its dynamic characteristics and grid frequency decoupled [3]. This potentially results in deteriorated primary frequency regulation performance due to the reduced system inertia [4,5]. Meanwhile, the existing inertia control reduces damping of the drive-train torsional mode, which may lead to speed oscillation instability [6,7].

In order to improve the incompetent of DFIGs in frequency and voltage support, as well as the ability of power grid to operate safely and stably, many researchers concentrate on the inertia and damping control strategies of DFIGs. Through imitating the common droop control methods of

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conventional units, reference [8] applied droop control into the active power control loop in the grid-connected converter. Though with this method units can react to the grid frequency change, but the inertia response is slow with poor effect. An improved strategy was put forward in reference [9], where an additional frequency differential link was added to the original droop control output to adjust the power output of DFIGs more quickly, so the commonly used first-order virtual inertia link emerged. Actually, under the control of the common first-order virtual inertia link, DFIG can provide active power support, but grid frequency always dips twice and the rotor speed recovers slowly, which is not conducive for DFIG to provide continuous and effective virtual inertia support. Reference [10] realized the problem, and then focused on the study of optimum control parameter match to avoid those defects.

In order to improve the virtual inertia control effect, in this paper, a virtual inertial control strategy of DFIG with additional inertia and damping torque is proposed. Based on analysis of virtual synchronous control mechanism and drawbacks of DFIG with common first-order virtual inertia control link, the improved virtual inertia control strategy is put forward and influences of different simulation parameters on control results are studied. The rest of this paper is organized as follows: Section 2 presents the virtual synchronous control mechanism. Section 3 proposes the improved virtual inertia control strategy. Section 4 shows the simulation example to demonstrate the effectiveness of the proposed method. Section 5 concludes main work.

2. Virtual synchronous active power-frequency control mechanism

Simulating the working principle of the synchronous generator by controlling the gird-connected converter is the essence of VSG technology, with the purpose of enabling the converters to obtain the similar operating characteristics of synchronous generator [11].

The modelling of virtual synchronous generator (VSG) includes the VSG body modelling and its operating control system modelling [12], as the former mimics the electromagnetic transient equation of synchronous generator, and the latter simulates the dynamic behaviour of the synchronous generator, which includes the active power-frequency regulation, reactive power-voltage regulation and other functions. This paper concentrates on the improved method of active power-frequency regulation scheme in VSG technology.

In fact, VSG's active power-frequency control aims to establish the relationship between unit power output and grid frequency, as the governor of synchronous units do. The mechanical motion equation of the synchronous generator can be expressed as:

$$T_{\mathrm{m}} - T_{\mathrm{e}} = \frac{J}{n_{\mathrm{p}}} \frac{\mathrm{d}\omega_{\mathrm{r}}}{\mathrm{d}t} \tag{1}$$

where, T_{m} and T_{e} represent mechanical torque and electromagnetic torque respectively, J is the inherent rotor inertia of the generator, n_{p} is the pole pairs of the rotor, ω_{r} is the speed of the rotor.

It can be seen from the equation (1) that, when the grid frequency changes, the change amount of kinetic energy of rotor is $\frac{J}{n_{\mathrm{p}}} \frac{\mathrm{d}\Delta\omega_{\mathrm{r}}}{\mathrm{d}t}$. The existence of J makes synchronous generator's rotor dynamics interact with the power grid frequency, equipping synchronous generators with inertia.

As for DFIGs, inertia is lacked as rotor speed decouples with grid frequency, so in VSG active power control scheme, the additional virtual torque is constructed to provide the inertia. The rotor inertia and damping characteristics are reflected by mechanical motion equation, which is usually expressed as:

$$T_{\mathrm{m}} - T_{\mathrm{e}} = \frac{J_{\mathrm{DFIG}}}{n_{\mathrm{p}}} \frac{\mathrm{d}\omega_{\mathrm{r}}}{\mathrm{d}t} - T_{\mathrm{ad}} \tag{2}$$

where, T_{ad} is the additional inertia and damping torque, which is used to realize the inertia and damping characteristics, and J_{DFIG} is the inherent rotor inertia of a DFIG.

The additional inertia and damping torque T_{ad} is commonly induced through the first-order virtual inertia link, and can be expressed as [13]:

$$T_{ad} = K_P \cdot \Delta f - K_D \cdot \frac{df}{dt} \tag{3}$$

where, f is the grid frequency, Δf is the frequency deviation, K_P is the ratio coefficient, K_D is the differential coefficient.

As equation (3) shows, when grid frequency changes, active additional virtual torque control loop in VSG will play a role in adjusting the DFIG electromechanical transient process, and then its output power is adjusted accordingly, so as to realize output power's response for the change of grid frequency, like inertia response process of synchronous generators. The VSG active control loop based on the first order inertia link is shown in figure 1.

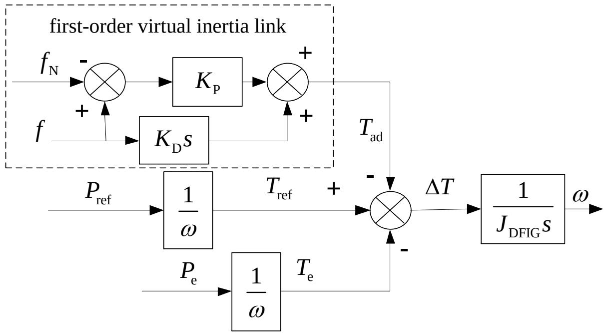

Figure 1. VSG active power control loop based on the first-order virtual inertia link.

In figure 1, the additional virtual torque T_{ad}, which is used as a torque control adjustment amount to adjust the reference value of the original torque control, is added to the VSG active power control loop. Under the control of the common first-order virtual inertia link, the control variables are only related to the changing rate of gird frequency. As a result, after the inertia control process, when the speed of DFIG returns to the optimal state, the rotor accelerates absorption of active power, it may cause the second frequency dip problem [14].

As the second frequency dip problem is caused by the active power shortage of power system during the speed recovery process, and the acceleration of rotor to absorb active power again, the improvement of virtual inertia control method should focus on coordinating power output amplitude and rotor speed changing rate.

3. Improved virtual inertia control strategy

As the DFIG steadily operates, its slip s_w is very small, then the electromagnetic torque can be approximated as [15]:

$$T_e \approx K_m \Phi_m^2 \frac{s_w \omega_s}{R_r} \tag{4}$$

where, K_m is the mechanical characteristic parameter of DFIG, Φ_m is the air-gap magnetic flux, ω_s is the angular synchronous frequency of power grid, R_r is the rotor resistance.

It can be seen from equation (4) that when the air-gap magnetic flux Φ_m approximately keeps unchanged, the electromagnetic torque is approximately proportional to slip s_w. It means that the control of electromagnetic torque can be realized by the control of slip s_w. In this way, a smooth and stable speed control effect can be achieved. At the same time, the slip signal embodies changes in the frequency of the power grid, thus the slip control can establish the coupling between the wind turbine and the power grid and it makes the DFIG electromagnetic torque response to grid frequency variation. Therefore, in virtual inertia control strategy with additional inertia and damping torque, the slip control is adopted to induce the virtual inertia control torque increment T_{ad_s}. T_{ad_s} is expressed as:

$$T_{ad\_s} = D_{eq} \cdot \Delta s_w + J_{eq} \cdot \frac{d\Delta s_w}{dt} \tag{5}$$

where, D_{eq} and J_{eq} represent damping coefficient and simulated rotor inertia respectively, $\Delta s_w = s_{w\_ref} - s_w$ is the slip deviation, s_w is the real time slip of DFIG rotor, s_{w_ref} is reference value of the slip. In order to strengthen the coupling between the DFIG torque and grid frequency, here s_{w_ref} is set as the per-unit of real time frequency of power grid. In addition, $D_{eq} \cdot \Delta s_w$ is used to imitate the damping characteristic, $J_{eq} \cdot \frac{d\Delta s_w}{dt}$ is used to imitate the inertia characteristic.

It can be seen from equation (5) that, when grid is stable without any frequency deviation, s_w remains a constant. When grid frequency f changes, s_w begins to take effect to reflect the frequency deviation. Moreover, when grid frequency recovers to the stable rating value, s_w fully reflects the change process of the rotor speed ω_r. This makes the proposed virtual inertia control, which based on slip feedback, turn into a speed restorer to help rotor speed return to the optimal state.

As mentioned previously above, the first order inertia link has the second frequency dip phenomenon. This phenomenon, appeared after inertia response, is caused by the low rotor speed after the action of virtual inertia control, as a result of the sharp fell of wind turbine power output. During the virtual inertia control process, the lower the rotor speed is, at the end of the wind turbine frequency modulation stage, the larger the output power drop amplitude is, and more serious the second frequency dip is. Therefore, virtual inertia control strategy with additional inertia and damping torque, with the speed recovery function, can avoid the problem.

Figure 2 shows the block diagram of the proposed virtual inertia control strategy of DFIG with additional inertia and damping torque. A low-pass filter link is added in this inertia control strategy to obviate the disturbances except grid frequency deviation, and the time constant of low-pass filter link is set as 3 s.

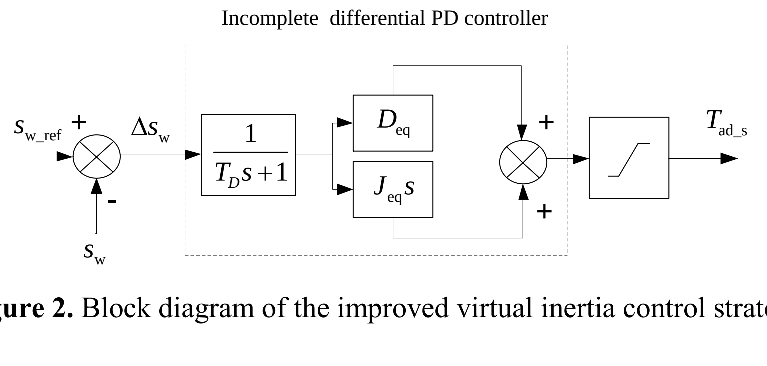

Figure 2. Block diagram of the improved virtual inertia control strategy.

4. Simulation

Based on DIgSILENT/powerfactory@, the simulation model of 60 MW DFIG wind farm, which is integrated into infinite bus power grids, was built to study the effect of different control parameter values, as well as to verify the effectiveness of the proposed control strategy. The inherent inertia time constant of the DFIG model is 0.2 s. The integrated model is shown in figure 3.

During the simulation, the wind speed is set as 11 m/s. At time t = 0.4 s, a sudden 20 MW increase in grid load in the 20 kV bus causes the grid frequency deviation.

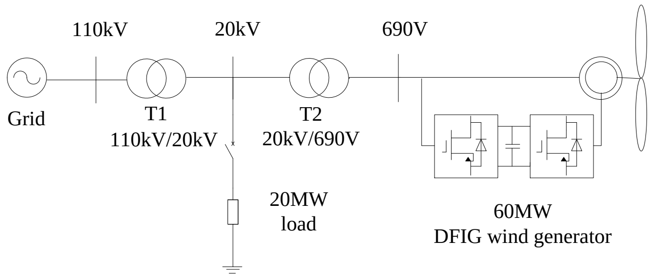

Figure 3. The integrated simulation model.

4.1. Effect of different control parameters value on the inertia response

It is obvious that different values of parameters in the virtual inertia control strategy with additional inertia and damping torque will have different control effects on the inertia control performance. Therefore, in order to determine the control parameter values of the proposed virtual inertia control strategy, this part compares these effects through simulation and gives a set of optimal control parameters of the proposed method.

As the inertia response of DFIG comes from the virtual inertia control torque increment T_{ad_s}, when the grid frequency changes, the T_{ad_s} varies accordingly to adjust the DFIG electromagnetic torque, so as to regulate active power output of DFIGs.

The different control effects on the virtual inertia control torque increment T_{ad_s} under different D_{eq} values are shown in figure 4.

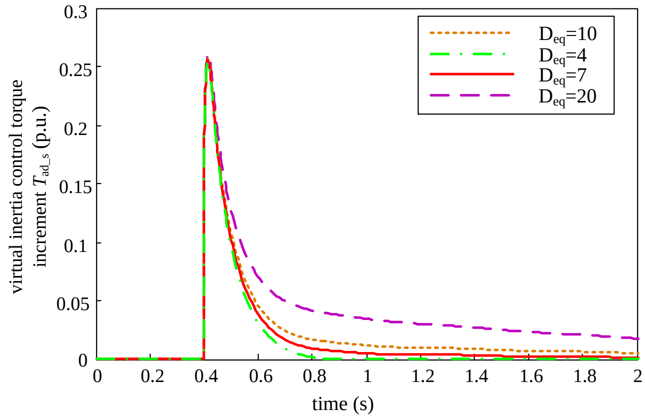

Figure 4. The effect of D_{eq} value on T_{ad_s}.

As shown in figure 4, the value of D_{eq} has little effect on the peak amplitude of T_{ad_s}. It means that the value of D_{eq} makes little difference on the increasing amount of active power output during the inertia response process. However, figure 4 shows that the length of the recovery process depends on the value of D_{eq}, namely, the value of D_{eq} determines the recovery speed of rotor speed. Moreover, the greater the value of D_{eq} is, the longer the length of the recovery process in inertia response is.

Therefore, to avoid influence on the effectiveness of inertia response in the forthcoming period, the value of D_{eq} cannot be set too large. Besides, a too small value will not guarantee the duration time of inertia response, so the value of D_{eq} is set as 7 in this paper.

The effect of J_{eq} value on T_{ad_s} is presented in figure 5.

As is obviously shown in figure 5, the value of J_{eq} do determine the peak amplitude of T_{ad_s}, and with the value of J_{eq} getting greater, the peak amplitude of T_{ad_s} gets greater. It means that the DFIG outputs more active power during the virtual inertia control process, and more active support is supplied to the power grid. Nevertheless, the value of J_{eq} cannot be too large, so as to avoid high-impact on the electromagnetic torque for the stable operation of DFIGs, so the value of J_{eq} is set as 9 in this paper.

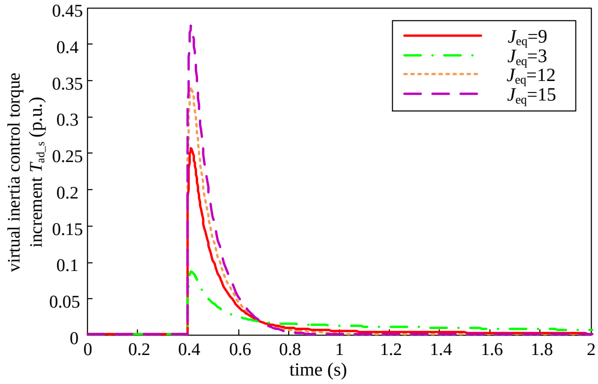

Figure 5. The effect of *J*eq value on *T*ad_s.

4.2. Comparison of the two virtual inertial control models

Based on the previous part, with the control parameters of the proposed virtual inertia control strategy fixed, the responses of DFIGs with the proposed virtual inertia control method have been observed and the conventional virtual inertia control method with the first-order virtual inertia link are also simulated for comparison.

For the conventional first-order virtual inertia control, K_P=5, K_D=30, T=0.1 s; for the proposed virtual inertia control, D_{eq}=7, J_{eq}=9, T_D=3 s. Following are the simulation results, which include grid frequency response curve in figure 6 and rotor speed curve in figure 7.

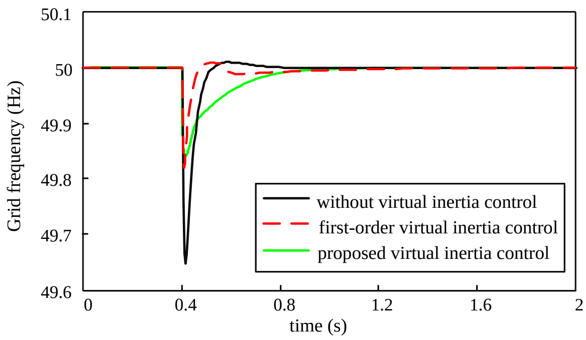

Figure 6. Grid frequency response under two different virtual inertia control methods.

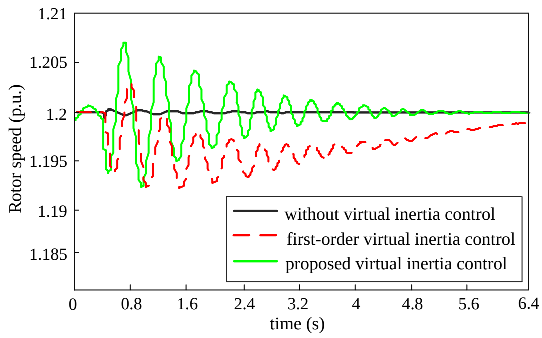

Figure 7. Rotor speed under two different virtual inertia control methods.

As is shown in figure 6, the simulation results indicate that when load increases suddenly, the grid frequency drops to 49.65 Hz. With the proposed virtual inertia control strategy, the grid frequency deviation is reduced and the grid frequency returns to 49.83 Hz compared with the first-order virtual inertia control's 49.81 Hz. Meanwhile, during the process, there exists no second frequency dip phenomenon, which appears under the first-order virtual inertia control.

As is shown in figure 7, the proposed virtual inertia control strategy can recover the rotor speed faster, which is favourable to the virtual inertia response of DFIGs in the next phase.

5. Conclusions

Virtual synchronous generator plays an important role in enabling doubly-fed induction generator with dual-PWM converter to provide active and reactive power support for power system voluntarily, so as to maintain the stability of power system automatically and realize autonomous parallel of various energy sources. This paper proposes a new virtual inertia control strategy of DFIG with additional inertia and damping torque. Simulation results demonstrated that, compared with first-order virtual inertia control, with the proposed virtual inertia control strategy, DFIG can respond to grid frequency deviation better without second frequency dip, and the rotor speed can also recover faster. This work has a certain significance to the DFIG virtual synchronous generator technology research, but the proposed control parameters are determined through classical literature and simulation, there are still some limitations in the optimal value of the control parameters. Scholars could continue to study the inertia control parameter tuning method in future studies.

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