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Control Strategy for DFIG-based Variable Speed Pumped Storage Power Plants Under Balanced and Unbalanced Grid Conditions

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Abstract: This paper proposes a vector control (VC) strategy for doubly fed induction generator (DFIG) in variable speed pumped storage power plants (PSPPs), which work in balanced and unbalanced grid conditions. The grid voltage oriented VC strategy with PI controller employed to DFIG operating in generation and electrical mode. Aiming to eliminate current oscillations under unbalanced grid conditions, the positive-negative sequences decomposition control strategy is employed to realize the low-voltage ride-through (LVRT) capability. Mathematical models of DFIG-based PSPPs are analyzed, and simulations are implemented in MATLAB to verify the theoretical findings, which show the effectiveness of the proposed control strategy.

Keywords: Doubly fed induction generator (DFIG), vector control, the positive-negative sequences decomposition, low voltage ride-through (LVRT), pumped storage.

1. Introduction

Pumped storage power plants (PSPPs) play an important role in frequency regulation and generation-load balance of power system. PSPPs is an attractive way of high capacity energy storage, and compared with the other form of energy storage, such as superconducting magnet flywheel and regenerative fuel cell, PSPPs are more economical and efficient[1, 2].

With the rapidly development of wind power generation, the application of doubly fed induction generators (DFIG) makes variable-speed operated PSPPs with reversible units focused and popular. Compared to conventional fixed-speed units, DFIG-based PSPPs can increase efficiency with smaller capacity and wider speed range [3]. Since the direct connection between stator and power grid, DFIG is sensitive to disturbance of grid voltage, so the low-voltage ride-through (LVRT) control strategy to PSPPs is necessary to maintain the grid stability[4].

This paper is organized in following sections. In section 2, the characteristic of DFIG-based PSPPs is introduced. In section 3, the proposed VC strategy under balanced voltage is derived in detail, and section 4 reveals the improved operation strategy under unbalanced voltage. In section 5, the models and simulations established in MATLAB. Conclusion is given in section 6.

2. Characteristics of DFIG-based PSPPs

The typical structure of DFIG-based PSPPs is shown as Fig.1 (a), where the stator connected to grid directly, and the rotor interfaced by a variable frequency power converter.

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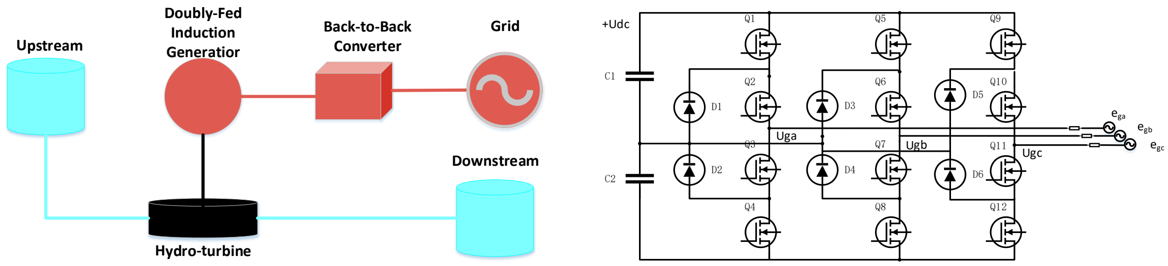
In order to cover a wide operation range from sub-synchronous to super-synchronous speed, the rotor side converter operate in bidirectional flow of energy. The back-to-back converter usually employ NPC three-level inverter with large output capacity, high output voltage, and low current harmonic content, as shown in Fig.1 (b).



(a) (b)

Fig 1: Structure of variable speed DFIG-based PSPPs, and the topology of NPC three-level inverter.

3. CONTROL STRATEGY

Based on the mathematical model of DFIG in d-q reference frame [5], the active power and reactive power can be decoupled by controlling the d-axis and q-axis component of i_s .This is the theoretical basis of vector control.

3.1. Control of grid-side converter

The aim of grid-side converter is to maintain the stability of DC bus voltage and operate in unit power factor. A stator voltage oriented method is implemented here, which contains an inner grid current loop and outer dc bus voltage loop.

According toFig.1 (b), the mathematical model of grid side converter in d-q reference frame can be expressed as

$$\begin{cases} u_g{}^d = R_g i_g{}^d + L_g p i_g{}^d - \omega_s L_g i_g{}^q + e_g{}^d \\ u_g{}^q = R_g i_g{}^q + L_g p i_g{}^q + \omega_s L_g i_g{}^d + e_g{}^q \end{cases} . \tag{1}$$

Where u_g, i_g, R_g, L_g indicate the voltage, current, resistance and inductance of grid- side converter respectively. e_{ga}, e_{gb}, e_{gc} are the three phase voltage of power source.

The active power and reactive power between power source and grid converter are

$$\begin{cases} P_g = e_g{}^d i_g{}^d \\ Q_g = -e_g{}^d i_g{}^q \end{cases} . \tag{2}$$

Where P_g and Q_g are active power and reactive power respectively.

Applying the grid voltage oriented VC method, $e_g{}^q$ is zero, so the new power equation is

$$\begin{cases} P_g = e_g{}^d i_g{}^d \\ Q_g = -e_g{}^d i_g{}^q \end{cases} . \tag{3}$$

Equation (3) indicate that the active power and reactive injected into the grid from grid-side converter (P_g and Q_g) can be decoupled by controlling the d and q axis components of grid current i_g, while i_g is controlled by grid-side converter output voltage u_g in equation (1). This mathematical relationship constitutes the current loop of the PI controller for grid-side converter control strategy.

According to the power balance principle, under the ideal conditions, the active power injected into the DC bus capacitor should be equal to the difference between the active power absorbed by the grid-side converter and the consumed power of the DC-side load, then the model of DC bus is

$$u_{dc}i_{dc} = Cu_{dc}pu_{dc} = -P_g - \Delta P. \tag{4}$$

Where u_{dc} and i_{dc} are DC bus voltage and DC bus charging current, C is capacitance of DC bus is the power consumption of DC side.

The expression indicates the DC bus voltage can be controlled by means of regulating the active power injected into the grid, which can change the DC bus capacitor in charge or discharge. This constitutes the outer voltage loop.

Based on the two control loops, the control strategy scheme of grid-side converter is shown as Fig.2.

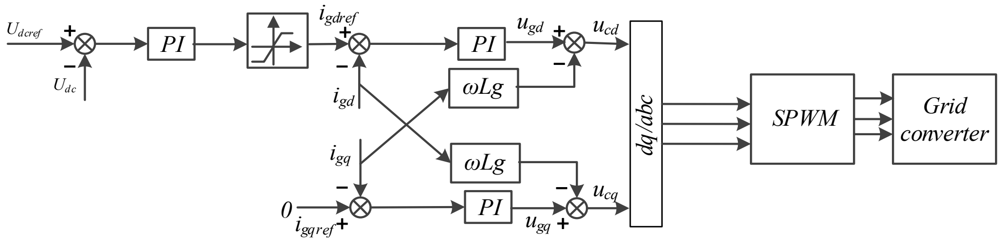


Fig. 2: The control strategy scheme of grid-side converter.

3.2. Control of rotor-side converter

The control strategy of the rotor-side converter includes soft cut-in strategy and interconnection operating strategy.

To soft cut-in the grid, the stator voltage of DFIG is supposed to be control consistently with grid voltage in phase, frequency and amplitude.

Before connecting with grid, the stator of DFIG is open circuit, which result in no closed loop, so $i_s{}^d = i_s{}^q = 0$.

By formula derivation and replacement, the rotor voltage can be obtained as

$$\begin{cases} u_r{}^d = R_r i_r{}^d + L_r p i_r{}^d - \omega_{sl} L_r i_r{}^q \\ u_r{}^q = R_r i_r{}^q + L_r p i_r{}^q + \omega_{sl} L_r i_r{}^d \end{cases}. \tag{5}$$

Then, the control objective, stator voltage can be expressed as

$$\begin{cases} u_s{}^d = -\omega_s L_m i_r{}^q \\ u_s{}^q = \omega_s L_m i_r{}^d \end{cases}. \tag{6}$$

Equation (6) indicate that the stator voltage u_s can be control by rotor current i_r, while in equation (5) the rotor current i_r can be control by the output voltage of rotor-side converter u_r. This mathematical relationship constitutes two closed loop of PI controller for rotor-side converter control strategy——outer stator voltage loop and inner rotor current loop. The scheme is shown as Fig.3.(a).

For interconnection operating strategy, the control objective is the stator power. Since the stator of DFIG is connected to grid directly, it can be expressed as

$$\begin{cases} u_s{}^d = \mathrm{e}_g{}^d \\ u_s{}^q = e_g{}^q = 0 \end{cases}. \tag{7}$$

Based on equation (7), the rotor voltage can be obtained by formula derivation and replacement

$$\begin{cases} u_r{}^d = (R_r + \sigma L_r p) i_r{}^d - \sigma \omega_{sl} L_r i_r{}^q - \dfrac{\omega_{sl} L_m}{L_s} \varphi_m \\ u_r{}^q = (R_r + \sigma L_r p) i_r{}^q + \sigma \omega_{sl} L_r i_r{}^d \end{cases}. \tag{8}$$

Substituting equation (7) into equation (3), the power equation rewritten as

$$\begin{cases} P_s = e_g{}^d i_s{}^d \\ Q_s = -e_g{}^d i_s{}^q \end{cases}. \tag{9}$$

Equation (8) indicate that the rotor voltage u_r can be control by rotor current i_r, which is controlled by stator current i_s. This constitutes the inner current loop of rotor-side converter control.

In equation (9), the stator active power and reactive power (P_s and Q_s) can be decoupled by controlling stator current i_s. This constitutes the outer stator power loop of rotor-side converter control strategy. Based on the two closed loop of PI controller for rotor-side converter, the control scheme of interconnection operating strategy is shown as Fig.3.(b).

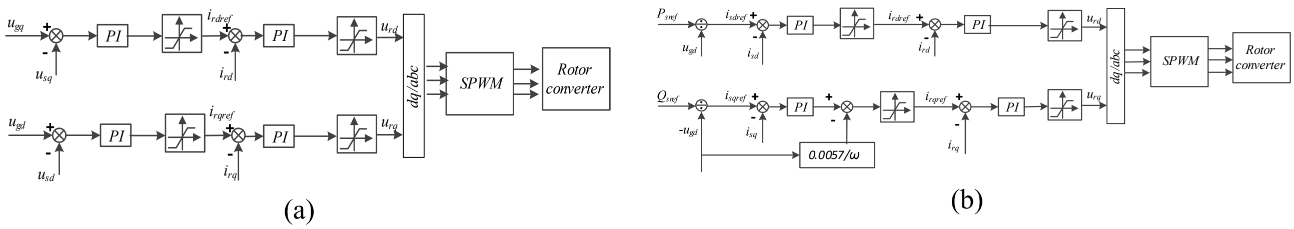


Fig.3:The control strategy scheme of rotor-side converter.

4. The positive-negative sequences decomposition control strategy for LVRT

When the asymmetrical voltage dip in the grid, the negative sequence component will appear in current, which can cause the power pulsation and frequency fluctuations, more seriously it will lead to current waveform distortion.

To enhance the LVRT ability, the negative sequence component is supposed to eliminate. Therefore, the positive-negative sequences decomposition control strategy for the rotor-side converter is employed as shown in Fig.4, where (a) and (b) are the grid side converter and rotor side converter control strategy schemes respectively.

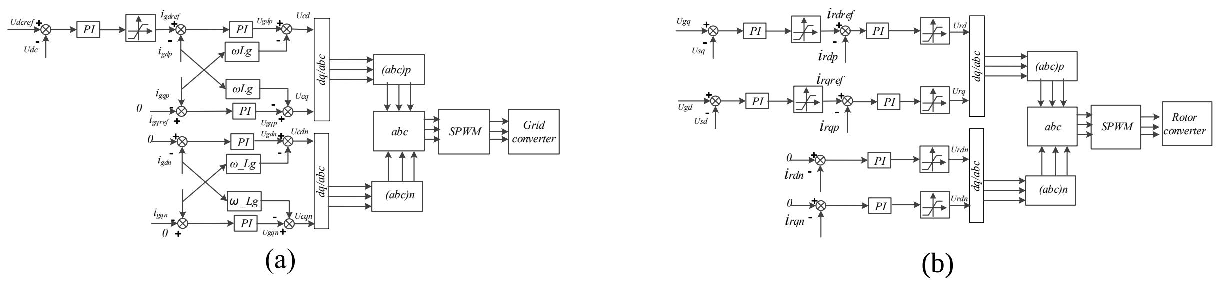


Fig 4:The positive-negative sequences decomposition control strategy schemes for the converters.

5. The Simulation results and analysis

The mathematic model of DFIG-based PSPPs controlled by the proposed strategy is implemented in MATLAB\SIMULINK, the related experimental parameters are shown in Table 1.

Table 1: Parameters in simulations of PSPPs.

Parameter	Value	Unit
e_g	690	V
U_{dc}	1200	V
ω_s	50	Hz
R_g	0.1	Ω

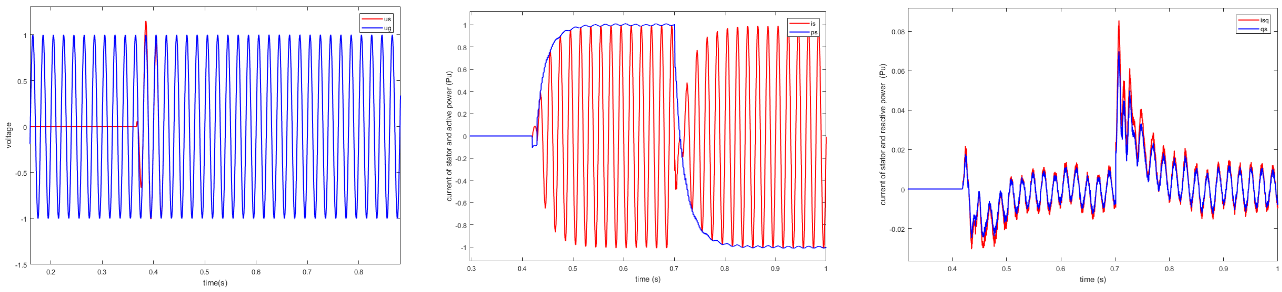
L_g	0.005	H
C	0.012	F

The Fig.5 illustrates the operation of the DFIG-based PSPPs under a balanced grid condition.

In Fig.5.(a), the DFIG can cut-in softly at 0.38 s when the stator voltage u_s is consist with grid voltage u_g in the phase, frequency and amplitude, which can protect the motor from current impact.

Then we simulate the system to see the active and reactive power changing with DFIG switching from generation to electrical mode. In Fig.5 (b), DFIG connected with grid at 0.41 s, the active power increase to 1 and operates in unit power factor, which is controlled by d axis component of stator current.

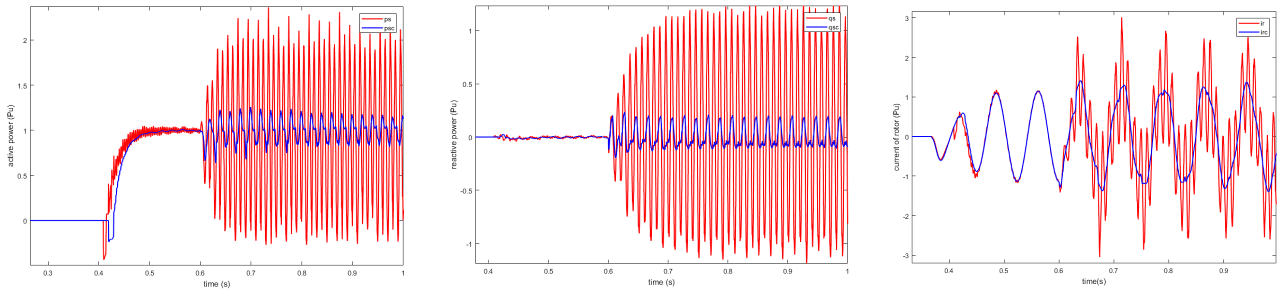
At 0.7 s, DFIG switches to electrical mode with the reversing of active power and stator current. In Fig.5 (b), the reactive power always remains to 0, which is controlled by q axis component of stator current, it fluctuates slightly when DFIG switching operating modes. Fig.5 shows that the proposed control strategy can effectively decouple active and reactive power.



(a) (b) (c)

Fig 5: Active and reactive power changing with DFIG swtiching from generation to electrical mode

In Fig.6, DFIG operates under unbalanced grid with the voltage of phase A and B dips 20% at 0.6s.



(a) (b) (c)

Fig 6: The positive-negative sequences decomposition strategy to achieve the LVRT ability under unbalanced grid

As we can see in Fig.6 (a), the active power has undergone intense oscillations at 0.6 s (the red curve), while with the positive-negative sequences decomposition strategy, the oscillation was eliminated effectively and stabilized to1 (blue curve). Fig.6 (b) illustrates the reactive power of DFIG. Compared with the seriously oscillation to 1.25 in red curve, the blue curve with LVRT control strategy can eliminate the oscillation for 80% to 0.25. Fig.6 (c) shows that the current of rotor controlled by the strategy can maintain the amplitude and phase to system operate stably. These figures proves that the proposed control strategy can enhance the LVRT performance effectively under unbalanced gird conditions.

6. Conclusion

This paper proposes a vector control (VC) strategy for DFIG-based variable speed pumped storage power plants (PSPPs). The grid voltage oriented VC strategy with PI controller employed to DFIG operating in generation and electrical mode. To achieve the low-voltage ride-through (LVRT) capability, the positive-negative sequences decomposition control strategy is employed to eliminate current oscillations in unbalanced grid conditions. Mathematical models of DFIG-based PSPPs is analyzed, and simulations is implemented in MATLAB to verify the theoretical findings, which show the effectiveness of the proposed control strategy.

7. Acknowledgements

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