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A control strategy for grid-side converter of DFIG under unbalanced condition based on Dig SILENT/Power Factory

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Abstract. The models of doubly fed induction generator (DFIG) and its grid-side converter (GSC) are established under unbalanced grid condition based on DIgSILENT/PowerFactory. According to the mathematical model, the vector equations of positive and negative sequence voltage and current are deduced in the positive sequence synchronous rotating reference frame d-q-0 when the characteristics of the simulation software are considered adequately. Moreover, the reference value of current component of GSC in the positive sequence frame d-q-0 under unbalanced condition can be obtained to improve the traditional control of GSC when the national issue of unbalanced current limits is combined. The simulated results indicate that the control strategy can restrain negative sequence current and the two times frequency power wave of GSC's ac side effectively. The voltage of DC bus can be maintained a constant to ensure the uninterrupted operation of DFIG under unbalanced grid condition eventually.

1. Introduction

With the rapid development of DFIG in recent years, some theories and control strategies for low voltage ride through (LVRT) under symmetrical fault has been increasing mature[1], and on the basis of this, the uninterrupted operation and control of DFIG under unbalance fault and condition has become one of the important trends of wind power technology development.

The State Grid Corporation of China has promulgated *Technical rule for connecting wind farm to power network* [4]. It shows that during the normal operation of power system, the negative sequence voltage unbalance of power system common connection point should not exceed 2%, short term may not exceed 4%.

Many researches have been done in [5-7], such as dynamic modeling and control, enhanced control of back-to-back PWM voltage-source converter and torque ripple elimination. However, the characteristics of the simulation software are not considered adequately, and it is difficult to realize them.

In this paper, the models of DFIG and its GSC are established under unbalanced grid condition based on Dig SILENT/Power Factory. The vector equations of positive and negative sequence voltage and current are deduced in the positive sequence synchronous rotating reference frame d-q-0 according to the mathematical model. Moreover, the reference value of current component of GSC in the positive sequence frame d-q-0 under unbalanced condition can be obtained when the national issue of unbalanced current limits is combined. At last, an improve control strategy of GSC is put forward to restrain negative sequence current.

2. Model of GSC under unbalanced condition

The main circuit of GSC is shown in Fig. 1. When the grid works under unbalanced condition, the vector equations of positive and negative sequence voltage and current in the positive and negative sequence synchronous rotating reference frame d-q-0 are expressed as (1)[8].

$$\begin{cases} \mathbf{U}_{\mathbf{tdq}}^{+} = R_g \mathbf{I}_{\mathbf{gdq}}^{+} + j\omega L_g \mathbf{I}_{\mathbf{gdq}}^{+} + \mathbf{U}_{\mathbf{gdq}}^{+} + L_g \dfrac{d\mathbf{I}_{\mathbf{gdq}}^{+}}{dt} \\ \mathbf{U}_{\mathbf{tdq}}^{-} = R_g \mathbf{I}_{\mathbf{gdq}}^{-} - j\omega L_g \mathbf{I}_{\mathbf{gdq}}^{-} + \mathbf{U}_{\mathbf{gdq}}^{-} + L_g \dfrac{d\mathbf{I}_{\mathbf{gdq}}^{-}}{dt} \end{cases} \quad (1)$$

In (1), Ugdq, Igdq, and Utdq are the space vectors of the GSC's AC voltage, GSC's AC current, and grid voltage. The superscripts such as +, - represent the positive and negative sequence components.

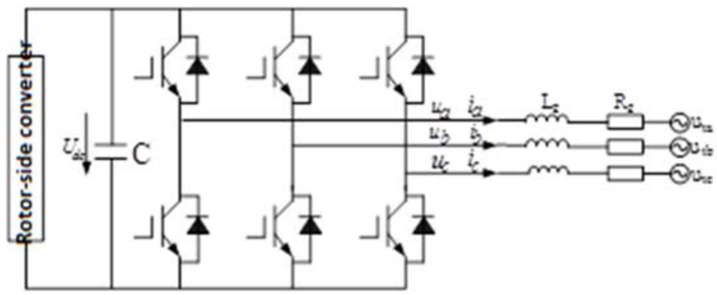

Figure 1. Main circuit of DFIG's grid side converter

The space vector diagram of GSC's ac voltage under unbalanced condition is shown in Fig. 2 according to (1), where δ is the angular difference of positive and negative sequence synchronous rotating reference frame d-q-0. ε is the initial value of δ, and δ=2ωt+ε.

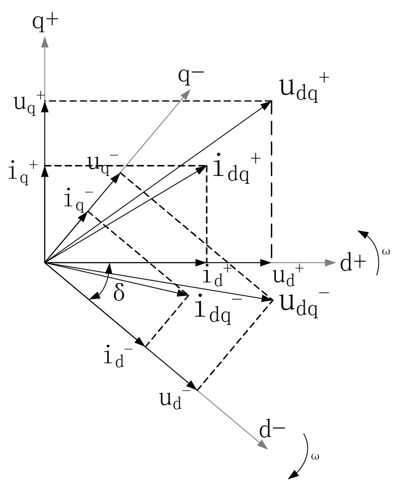

Figure 2. The space vector diagram of GSC's ac voltage

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Because the control module of DFIG in Dig SILENT/Power Factory software only contains positive sequence d and q axis components, the following transformation of negative sequence d and q axis components should be done to project them to positive sequence frame d-q-0:

$$\begin{cases} \mathbf{u_{gd}^-} = u_{gd}^- \cos\delta(d^+axis) + (-u_{gd}^- \sin\delta)(q^+axis) \\ \mathbf{u_{gq}^-} = u_{gq}^- \sin\delta(d^+axis) + u_{gq}^- \cos\delta(q^+axis) \\ \mathbf{i_{gd}^-} = i_{gd}^- \cos\delta(d^+axis) + (-i_{gd}^- \sin\delta)(q^+axis) \\ \mathbf{i_{gq}^-} = i_{gq}^- \sin\delta(d^+axis) + i_{gq}^- \cos\delta(q^+axis) \end{cases} \tag{2}$$

The projections of negative sequence d and q components on positive sequence frame d-q-0 are two times frequency components.

Thus, the d and q axis components for GSC of DFIG (all the d and q axis components without superscripts are positive sequence components which positive and negative components are calculated to, such as (3)) can be expressed as (3).

$$\begin{cases} \mathbf{u_{gd}} = u_{gd}^+ + u_{gd}^- \cos\delta + u_{gq}^- \sin\delta \\ \mathbf{u_{gq}} = u_{gq}^+ - u_{gd}^- \sin\delta + u_{gq}^- \cos\delta \\ \mathbf{i_{gd}} = i_{gd}^+ + i_{gd}^- \cos\delta + i_{gq}^- \sin\delta \\ \mathbf{i_{gq}} = i_{gq}^+ - i_{gd}^- \sin\delta + i_{gq}^- \cos\delta \end{cases} \tag{3}$$

The whole d and q axis components are of two times frequency. Then, the active and reactive power can be deduced as (4).

$$\begin{cases} P_g = \frac{3}{2}\left(\left(u_{gd}^+ i_{gd}^+ + u_{gq}^+ i_{gq}^+ + u_{gd}^- i_{gd}^- + u_{gq}^- i_{gq}^-\right) + \left(u_{gd}^+ i_{gd}^- + u_{gq}^+ i_{gq}^- + u_{gd}^- i_{gd}^+ + u_{gq}^- i_{gq}^+\right)\cos\delta + \left(u_{gd}^+ i_{gq}^- - u_{gq}^+ i_{gd}^- - u_{gd}^- i_{gq}^+ + u_{gq}^- i_{gd}^+\right)\sin\delta\right) \\ Q_g = \frac{3}{2}\left(\left(-u_{gd}^+ i_{gq}^+ + u_{gq}^+ i_{gd}^+ - u_{gd}^- i_{gq}^- + u_{gq}^- i_{gd}^-\right) + \left(-u_{gd}^+ i_{gq}^- + u_{gq}^+ i_{gd}^- - u_{gd}^- i_{gd}^+ + u_{gq}^- i_{gq}^+\right)\cos\delta + \left(u_{gd}^+ i_{gd}^- + u_{gq}^+ i_{gq}^- - u_{gd}^- i_{gd}^+ - u_{gq}^- i_{gq}^+\right)\sin\delta\right) \end{cases} \tag{4}$$

As the voltage and current of GSC, the power also contains second harmonic. The steady of DC bus voltage of DFIG may be threatened if the second harmonic is not restrained.

The second harmonic in active and reactive power can be restrained effectively if the negative sequence components of GSC are eliminated. According to *Rotating electrical machines—Rating and performance GB 755-2008*, the negative sequence components of three phase alternators cannot exceed 5% of positive sequence components, as shown in (5),where ε i2 can be looked upon as unbalance factor of negative sequence current and its value is 0.05.

$$i_2 / i_1 \le \varepsilon_{i2} \tag{5}$$

According to symmetrical component method, the equation (6) is as follows, where $a = e^{j120^\circ}$.

$$\begin{bmatrix} \mathbf{I_{a(1)}} \\ \mathbf{I_{a(2)}} \\ \mathbf{I_{a(0)}} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} \mathbf{I_a} \\ \mathbf{I_b} \\ \mathbf{I_c} \end{bmatrix} \tag{6}$$

$\mathbf{I_{a(1)}}$, $\mathbf{I_{a(2)}}$ and $\mathbf{I_{a(0)}}$ are the three sequence current components of a phase. The subscript a will be omitted in this paper following.

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Because the connection way of DFIG is star connection, there is no zero sequence current in the system no matter the system works in what kind of operation mode. The relationship should be satisfied. Thus, (6) can be expressed as (7).

$$\begin{bmatrix}\mathbf{I_1}\\ \mathbf{I_2}\end{bmatrix}=\frac{1}{3}\begin{bmatrix}1-a^2 & a-a^2\\ 1-a & a^2-a\end{bmatrix}\begin{bmatrix}\mathbf{I_a}\\ \mathbf{I_b}\end{bmatrix} \tag{7}$$

The instantaneous current of a and b phase can be expressed as (8).And according to this, the rotating phasors are shown in (9).

$$\begin{bmatrix}i_a\\ i_b\end{bmatrix}=\begin{bmatrix}I_{am}\cos(\omega t+\phi_{ia})\\ I_{bm}\cos(\omega t+\phi_{ib})\end{bmatrix} \tag{8}$$

$$\begin{bmatrix}\mathbf{I_a}\\ \mathbf{I_b}\end{bmatrix}=\begin{bmatrix}I_{am}\cos(\omega t+\phi_{ia})+jI_{am}\sin(\omega t+\phi_{ia})\\ I_{bm}\cos(\omega t+\phi_{ib})+jI_{bm}\sin(\omega t+\phi_{ib})\end{bmatrix}=\begin{bmatrix}i_a\\ i_b\end{bmatrix}+j\omega\int\begin{bmatrix}i_a\\ i_b\end{bmatrix} \tag{9}$$

The instantaneous positive and negative sequence current can be obtained by substituting Eq. (9) into Eq. (7), such as the following equation (10) [9-10].

$$\begin{bmatrix}i_1\\ i_2\end{bmatrix}=\mathrm{Re}\left(\frac{1}{3}\begin{bmatrix}1-a^2 & a-a^2\\ 1-a & a^2-a\end{bmatrix}\begin{bmatrix}\mathbf{I_a}\\ \mathbf{I_b}\end{bmatrix}\right)=\mathrm{Re}\left(\frac{1}{3}\begin{bmatrix}1-a^2 & a-a^2\\ 1-a & a^2-a\end{bmatrix}\left(\begin{bmatrix}i_a\\ i_b\end{bmatrix}+j\omega\int\begin{bmatrix}i_a\\ i_b\end{bmatrix}\right)\right) \tag{10}$$

Without zero sequence current in the system, Park transformation can be simplified as (11), where θ is the angle between frame a-b-c and positive sequence frame d-q-0.

$$\begin{bmatrix}i_a\\ i_b\end{bmatrix}=\frac{4}{3}\begin{bmatrix}\cos\theta & -\sin\theta\\ -\cos(\theta+\pi/3) & \sin(\theta+\pi/3)\end{bmatrix}\begin{bmatrix}i_d\\ i_q\end{bmatrix} \tag{11}$$

Equation (12) can be obtained by substituting Eq. (11) into Eq. (10).

$$\begin{aligned}\begin{bmatrix}i_1\\ i_2\end{bmatrix}&=\mathrm{Re}\left(\frac{1}{3}\begin{bmatrix}1-a^2 & a-a^2\\ 1-a & a^2-a\end{bmatrix}\left(\begin{bmatrix}i_a\\ i_b\end{bmatrix}+j\omega\int\begin{bmatrix}i_a\\ i_b\end{bmatrix}\right)\right)\\ &=\mathrm{Re}\left(\frac{1}{3}\begin{bmatrix}1-a^2 & a-a^2\\ 1-a & a^2-a\end{bmatrix}\left(\frac{4}{3}\begin{bmatrix}\cos\theta & -\sin\theta\\ -\cos(\theta+\pi/3) & \sin(\theta+\pi/3)\end{bmatrix}\begin{bmatrix}i_d\\ i_q\end{bmatrix}+j\omega\int\frac{4}{3}\begin{bmatrix}\cos\theta & -\sin\theta\\ -\cos(\theta+\pi/3) & \sin(\theta+\pi/3)\end{bmatrix}\begin{bmatrix}i_d\\ i_q\end{bmatrix}\right)\right)\end{aligned} \tag{12}$$

The values of positive sequence d and q axis current should be adjust to ensure the positive and negative sequence current satisfy Eq. (5). Eq. (12) can also be used to obtain negative sequence current and determine whether it exceeds the limits.

3. GSC's control system design

The improved control diagram to restrain negative sequence current is shown as Fig. 3.

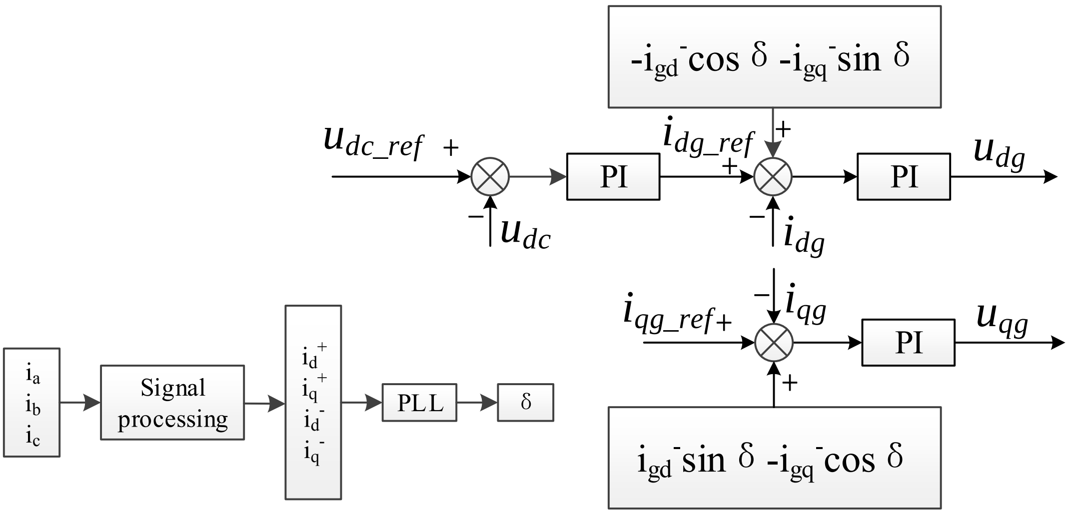

Figure 3. Improved control diagram of GSC

According to Eq. (3), the feedback quantities of negative sequence current are added to the reference value of positive sequence d and q axis current of GSC to eliminate negative sequence current. The negative sequence current decision module is also added to the protection module of GSC to verify the strategy in Fig. 3. The flow chart is shown as Fig. 4.

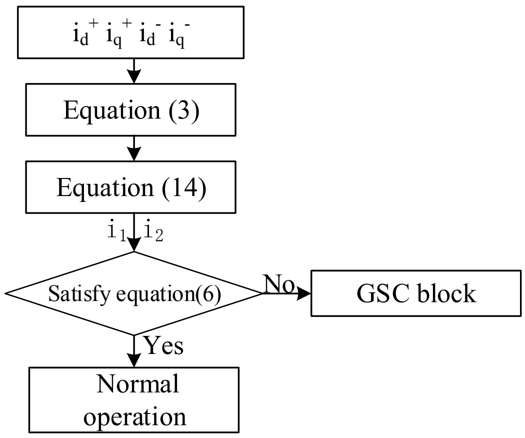

Figure 4. Overcurrent judgment flowchart for negative sequence current

4. Analysis of simulation and examples

To validate the availability of the control strategy under unbalanced condition, models of DFIG and its GSC are established in DigSILENT/PowerFactory. The specific parameters of GSC are shown in the Table 1.

Table 1. Simulation parameters of single GSC

Rated AC voltage	690 [V]
rated voltage of DC link	1.15 [kV]
rated power	2 [MVA]
incoming line inductance	1 [mH]

As shown in Fig. 5, the system begins to operate under unbalanced condition at 2.5s and get right at 2.7s. Simulation results of traditional control are shown in this figure. Obviously, the ratio between negative sequence current and positive sequence current is too large, and the negative sequence current exceeds the limit.

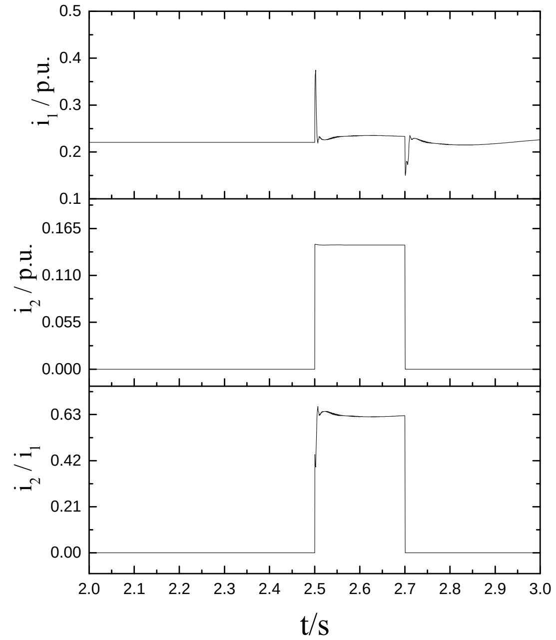

Figure 5. Simulation results of traditional control strategy

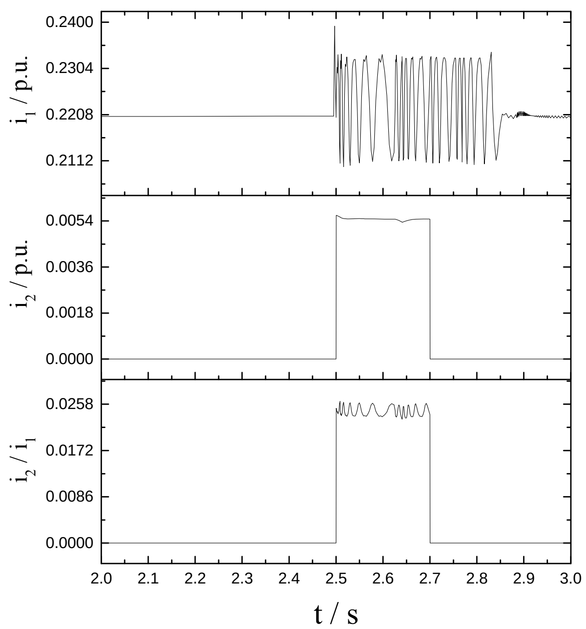

Figure 6. Simulation results of improved control strategy

Simulation results are shown in Fig. 6 when improved control strategy is used under the same simulated condition. The ratio between negative sequence current and positive sequence current is small and it satisfy Eq. (5). A deficiency lies in the figure is that a two times frequency wave whose amplitude is ±4% may occur in GSC's positive sequence current. But the wave is controllable.

Conclusion

Detailed theoretical analysis of GSC's running mechanisms under unbalanced grid voltage condition is done on the basis of the mathematical models of DFIG and its GSC and models of them in DIgSILENT/PowerFactory. The vector equations of positive and negative sequence voltage and current are deduced in the positive sequence synchronous rotating reference frame d-q-0 when the characteristics of the simulation software are considered adequately. And the negative sequence current is projected to positive sequence frame d-q-0. Then an improved control strategy is put forward to restrain negative sequence current. At last, compared with the traditional control strategy, the negative sequence current can be restrain more effectively when the improved control strategy is used. The power wave of GSC can be depressed as well to maintain DC bus stability.

Acknowledgments

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