Research on Real Time Active Power Characteristics of DFIG Rotor under Changes of Slip

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***Abstract* — When wind speed changes, the slip of Doubly-Fed Induction Generator (DFIG) changes first, then it causes changes to the state of the DFIG. When the DFIG runs on hyper-synchronous power generating state, rotor and stator generate active power to outside. When the DFIG runs on sub-synchronous power generating state, the rotor absorbs active power and stator generates active power to outside. When the real-time requirement is high, the process needs to be calculated in real time. This paper uses the real time calculation formula about slip, stator current vector and rotor active power to analyze change laws of rotor active power under changes of slip. The results show that the formula can calculate the active power of rotor in real time, and with increasing of slip, the active power absorbed by DFIG rotor gradually decreases, the active power generated by DFIG rotor gradually increases.**

Keywords - DFIG; rotor; active power; real time; slip

I. INTRODUCTION

As typical VSCF wind power generator, the doubly-fed wind power generators have been widely applied. For doubly-fed wind power generator, the DFIG (doubly-fed induction generator) is its core parts, which can operate as synchronous motor and operate in sub-synchronous power generating state and hyper-synchronous power generating state after grid connection [1-4]. The changes of wind speed will cause the changes to slip, the slip of DFIG changes first, then it causes changes to state of wind power generators. Then the control mechanism will control rotor current vector by rotor voltage vector and finally achieve control of stator current vector; the stator current vector determines generated power of doubly-fed wind power generators. The current researches, represented by literatures [5-9], infer the relation formula between rotor current vector and power characteristics of rotor side. However, the rotor current vector is not decisive factor to influence generated power of wind power generator, but the factor to influence stator current vector. Therefore, the active power characteristics of rotor can be calculated in real time through corresponding slip and stator current vector. And there is no research on the real time calculation of rotor active power.

This paper uses the real time calculation formula about slip, stator current vector and rotor active power to analyze change laws of rotor active power under changes of slip, the calculation results show the advantage of the formula in real time calculation, and show the change laws of rotor active power under changes of slip.

II. ANALYSIS ON ROTOR ACTIVE POWER

A. Equivalent Circuit And Basic Operating State of DFIG

The stator winding of DFIG is directly connected to grid. The generator-side converter provides exciting current for rotor winding of DFIG through certain control strategy and finally ensures the normal operation of doubly-fed wind power generator. The typical over-all structure of doubly-fed wind power generator which adopts AC-DC-AC converter is shown as Figure 1.

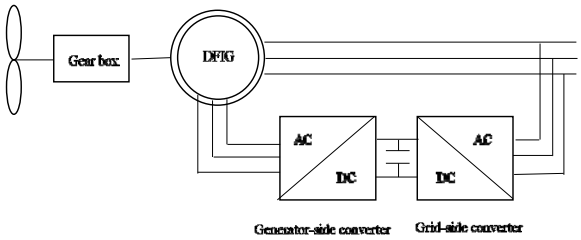

Figure 1. The structure diagram of doubly-fed wind power generator

This paper has made analysis according to equivalent circuit when analyzing active power of DFIG rotor. The figure of DFIG equivalent circuit is shown as Figure 2.

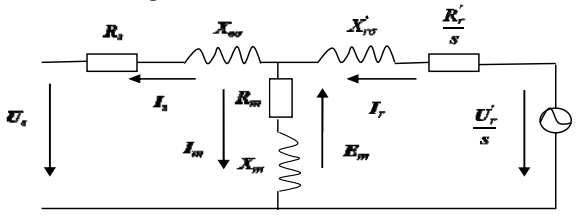

Figure 2. DFIG equivalent circuit

This paper has obtained figure of equivalent circuit by common practice of generator and make analysis of active power more clearly and concisely. R_s and $R_r^{'}$ in Figure 2 respectively represents stator resistance and rotor resistance calculated to stator side; $X_{s\sigma}$ and $X_{r\sigma}^{'}$ respectively represents leakage reactance of stator side and rotor leakage

reactance calculated to stator side; R_m and X_m respectively represents equivalent resistance of stator iron loss and mutual reactance between stator and rotor. $\boldsymbol{U}_s$ and $\boldsymbol{I}_s$ respectively represents voltage vector of stator terminal and stator current vector. $\boldsymbol{U}_r^{'}$ and $\boldsymbol{I}_r$ respectively represents voltage vector of rotor terminal and rotor current vector calculated to stator side. $\boldsymbol{E}_m$ and $\boldsymbol{I}_m$ respectively represents induced electromotive force of vector of air-gap field and exciting current vector. The AC-DC-AC converter shown in Figure 1 is usually adopted for converter of doubly-fed wind power generator, so the rotor side in equivalent circuit diagram is equivalent by voltage source.

According to equivalent circuit diagram of DFIG, it can infer the fundamental relation between each parameter.

$$\boldsymbol{U}_{\mathrm{s}} = \boldsymbol{E}_m - \boldsymbol{I}_s (R_s + \mathrm{j}\, X_{s\sigma}) \tag{1}$$

$$\boldsymbol{U}_r^{'} = \mathrm{s}\, \boldsymbol{E}_m + \boldsymbol{I}_r\, R_r^{'} + \mathrm{j s}\, X_{r\sigma}^{'} \tag{2}$$

$$\boldsymbol{E}_m = \boldsymbol{I}_m \,.\mathrm{j}\, X_m \tag{3}$$

$$\boldsymbol{I}_m = \boldsymbol{I}_r - \boldsymbol{I}_s \tag{4}$$

The stator terminal of DFIG is connected with grid; the stator winding enters into power-frequency three-phase alternating current (f_s =50Hz) and generates corresponding rotating magnetic field, its angular velocity of rotation is n_s which is defined as synchronous angular velocity. The generator-side converter is connected to rotor winding for three-phase alternating current, its frequency is f_r and generates rotating magnetic field in which the angular velocity of rotation is n_r relative to rotor itself. To ensure operation of variable speed constant frequency, the angular velocity *n,* n_s and n_r in rotor rotation should keep the following relation:

$$n = n_s - n_r \tag{5}$$

What state the operation of DFIG is in, what power flow the rotor and stator have is closely related to slip. The slip is defined as:

$$S = \frac{n_s - n}{n_s} \tag{6}$$

When the DFIG is operated in hyper-synchronous power generating state, *n* is greater than *ns*, the slip ratio *s* is less than 0, and the rotor and stator generate active power to outside. When the DFIG is operated in sub-synchronous power generating state, *n* is less than *ns*, the slip ratio *s* is greater than 0, the rotor side absorbs active power and stator generates active power to outside.

B. Real time Calculation Formula

In this paper, the active power absorbed by rotor is positive, so the active power outputted by rotor is negative, P_r is active power absorbed by rotor. The derivation of the formula is as follows [10]:

$$P_r = 3\mathrm{Re}[\boldsymbol{U}_r^{'}\, \boldsymbol{I}_r^{*}] \tag{7}$$

From formula (2), it can be known that

$$\boldsymbol{U}_r^{'}\, \boldsymbol{I}_r^{*} = s\, \boldsymbol{E}_m\, \boldsymbol{I}_r^{*} + (R_r^{'} + \mathrm{j} s\, X_{r\sigma}^{'})\, \boldsymbol{I}_r^2 \tag{8}$$

Set $\boldsymbol{U}_s$ as standard vector quantity in which the phase angle is 0, thus $\boldsymbol{I}_s = I_{sa} + \mathrm{j}\, I_{sr}$, I_{sa} is active component of stator current and I_{sr} is reactive component of stator current. U_s is effective value of stator voltage and I_s is effective value of stator current. Thus in formula (1)

$$\boldsymbol{E}_m = (R_s\, I_{sa} - X_{s\sigma}\, I_{sr} + U_s) + \mathrm{j}(X_{s\sigma}\, I_{sa} + R_s\, I_{sr}) \tag{9}$$

Thus $\boldsymbol{I}_r$ can be represented as

$$\boldsymbol{I}_r = \frac{1}{X_m} (X_{s\sigma}\, I_{sa} + R_s\, I_{sr}) - \mathrm{j}\, \frac{1}{X_m} (R_s\, I_{sa} - X_{s\sigma}\, I_{sr} + U_s) \tag{10}$$

Substitute formula (9) and (10) in formula (8), it can be known the active power absorbed by rotor side

$$P_r = 3\{ I_s^2 [R_r^{'}\, R_s^2 + R_r^{'} (X_{s\sigma} + X_m)^2 + s\, X_m^2\, R_s] + R_r^{'}\, U_s^2 + U_s [I_{sa} (2 R_r^{'}\, R_s + s\, X_m^2) - 2 R_r^{'} (X_{s\sigma} + X_m)\, I_{sr}] \} / X_m^2 \tag{11}$$

As mentioned in introduction, the current related researches starts from rotor current vector to study power characteristics of rotor side, and the formula (11) can accurately reflect relationships between the slip, effective value of stator current, active current of stator, reactive current of stator and rotor active power. Also decreases unnecessary interference factor.

III. ANALYSIS OF EXAMPLES FOR ROTOR ACTIVE POWER UNDER CHANGES OF SLIP

To accurately reflect change law of rotor active power under changes of slip, this paper takes single GE 1.5MW doubly-fed wind power generator as example, the parameters of doubly-fed wind power generators are shown as below: R_s =0.00156Ω, $X_{s\sigma}$ =0.03768Ω, $R_r^{'}$ =0.0011Ω and X_m =0.6393Ω. By adopting the maximum power tracing, the wind speed is 15m/s. In this example, the slip always changes. After grid connection, the doubly-fed wind power generators are gradually transited from sub-synchronous power generating state to hyper-synchronous power generating state. Take active current of stator, reactive current of stator and slip to calculate and take 400 sample points, the results of example are shown as Figure 3 to Figure 6.

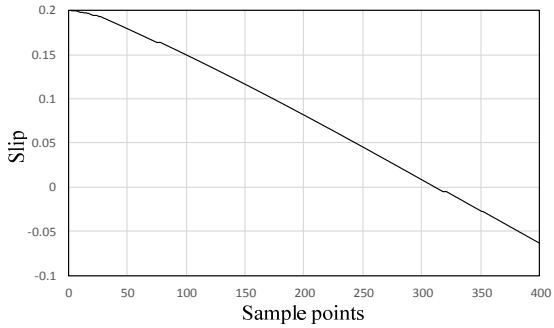

Figure 3. The changes of slip

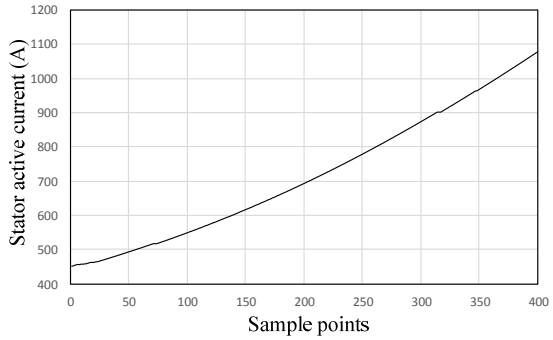

Figure 4. The changes of stator active current

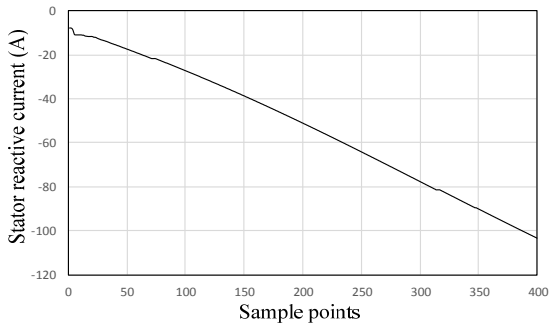

Figure 5. The changes of stator reactive current

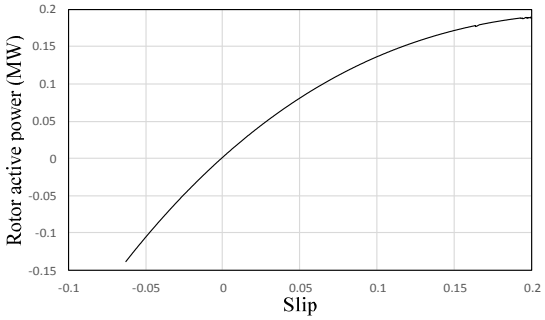

Figure 6. Active power absorbed by rotor under changes of slip

As shown in Figure 3 to Figure 6, with decreasing of slip, the active current of stator gradually increases and the reactive current input to stator side through grid gradually increases. As the slip decreases to -0.0631, the active power absorbed by rotor decreases from 0.1886 MW to -0.1384 MW in accordance with the change law reflected in curve. When slip is -0.0004, active power absorbed by rotor is 0.0014 MW. It can be known that the slip changes first, the changes to active power absorbed by rotor falls behind changes to slip, which conforms to the operating state of doubly-fed wind power generators mentioned in introduction. When active power absorbed by rotor is negative, the rotor generates active power to outside, the changes to rotor active power under changes of slip can be calculated through formula (11). With gradual decreasing of slip, the active power absorbed by rotor gradually decreases, and the active power outputted by rotor gradually increases.

IV. CONCLUSIONS

According to slip, effective value of stator current, active current of stator and reactive current of stator, the real time calculation formula (11) can accurately calculate changes to rotor active power under changes of slip. As shown in calculation results, with gradual decreasing of slip, when the DFIG run on sub-synchronous power generating state, the active power absorbed by rotor gradually decreases, when the DFIG run on hyper-synchronous power generating state, the active power outputted by rotor gradually increases.

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