A FUZZY WITH TRANSIENT CONTROL OF REACTIVE CURRENT FOR LINE-SIDE CONVERTER OF BRUSHLESS DOUBLY FED INDUCTION GENERATOR

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ABSTRACT: In this paper, the transient control algorithm of the reactive current by the line-side converter (LSC) control is proposed when the inductive load is suddenly connected or disconnected from the stator power winding (PW) of the brushless doubly fed induction generator (BDFIG). In stand-alone operation, the quality of the voltage waveform at the point of common coupling (PCC) will be strongly affected due to the reactive power change of load. When the amplitude of the PCC voltage is higher than the DC-link voltage, the LSC cannot work normally. To tackle this problem, many control strategies such as predictive current control, direct voltage control are usually developed in machine-side converter (MSC) to supply the reactive power. But the LSC can also assist in stabilizing the PCC voltage fluctuation by supplying or absorbing reactive current. This paper analyzes the transient state of the load current and the PCC voltage when the load is suddenly connected to the stator PW. Then the controllability of the LSC during the PCC voltage swell is analyzed when the load is disconnected from the stator PW. A high voltage ride-through (HVRT) control strategy is proposed by using the reactive current of the LSC. The correctness of the proposed method is demonstrated by simulations and experiments.

Index Terms--Brushless doubly fed induction generator (BDFIG), reactive current compensation, stand-alone operation, transient response.

I. INTRODUCTION

Brushless doubly-fed induction generator (BDFIG) is a new type of induction machine which has the advantages of DFIG that it only requires a low-power rating of the converter compared to the nominal power of the machine. Furthermore, the absence of brush gear and slip rings in the BDFIG can increase the system reliability and decrease the high maintenance costs [1]. With the independent control of the active and reactive power, the BDFIG as a stand-alone power generation has a wide application of variable-speed constant-frequency generator in some embedded generation systems, such as ship shaft generation systems [2], [3]. The BDFIG has two sets of three-phase stator windings. One is the stator power winding (PW) which is used for generating power and connected to the load, the other set of stator windings, called the stator control winding (CW), is supplied with a variable voltage and frequency power converter which is also connected to the stator PW [4]. The rotor winding (RW) is used to couple to the two stator windings. In the stand-alone BDFIG system, the generator should be controlled to build up a constant stator PW voltage to support the loads, but the voltage at the point-of-common coupling (PCC) will fluctuate in case of larger variations of the loads. Especially, the load is connected or disconnected from the PCC. The voltage fluctuation degrades the performance of other loads connected to the PCC and introduces torque pulsations [5].

SOFTWARE REQUIREMENTS

MATLAB APPLICATIONS

a) Industrial applications.
b) Renewable Energy applications.
c) Drive applications, like fans and pumps.
II. WIND TURBINES:
There are two types of wind turbine in relation to their rotor settings. They are:
1. Horizontal-axis rotors, and
2. Vertical-axis rotors.

A. Number of rotor blades:
The three bladed rotors are the most common in modern aero generators. Compared to three bladed concepts, the two and one bladed concepts have the advantage of representing a possible saving in relation to cost and weight of the rotor. However, the use of fewer rotor blades implies that a higher rotational speed or a larger chord is needed to yield the same energy output as a three bladed turbine of a similar size. The use of one or two blades will also result in more fluctuating loads because of the variation of the inertia, depending on the blades being in horizontal or vertical position and on the variation of wind speed when the blade is pointing upward or downward.

Therefore, the two and one bladed concepts usually have so-called teetering hubs, implying that they have the rotor hinged to the main shaft. This design allows the rotor to teeter in order to eliminate some of the unbalanced loads. One bladed wind turbines are less widespread than two-bladed turbines. This is because they in addition to a higher rotational speed, more noise and visual intrusion problems, need a counter weight to balance the rotor blade.

The turbine can be coupled with the generator to provide an indirect drive through a mechanical accumulator (weight lifted by hydraulic pressure) or chemical storage (battery). Thus, generator control is independent of turbine operation.

The generators used with wind machines are i) Synchronous AC generator ii) Induction AC generator and iii) Variable speed generator.

Offshore wind power refers to the construction of wind farms in bodies of water to generate electricity from wind. Unlike the typical usage of the term "offshore" in the marine industry, offshore wind power includes inshore water areas such as lakes, fjords and sheltered coastal areas, utilizing traditional fixed-bottom wind turbine technologies, as well as deep-water areas utilizing floating wind turbines. A subcategory within offshore wind power can be near shore wind power.
III. FUZZY LOGIC

In recent years, the number and variety of applications of fuzzy logic have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection.

Fig. 3 Primary GUI Tools Of the Fuzzy Logic Toolbox.

Fig 3 shows the five primary GUIs can all interact and exchange information. Any one of them can read and write both to the workspace and to the disk. The FIS Editor handles the high level issues for the system: How much input and output variables? What are their names? The Fuzzy Logic Toolbox doesn't limit the number of inputs. However, the number of inputs may be limited by the available memory of your machine. If the number of inputs is too large, or the number of membership functions is too big, then it may also be difficult to analyze the FIS using the other GUI tools.

The Membership Function Editor is used to define the shapes of all the membership functions associated with each variable. The Rule Editor is for editing the list of rules that defines the behavior of the system.

A. FIS EDITOR:

Following discussion walks you through building a new fuzzy inference system from scratch. If you want to save time and follow along quickly, you can load the already built system by typing fuzzy tipper This will load the FIS associated with the file tipper.fis (the .fis is implied) and launch the FIS Editor. However, if you load the pre-built system, you will not be building rules and constructing membership functions.

![FIS Editor](image)

You will see the fig. 4 updated to reflect the new names of the input and output variables. There is now a new variable in the workspace called “tipper” that contains all the information about this system.

![Save to workspace as...’ window.](image)

By saving to the workspace with a new name, you also rename the entire system. Your window will look like as shown in Fig.5.

![Updated FIS Editor.](image)
Fig. 6 leave the inference option in the lower left in their default positions for now. You have entered all the information you need for this particular GUI.

B. MEMBERSHIP FUNCTION EDITOR:

![Image of Membership Function Editor]

Fig. 7 Membership Function Editor shares some features with the FIS Editor. In fact all of the five basic GUI tools have similar menu options, status lines and help and close buttons.

![Image of Updated Membership Function Editor]

Fig. 8 Updated Membership Function Editor.

In Fig. 8 when you open the Membership Function Editor to work on a fuzzy inference system that does not already exist in the workspace, there is not yet any membership functions associated with the variables that you have just defined with the FIS Editor.

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Tab: 1 Fuzzy rules.

Table shows the fuzzy logic rules are as given above. The Rule Editor additionally has some well-known milestones, like those in the FIS Editor and the Membership Function Editor, including the menu bar and the status line.

IV. PROJECT DISCRISION AND CONTROL DESIGN

A. BASIC PRINCIPLE AND CONFIGURATION OF THE BDFIG:

The BDFIG comprises two electrically separated stator windings, called the stator PW and stator CW. The stator PW produces a pp pole-pair field rotating at speed of \( \omega_p \) and the stator CW produces a pc pole-pair field rotating at speed of \( \omega_c \) [16]. The RW is specially designed to couple to the two stator windings. The BDFIG is normally operated in the synchronous mode, called doubly-fed mode as well, as shown in Fig. 1 [3].

In Fig. 1, the RW will produce the induced current of angular speed \( \omega_{rp} \) and \( \omega_{rc} \) in response to the stator PW and stator CW. The angular speeds in the rotor reference frame are

\[
\omega_{rp} = \omega_p - \beta_p \omega_r
\]
\[
\omega_{rc} = \omega_c - \beta_c \omega_r
\]

For the only one set of RW is through the same current, it is required that \( \omega_{rp} = -\omega_{rc} \). Then, the shaft angular speed \( \omega_r \) is expressed by
\[
\omega_r = \frac{\omega_p + \omega_c}{\rho_p + \rho_c}
\]

(2)

Where, \(\omega_p\) and \(\omega_c\) are the angular speed of the stator PW and the stator CW, respectively.

From (2), it can be seen that with the variable speed \(\omega_r\) of the BDFIG, \(\omega_p\) can be kept constant by controlling \(\omega_c\). It is the operation principle of the BDFIG. When the angular speed of the stator CW is zero, the shaft angular speed \(\omega_r\) is given by

\[
\omega_r = \frac{\omega_p}{\rho_p + \rho_c}
\]

(3)

The converters are with a Common dc-link and are also connected to the stator PW at the PCC.

Fig. 10. Scalar control diagram of the BDFIG.

In Fig. 10, a Y-connected filtering capacitor \(C_g\) is equipped with the output of the stator PW of the BDFIG. This capacitor can reduce the ripples in the stator PW voltage and filter out the harmonics produced by the LSC which works under the pulse width modulation (PWM) control method [17]. The three-phase asynchronous motor which is controlled by the Siemens inverter is used to emulate variable-speed operation of prime movers. LL and RL are the equivalent inductance and resistance of the load, respectively. Usually, the MSC is used to control the stator CW current so as to regulate the voltage of the stator PW. The focus of this paper is the reactive current control of the LSC, so the scalar control scheme is used for the BDFIG in the control of the MSC based on (2), shown in Fig. 10 [18].

In Fig. 10, \(U_m\) is the amplitude of the PCC voltage \(u\) and \(I_{sc}\) is the amplitude of the stator CW current \(i\). \(V_{cm}\) and \(\theta_c\) are the amplitude of the phase voltage \(v_c\) and phase angle of the MSC, respectively. When the amplitude of the PCC voltage is smaller than the reference value, the stator CW current will increase and vice versa. It is the simple and reliable control method for the BDFIG and avoids identifying motor parameters. This method is sufficient for low-performance drive applications, like fans and pumps.
V. TRANSIENT REACTIVE CURRENT COMPENSATION METHOD IN CASE OF THE INDUCTIVE LOAD CONNECTION

A. Transient Analysis of the Voltage Drop in Case of the Inductive Load Connection:

With the help of the equivalent circuit of the BDFIG, the operating conditions of the BDFIG and its associated converters can be obtained quickly. Fig.11 shows a per-phase steady-state equivalent circuit of the BDFIG [16]. So the stator PW side circuit is equivalent to the combination of induced electromotive force denoted by $e_{sp}$ and stator PW resistance and leakage inductance denoted by $R_{sp}$ and $L_{sp}$, respectively. In the BDFIG neglecting losses, the expressions for the power balance is given by $P_{sc} = s_b P_{sp}$ [19], $s_b$ is the total slip of the BDFIG. Supposed that the LSC is operated under unity power factor, the relationship between $a$-phase current $i_a$ of the LSC and $a$-phase output current of the stator PW $i_{sp}$ can be written as

$$i_a = s_b i_{spa} \cos \theta_p$$  \hspace{1cm} (4)

Where,

$\theta_p$ is the power factor angle of the stator PW. Then, the LSC can be seen as a controlled current source. Since the LSC and MSC are with a common capacitive dc-link and can be decoupled by the capacitance $C_{dc}$, the MSC is not considered in the circuit for LSC analysis. The $a$-phase equivalent circuit for the stand-alone BDFIG system seen from the stator PW side is shown in Fig. 12. In Fig. 12, $i_{La}$ is the $a$-phase load current and $u_a$ is the $a$-phase PCC voltage.

Fig. 12 A-phase equivalent circuit of the stand-alone BDFIG system.

Taking the initial angle of $a$-phase voltage as the reference angle, $e_{spa}$ in time domain is described as follows:

$$e_{spa}(t) = U_m \cos (\omega t) \hspace{1cm} (5)$$

Where,

$U_m$ and $\omega$ are the amplitude of the phase voltage and angular frequency, respectively. Then, $e_{spa}$ in complex frequency domain can be deduced by the Laplace transformation

$$e_{spa}(s) = \frac{U_m s}{s^2 + \omega^2}. \hspace{1cm} (6)$$
B. Transient Reactive Current Compensation by LSC Based on V–I Doubly Closed Loop:

Both the LSC and the stator PW can supply the reactive power to the load. With the higher control bandwidth of the LSC, the LSC can quickly respond to the change of the PCC voltage. So it is easier and more reliable to choose the LSC to compensate the reactive current of the load. Implementing the PCC voltage-oriented reference frame, the control scheme of the LSC adopts the voltage and current double closed-loop structure shown in Fig. 13 [20]. In Fig. 13, the phase angle $\theta$ for the coordinate transformation is calculated by the single synchronous reference frame software phase-locked loop [21]. With the conventional PI controller, the output of the voltage loop is given as the $d$-axis reference current to control the dc-link voltage, and the negative reactive component of the load current $i_{Lq}$ is given as the $q$-axis reference current to compensate for reactive stator PW current caused by load. When the inductive load is connected to the stator PW of the BDFIG, the reactive current of the load is calculated according to the classic instantaneous reactive power (IRP) theory. Then, the LSC will supply the reactive current to the load assisting in stabilizing the PCC voltage fluctuation.

C. TRANSIENT REACTIVE CURRENT CONTROL AFTER SUDDEN LOAD DISCONNECTION:

a) Reactive Current Control of the LSC during the Voltage Swell at the PCC:

When the load is suddenly disconnected from the stator PW, the voltage swell at the PCC may be generated due to the abrupt interruption of the current. This voltage swell may cause the LSC uncontrollable due to the dc-link voltage limitation [26]. Under the PCC voltage-oriented reference frame, the voltage of the LSC in the synchronous dq axis reference frame can be expressed as [27]

$$U_m = R_s i_d + L_s \frac{di_d}{dt} - \omega L_s i_q + v_d \rightarrow (7)$$

Where $L_s$ and $R_s$ are the LSC filter inductance and inner resistance, respectively. If neglecting the resistance $R_s$ and operating under the unity power factor, the relationship of voltage space vectors of LSC in the steady state can be simplified as

$$v_d = U_m + \omega L_s i_q$$
$$v_q = -\omega L_s i_d.$$  

The diagram is described as Fig. 14. Taking the principle of modulation into consideration, the maximum available LSC voltage has to be limited [24]
Where $m$ is the modulation index, and there is $m = 2$ for sinusoidal pulse width modulation and $m = \sqrt{3}$ for space vector pulse width modulation. With (8) and (9), the lowest limit of the dc-link voltage of the LSC can be obtained as following expression

$$\sqrt{(U_m + \omega L_s i_q)^2 + (\omega L_s i_d)^2} \leq \frac{u_{dc}}{m}. \quad (10)$$

Based on the (4), $i_d$ will increase when the load becomes large. So from (10), the larger the load is, the higher the dc-link voltage is needed. Even at no-load situation, the dc-link voltage has the minimum value $U_m$ which is the magnitude of the PCC voltage. To simplify the analysis, the LSC is controlled to compensate all the reactive current produced by the inductive load. So in this steady-state situation, there is only active current $i_{spd}$ in the stator PW of the stand-alone BDFIG and the reactive current $i_{sq}$ is zero. Meanwhile, the main role of the MSC control is to regulate the magnitude of the PCC voltage as desired value $U_m$, so the active current of the load $i_{ld}$ can be expressed as

$$i_{ld} = \frac{2 P_L}{3 u_d} = \frac{2 P_L}{3 U_m}. \quad (11)$$

Where $P_L$ is the active power of the load.

When the load is suddenly disconnected from the stator PW, the load current is cut off. So $\Delta i_{sq} = i_{ld}$. Then, the voltage swell at the PCC can be obtained based on (12)

$$\Delta u_d = R_{sp} \Delta i_{spd} + L_{sp} \frac{\Delta i_{spd}}{\Delta t} = \frac{2 R_{sp} P_L}{3 U_m} + \frac{2 L_{sp} P_L}{3 U_m \Delta t}. \quad (12)$$

Where, $U_m$ is the instantaneous amplitude of the phase voltage at the PCC, and $U_m$ is the rated value of the voltage. $K$ insures that it does not exceed a maximum current $i_{max}$ of the LSC. With the regulation of the BDFIG system, the output voltage of the PW will be regulated to the rated value at the steady state. Then, $iq$ will return to the steady state. The LSC can be simply controlled in case of the voltage swell.

b) Transient Response of the DC-Link Voltage During Sudden Unload:

Using (7), the relationship of voltage space vectors of LSC in the transient state can be obtained

$$\frac{di_d}{dt} = \frac{U_m - v_d + \omega L_s i_q}{L_s}. \quad (13)$$

With the above equation, it can be seen that if we want to guarantee the fastest transient response of the active current $i_d$, the rising and falling slopes of the active current $i_d$ must be larger [28]. In (13), the $U_m$ and $L_s$ are the constant value. So the transient response of the active current depends on the voltage $v_d$ and the reactive current $iq$ of the LSC. When the load is disconnected from the stator PW, the d-axis reference current given by the outer loop voltage should decrease. The negative maximum voltage is required across the inductor $L_s$ for the fast transient response and then the LSC voltage $v_d$ should be changed into the positive maximum value. So the minimum possible time for tracking the reference current can be calculated as

$$\Delta T = L_s \frac{i_d - i_d}{v_{d_{max}} - \omega L_s i_q - U_m}. \quad (14)$$

Where, $v_{d_{max}}$ is the maximum voltage generated by the LSC.

However, the maximum voltage $v_{d_{max}}$ is bounded as (9) if a PWM is used. So the value of $(v_{d_{max}} - \omega L_s i_q - U_m)$ is very small and $\Delta T$ becomes long. Therefore, if the d-axis reference current decreases, the current regulation is very slow due to the voltage constraint of the converter. This will make the dc link voltage swell in a long transient period. Moreover, this
phenomenon becomes more serious in the case of higher PCC voltage.

From (14), we can see that when the reactive current $i_q$ becomes negative, the falling slope of the active current $i_d$ becomes larger. Therefore, by utilizing the negative $q$-axis current, the less transient period is possible and the dc-link voltage can be fast tracking to the reference value. The simulation of the HVRT control strategy of the LSC.

When the load is suddenly disconnected from the stator PW, the swell of the voltage at the PCC will be generated. Fig. 19 shows the normal operation of the LSC. It can be seen that the LSC fails to control the current and the dc-link voltage also exceeds the rating of the converter much more. However, with the transient negative reactive current injected into the PCC, the LSC can remain controllable under the proposed HVRT control shown in Fig. 20. The transient response of the proposed current controller is much faster than that of the conventional PI regulator, and it is helpful to reduce the dc-link overvoltage.

VI. SIMULATION RESULTS

Fig. 15 complete block diagram of simulation fuzzy logic controller.

The simulation is performed using the PLECS software to verify the performance and effectiveness of the proposed control. The configuration is given in Fig. 10. The parameters of the BDFIG system referred to the stator PW.

Fig. 16 Simulation Fuzzy logic results of the PCC voltage reactive current control without compensation.

Fig. 17 Simulation Fuzzy logic results of the PCC voltage reactive current control with fully compensation.
As soon as the PCC voltage is in the steady state, the system control strategy is switched to the coordinated reactive power control scheme. The coordinator block calculates the desired reactive power of the load and shares it to the LSC and MSC by changing the reactive power reference value of the controller, respectively. The strategy of allocation about the reactive power reference value is based on the outcome of the optimization problem [25].

In order to verify the proposed control strategy, an 80kVA/380V stand-alone BDFIG system is constructed. The BDFIG is rotated by a 90kW three-phase asynchronous motor emulated as a prime mover with the speed control, shown in this figure for all X-axis=10ms/div. and Y-axis is 800 to -800 (voltage).

VII. CONCLUSION

This paper has proposed a transient reactive current control approach for a stand-alone BDFIG
system to enhance the performance of the PCC voltage and the controllability of the LSC. The stator PW current and the voltage at the PCC are carried out when the resistance–inductance load is suddenly connected to the BDFIG. It results in the voltage drop and distortion at the PCC, and if only the positive-sequence fundamental reactive load current is used as the reference value of the q-axis current control loop in the LSC, the stator voltage can be significantly compensated. Another, the controllability of the LSC with limited rating considered during the PCC voltage swell is analyzed. A HVRT control strategy of the LSC is proposed by using the reactive current of the LSC, and it also improves the fast response the dc-link voltage in the transient region. The experimental results indicate that the compensation method performs well and can be used in practice.

REFERENCES


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