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Study on Fault Current of DFIG during Slight Fault Condition

Xiangping Kong*[1], Zhe Zhang[2], Xianggen Yin[3], Zhenxing Li[4]
[1,2,3,4]The State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science & Technology, Wuhan 430074, China
*Corresponding author, e-mail: kongxphust@163.com

Abstract

In order to ensure the safety of DFIG when severe fault happens, crowbar protection is adopted. But during slight fault condition, the crowbar protection will not trip, and the DFIG is still excited by AC-DC-AC converter. In this condition, operation characteristics of the converter have large influence on the fault current characteristics of DFIG. By theoretical analysis and digital simulation, the fault current characteristics of DFIG during slight voltage dips are studied. And the influence of controller parameters of converter on the fault current characteristics is analyzed emphatically. It builds a basis for the construction of relay protection which is suitable for the power gird with accession of DFIG.

Keywords*: slight fault condition, DFIG, operation characteristic of converter, fault current characteristics, controller parameters*

1. Introduction

Under the pressure of increasing demand of electric power, gradual exhaustion of fossil energy and environmental protection, the development and efficient utilization of renewable energy which is represented by wind power has received extensive attention in the world wide. Wind power generation has been the important development direction of electric power technology. Doubly-Fed Induction Generator (DFIG) is widely applied in existing wind farms as it has advantages of high energy conversion efficiency, small capacity of converters, flexible control of active power and reactive power, and well regulation performance [1-5].

However, with the increase of capacity of gird-connected wind power, the risk of safe and stable operation of power systems which is brought by wind turbines is more and more obvious. Hence, power system operators establish new grid code for wind power which requires wind turbines should the capability of Low Voltage Ride Through (LVRT) [6, 7]. LVRT refers to the capability of wind turbines to remain connected, dynamically stable, and offer network support throughout a serious voltage disturbance on the power gird.

In order to meet the new grid code, realize the LVRT of wind turbines, and ensure the safe and stable operation of power grid and wind turbines at the same time, it needs to study relay protection principle and cooperation mechanism between protections of power grid and wind turbine which is applicable to the power grid with accession of wind turbines. While, the power generation mode and grid connected mode of wind turbine are different from those of traditional synchronous motor, which brings in many new problems and challenge to the study of relaying protection. In condition of severe fault, crowbar protection [8, 9] which trips to short circuit the rotor winding of DFIG and diverts current from Rotor Side Converter (RSC) is adopted to protect the safety of DFIG. But in condition of slight fault, crowbar protection will not trip, and the rotor winding of DFIG is still excited by AC-DC-AC converters. The fault current characteristics of DFIG, such as transient components and damping characteristics, are different in these two conditions. And they are both different from those of traditional synchronous motor. Therefore, it is necessary to study the fault current characteristics of DFIG in these two conditions separately and specifically.

For the fault current characteristics of DFIG in condition of three-phase fault, scholars have carried out lots of research works [10-12]. J. Lopez [10] analyzed the dynamical characteristics of DFIG in condition of three-phase fault. And the characteristics of current of

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stator winding and voltage of rotor winding are studied when the rotor winding is open-circuit. From the point of view of conservation principle of flux linkages, J. Morren [11] analyzed the fault current of DFIG in condition that three-phase fault happens and crowbar protection trips through the comparison with that of induction motor. Superposition principle is adopted by Zhang [12] to analyze the fault current of DFIG when fault happens at the generator terminal.

In conclusion, the analysis of the fault current characteristics of DFIG in condition of three-phase fault mainly focus on the condition that the rotor winding is open-circuit or short circuited by a resistance. Few research works have been implemented to study the fault current characteristics of DFIG in condition that the rotor winding still connects with AC-DC-AC converters. While, in condition of slight fault, crowbar protection will not trip, and the rotor winding of DFIG is still excited by AC-DC-AC converters. In this condition, the dynamical operation characteristics of AC-DC-AC converters have large influence on the fault current characteristics of DFIG which is much more complicated.

Aimed at it, from the both aspects of stator winding current and current at AC side of grid side converter (GSC), the fault current characteristics of DFIG during slight fault condition are analyzed. The influence of controller parameters of AC-DC-AC converters on fault current characteristics is studied emphatically. In the end, the theoretical analysis results are verified by digital simulation.

2. Control Strategy of DFIG

2.1. Control Strategy of GSC

Stable DC bus voltage is the key of well-performance AC excitation of DFIG. Hence, the primary control purpose of GSC is to keep the DC bus voltage stable. At present, vector control scheme based on alignment of grid voltage in synchronous dq reference frame is adopted for control of GSC, as shown in Figure1.

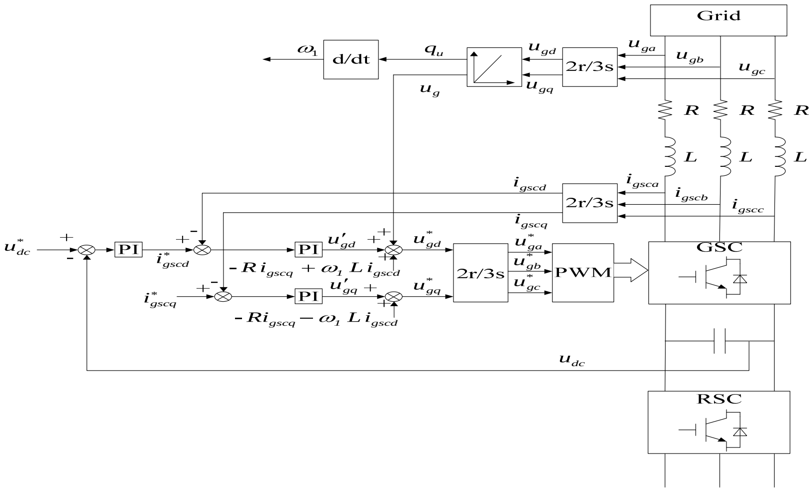


Figure 1. Control Diagram of GSC

In Figure 1, the d-axis reference signal of grid current of GSC i_{gscd}^* can be obtained with the error between reference signal of DC bus voltage u_{dc}^* and feedback signal u_{dc} being regulated by external DC voltage PI controller. As unity power factor is the control purpose of GSC, $i_{gscq}^* = 0$. The errors between i_{gscd}^*, i_{gscq}^* and corresponding feedback signals are processed by inner grid current PI controller to give u'_{gd} and u'_{gq}. In order to ensure good tracking of theses currents and high anti-disturbance capability, the cross-related current terms and feed-forward compensation of gird voltage are added to u'_{gd} and u'_{gq}.obtain the voltage reference signals u_{gd}^* and u_{gq}^*.

2.2. Control Strategy of RSC

The excitation currents are provided by RSC to realize the vector control of DFIG, capture the maximum wind power and regulate the reactive power. Vector control scheme based on alignment of stator winding voltage in synchronous dq reference frame is adopted for control of RSC, as shown in Figure 2.

As shown in Figure 2, control scheme based on dual control loops with external power control loop and inner rotor winding current control loop is adopted. For the external power control loop, the reference signal of active power P_s^* is given according to the maximum power curve of wind turbine. In order to make the DFIG operate with unity power factor, $Q_s^* = 0$. Feedback signal of active power and reactive power P_s, Q_s are calculated with three-phase currents and voltages of stator winding. Reference signal of rotor winding current i_{rd}^* and i_{rq}^* are obtained with processing of the errors between reference signals and feedback signals of active power and reactive power by external power PI controller. u_{rd}^* and u_{rq}^* can be obtained with the error between i_{rd}^*, i_{rq}^* and corresponding feedback signals being regulated by inner rotor winding current PI controller, feed-forward compensation and decoupling.

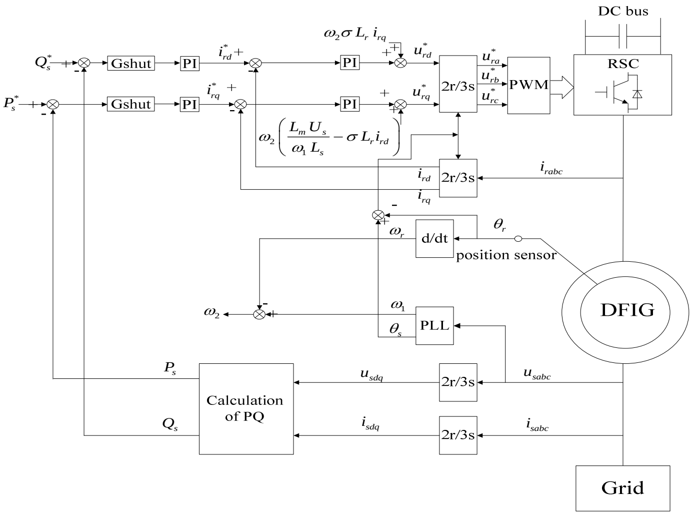


Figure 2. Control Diagram of RSC

During the fault transient period, it is not reasonable to make the DFIG operate with unity power factor and capture maximum wind power. Meanwhile, the measurements of active power and reactive power are not accurate. Hence, the external power control loop should be shut down in condition that gird voltage dips caused by fault has been detected. It is realized by the shut down signal Gshut as shown in Figure 2. If the gird voltage is smaller than 0.9p.u., Gshut changes from 1 to 0 to shut down the external power control loop.

3. Theoretical analysis of influence factors of fault current characteristics of DFIG

As the rotate inertia time constant of DFIG is large, the change of rotate speed is much slower than that of electrical quantity. Hence, the rotate speed is considered as constant in the following analysis.

3.1. Influence Factors of Stator Winding Current Characteristics

The voltage equations based on fault component are adopted for convenience, which are shown in (1).

$$\begin{cases} \Delta u_{sd} = -R_s \Delta i_{sd} - \omega_1 \left(-L_s \Delta i_{sq} + L_m \Delta i_{rq} \right) + p\left(-L_s \Delta i_{sd} + L_m \Delta i_{rd} \right) \\ \Delta u_{sq} = -R_s \Delta i_{sq} + \omega_1 \left(-L_s \Delta i_{sd} + L_m \Delta i_{rd} \right) + p\left(-L_s \Delta i_{sq} + L_m \Delta i_{rq} \right) \\ \Delta u_{rd} = R_r \Delta i_{rd} - \omega_s \left(-L_m \Delta i_{sq} + L_r \Delta i_{rq} \right) + p\left(-L_m \Delta i_{sd} + L_r \Delta i_{rd} \right) \\ \Delta u_{rq} = R_r \Delta i_{rq} + \omega_s \left(-L_m \Delta i_{sd} + L_r \Delta i_{rd} \right) + p\left(-L_m \Delta i_{sq} + L_r \Delta i_{rq} \right) \end{cases} \quad (1)$$

Where "Δ" corresponds fault component.

As the axis-d is aligned with stator voltage vector $\dot{U}_s$, the fault voltage components can be expressed in (2).

$$\Delta u_{sd} = -\lambda U_{sn}, \ \Delta u_{sq} = 0 \quad (2)$$

Where U_{sn} is the rated stator winding voltage and λ is the voltage dips amplitude.

For the external power control loop is shut down, the reference values of rotor winding current i_{rd}^* and i_{rq}^* keep constant which means:

$$\Delta i_{rd}^* = 0, \ \Delta i_{rq}^* = 0 \quad (3)$$

After the transient process caused by fault, the PI controller will make the rotor winding currents track the reference values again. Hence,

$$\Delta i'_{rd} = 0, \ \Delta i'_{rq} = 0 \quad (4)$$

Where superscript "$'$" represents steady state amplitude of fault component.

If the DFIG is in fault steady state operation condition, and the stator winding resistance is neglected, the first two equations in (1) can be expressed as shown in (5).

$$\begin{cases} \Delta u_{sd} \approx \omega_1 \left(L_s \Delta i'_{sq} - L_m \Delta i'_{rq} \right) \\ \Delta u_{sq} \approx \omega_1 \left(-L_s \Delta i'_{sd} + L_m \Delta i'_{rd} \right) \end{cases} \quad (5)$$

Substituting (2) and (4) into (5), the steady state amplitudes of stator winding current fault components can be obtained as expressed in (6).

$$\begin{cases} \Delta i'_{sd} \approx 0 \\ \Delta i'_{sq} \approx -\lambda U_s / \left(\omega_1 L_s \right) \end{cases} \quad (6)$$

It can be obtained from (6) that the steady state amplitude of stator winding fault current $\dot{I}_s$ is not affected by controller parameters of converters. The d-axis component of stator winding current keeps unchanged, and the variation of q-axis component is proportional to voltage dips amplitude.

As there is coupling between GSC, RSC and stator winding, the transient characteristics of stator winding fault current are affected by the controller parameters of GSC and RSC. Proportional element plays leading role at begin and middle of fault transient process to response to disturbance quickly. Integral element plays leading role at end of fault transient process to ensure zero steady state error. Hence, transient characteristics of stator winding fault current are mainly affected by proportional gain of controllers, and it is basically not affected by integral gains.

3.2. Influence Factors of Grid Current Characteristics of GSC

As the q-axis reference signal of grid current of GSC i_{gscq}^* is still set as 0 during the fault condition, the steady state amplitude of q-axis component of grid current of GSC in fault condition which is denoted as i'_{gscq} also keeps the same with that in normal operation condition. But the fault condition will result in fluctuation of active power transmitted from RSC to GSC which will cause fluctuation of DC bus voltage. From the control scheme of GSC as shown in Figure 1, fluctuation of DC bus voltage may result in the variation of steady state value of i^*_{gscd} . In this condition, the steady state amplitude of d -axis component of grid current of GSC will change.

With the regulation of external DC voltage PI controller, the steady state value of DC bus voltage in fault condition will track the reference signal and keeps the same with that in normal operation condition. It means that the active power transmitted from grid to GSC is equal to that transmitted form GSC to RSC in fault steady state,

$$i'_{gscd}u'_{gd} = i'_{rd}u'_{rd} + i'_{rq}u'_{rq} \tag{7}$$

Where i'_{gscd} is the steady state amplitude of d -axis component of gird current, $u'_{gd} = (1-\lambda)U_{gn} = (1-\lambda)U_{sn}$ which is the steady state amplitude of gird voltage, u'_{rd} 、u'_{rq} correspond steady state amplitudes of d - and q -axis components of rotor winding voltage.

From the regulation characteristics of RSC controller, it can be obtained that u'_{rd} 、u'_{rq} are only affected by parameters of inner rotor winding current controller under the same grid voltage. Meanwhile, i'_{rd} 、i'_{rq} are not affected by any parameters of controllers. Hence, i'_{gscd} is only affected by parameters of inner rotor winding current controller.

Hence, the steady state amplitude of gird fault current of GSC $\dot{I}_{gsc}$ is only affected by controller parameters of inner rotor winding current controller. While, the transient characteristics of $\dot{I}_{gsc}$ are affected by the controller parameters of GSC and RSC. Transient characteristics of $\dot{I}_{gsc}$ are mainly affected by proportional gains of controllers, but basically not affected by integral gains, as the same with that of stator winding fault current.

3.3. Influence Factors of Fault Current Characteristics of DFIG

Actually, the fault current provided by DFIG which is denoted as $\dot{I}_g$ consists of $\dot{I}_s$ and $\dot{I}_{gsc}$. Operation characteristics of RSC and GSC both have affect on characteristics of $\dot{I}_g$. The steady state amplitude of $\dot{I}_g$ is only affected by controller parameters of inner rotor winding current controller of RSC. The transient characteristics of $\dot{I}_g$ are affected by the controller parameters of GSC and RSC. But the capacity of GSC is only one third of that of DFIG [13], so the fault current provided by GSC which is $\dot{I}_{gsc}$ actually is small. Hence, the influence of controller parameters of GSC on fault current characteristics of DFIG is smaller than that of controller parameters of RSC. Meanwhile, transient characteristics of $\dot{I}_g$ are mainly affected by proportional gains of controllers, but basically not affected by integral gains.

4. Simulation Analysis of Influence Factors of Fault Current Characteristics of DFIG

The model shown in Figure 3 is adopted for simulation examples to study the fault current characteristics of DFIG [14].

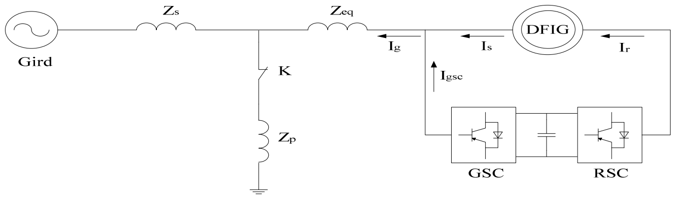


Figure 3. Simulation Model

In Figure 3, Z_{eq} is the equivalent impedance of transmission line and step-up transformer which is interface of DFIG to power grid. Z_s is the internal equivalent impedance of infinite power supply. Breaker K is open in normal operation condition. When fault happens on power grid, make K closed to inject the parallel impedance Z_p and simulate voltage dips caused by fault. Different voltage dips can be realized by change of Z_p.

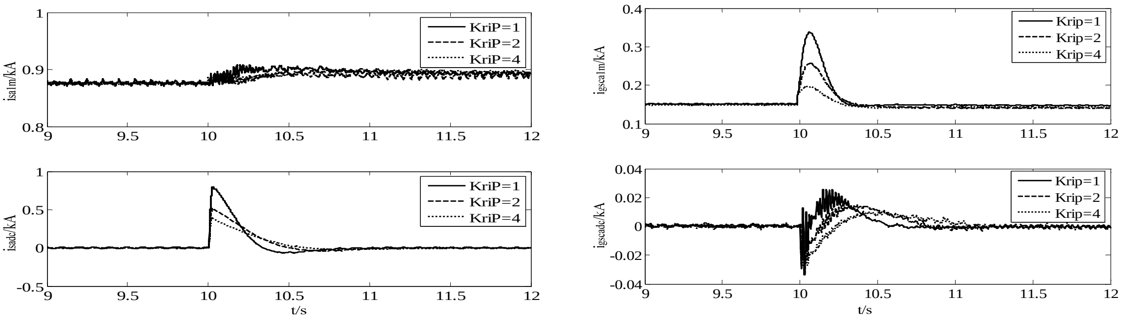
The parameters of DFIG are:

Nominal power: 1.5 MVA; nominal line-line voltage: 690 V; stator resistance (p.u.):0.00756; stator leakage inductance (p.u.):0.1425; rotor resistance (p.u.):0.00533; rotor leakage inductance (p.u.):0.1425; mutual inductance (p.u.):2.1767; rated rotate speed (p.u.): 1.2.

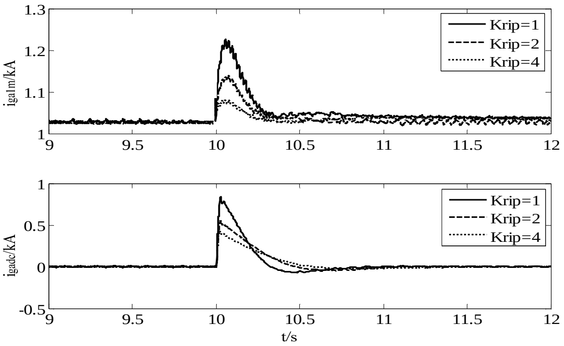
4.1. Influence of Controller Parameters of Inner Rotor Winding Current Controller of RSC

(1) Influence of proportional gain

The waveforms of fundamental component amplitudes and dc components of stator winding fault current i_{sa}, grid fault current of GSC i_{gsca} and fault current of DFIG i_{ga} in condition that proportional gain of inner rotor winding current controller of RSC denoted as k_{riP} is 1, 2 and 4 are shown in Figure 4. Subscript "$1m$" corresponds fundamental component amplitude, and "dc" corresponds dc component.



(a) Stator winding fault current (b) Grid fault current of GSC



(c) Fault current of DFIG

Figure 4. Influence of Proportional Gain on Fault Current Characteristics

From Figure 4(a), it can be obtained that with the increase of k_{riP}, dc component of stator winding fault current decreases, and its damping time constant increases, while the steady state amplitude of fundamental component keeps constant. From Figure 4(b), it can be obtained that with the increase of k_{riP}, dc component of grid fault current of GSC decreases, and its damping time constant increases, while the steady state amplitudes of fundamental component increases. The influence of k_{riP} on fault current characteristics of DFIG is the same with that on grid fault current characteristics of GSC, as shown in Figure 4(c). The simulation results verify the theoretical analysis results stated above.

(2) Influence of integral gain

The waveforms of fundamental component amplitudes and dc components of fault current of DFIG i_{ga} in condition that integral gain of inner rotor winding current controller of RSC denoted as k_{riI} is 1, 2 and 4 are shown in Figure 5.

It can be seen that k_{riI} nearly has no influence on fault current characteristics of DFIG, as analyzed in previous section.

4.2. Influence of Controller Parameters of External DC Voltage Controller of GSC

(1) Influence of proportional gain

The waveforms of fundamental component amplitudes and dc components of stator winding fault current i_{sa} , grid fault current of GSC i_{gsca} and fault current of DFIG i_{ga} in condition that proportional gain of external DC voltage controller of RSC denoted as k_{geP} is 1, 2 and 4 are shown in Figure 6.

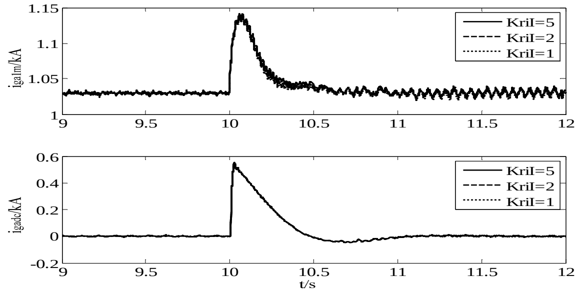
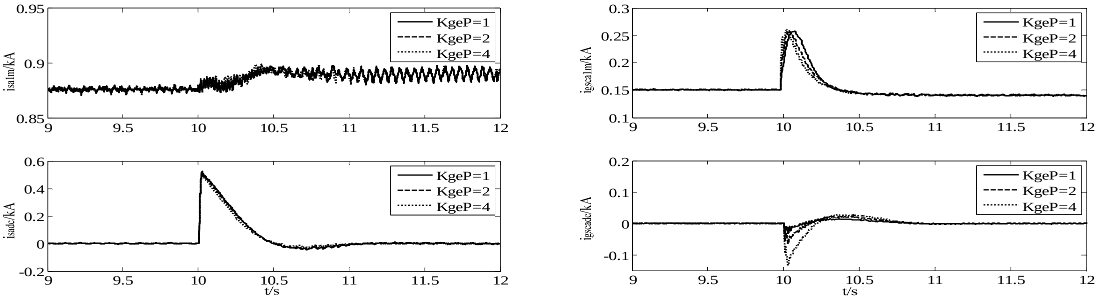
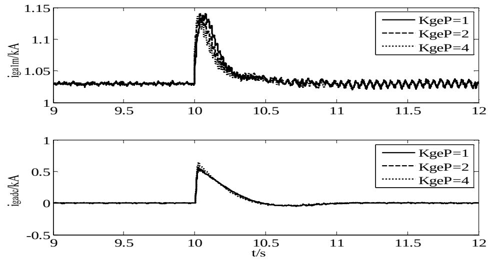


Figure 5. Influence of Integral Gain on Fault Current Characteristics



(a) Stator winding fault current

(b) Grid fault current of GSC



(c) Fault current of DFIG

Figure 6. Influence of Proportionality Factor on Fault Current Characteristics

From Figure 6(a), it can be obtained that with the increase of k_{geP} , dc component of stator winding fault current decreases, and its damping time constant increases. The influences of k_{geP} on dc component of GSC grid current and dc component of fault current of DFIG are opposite with that on dc component of stator winding fault current, as shown in Figure 6(b) and

Figure 6(c). It also can be seen that the steady state amplitudes of fundamental component of stator winding fault current, GSC grid current and fault current of DFIG keep constant. The simulation results verify the theoretical analysis results stated above.

(2) Influence of integral gain

The waveforms of fundamental component amplitudes and dc components of fault current of DFIG i_{ga} in condition that integral gain of external DC voltage controller of GSC denoted as k_{geI} is 10, 5 and 2.5 are shown in Figure 7.

It can be seen that k_{geI} nearly has no influence on fault current characteristics of DFIG, as analyzed in previous section.

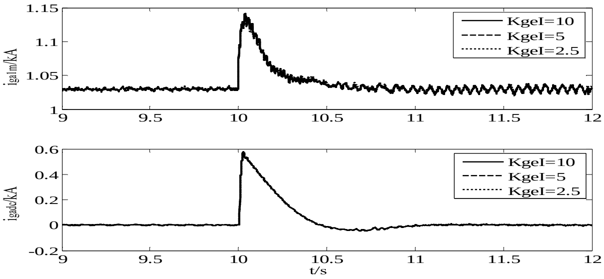
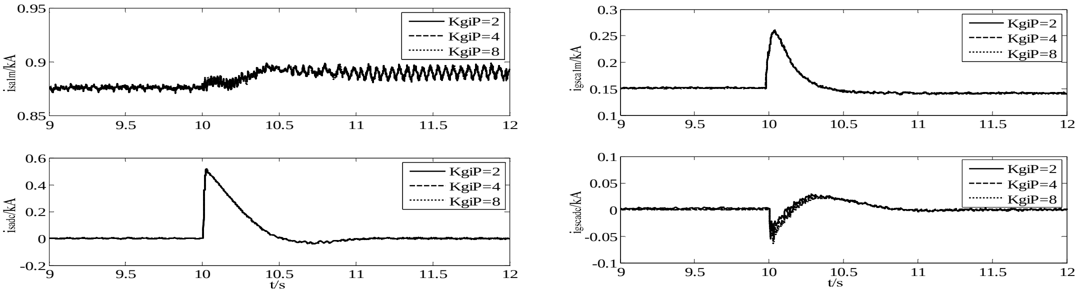


Figure 7. Influence of Integral Factor on Fault Current Characteristics

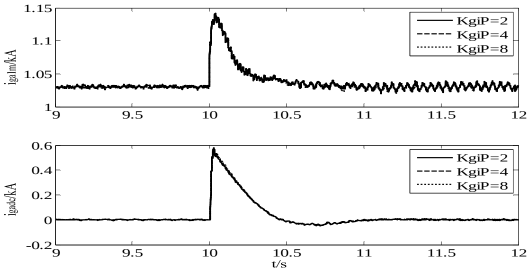
4.3. Influence of Controller Parameters of Inner Grid Current Controller of GSC

(1) Influence of proportional gain

The waveforms of fundamental component amplitudes and dc components of stator winding fault current i_{sa} , grid fault current of GSC i_{gsca} and fault current of DFIG i_{ga} in condition that proportional gain of inner grid current controller of RSC denoted as k_{giP} is 2, 4 and 8 are shown in Figure 8.



(a) Stator winding fault current (b) Grid fault current of GSC



(c) Fault current of DFIG

Figure 8. Influence of Proportionality Factor on Fault Current Characteristics

It can be obtained that k_{geI} has no influence on steady state amplitudes of fundamental component of stator winding fault current, GSC grid current and fault current of DFIG. And it nearly has no influence on transient characteristics of stator winding fault current and fault current of DFIG. Meanwhile, the influence of k_{geI} on transient characteristics of GSC grid current is small. The reason is that the capacity of GSC is small and the dynamical response of inner grid current controller of GSC is fast enough.

(2) Influence of integral gain

The waveforms of fundamental component amplitudes and dc components of fault current of DFIG i_{ga} in condition that integral gain of inner grid current controller of GSC denoted as k_{giI} is 10, 5 and 2.5 are shown in Figure 9.

It can be seen that k_{giI} nearly has no influence on fault current characteristics of DFIG, as analyzed in previous section.

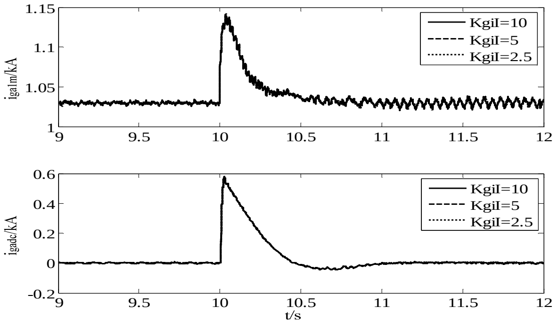


Figure 9. Influence of Integral Factor on Fault Current Characteristics

5. Conclusion

With the combination of theoretical analysis and simulation verification, the fault current characteristics of DFIG are analyzed in slight fault condition. The obtained conclusions can be drawn as follows.

(1) The operation characteristics of GSC and RSC both have influence on the fault current characteristics of DFIG. The steady state amplitude of fault current is only affected by controller parameters of inner rotor winding current controller of RSC. But the transient characteristics are affected by the controller parameters of GSC and RSC. Meanwhile, transient characteristics are mainly affected by proportional gains of controllers, but basically not affected by integral gains.

(2) With the increase of proportional gain of inner rotor winding current controller of RSC, dc component of fault current decreases, damping time constant increases, and the steady state amplitude of fundamental component increases.

(3) With the increase of proportional gain of external DC voltage controller of GSC, dc component of fault current increases, damping time constant decrease and the steady state amplitude of fundamental component keeps constant. But due to the limitation of capacity of GSC, the influence of proportional gain of external DC voltage controller of GSC on fault current characteristics is smaller than that of inner rotor winding current controller of RSC.

(4) But due to the limitation of capacity of GSC and its fast dynamic response, the proportional gain of inner grid current controller of GSC nearly has no influence on fault current characteristics of DFIG.

The study results of this paper are of great significance for the improvement of transient operation characteristics of DFIG, improvement of LVRT capability of DFIG and construction of novel protection scheme which is applicable for power grid with integration of DFIG.

Acknowledgments

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