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EVALUATION OF FAULT CURRENT CHARACTERISTICS OF THE DFIG USING DYNAMIC RESPONSE OF THE RSC

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ABSTRACT: This paper presents, an analysis method for the fault current characteristics of the DFIG under non severe fault conditions is proposed. First, the dynamic response of the RSC is analyzed on condition that the external power control loop is shut down and the reference signals of the inner rotor current control loop are kept constant. Then, the simplified calculation models of the rotor fault current are established according to different design principles of the inner rotor current controller. Based on it, the fault characteristics of the stator current are studied and the analytical expressions of the stator fault current are obtained. Finally, digital simulation results validate the analytical results. The proposed analysis method is applicable for the study of fault current characteristics of DFIG with different control strategies for low-voltage ride through. The research results are helpful to the construction of adequate relaying protection for the power grid with penetration of DFIGs. Simulation is carried out MATLAB/SIMULINK software.

Keywords: *Doubly fed induction generator (DFIG), dynamic response, fault current characteristics, non-severe fault.*

I. INTRODUCTION:

The wind power generation technology has received world-wide attention and developed very quickly. The mainly common type of wind turbine which has be extensively applied in the existing wind farms is the doubly fed induction generator (DFIG), due to its easy structure, little capacity of the converter, with flexible power control. Among the growing grid-connected wind power capacity, in arrange to make the wind turbines supply grid support all over the grid voltage dips, the new grid codes have been developed to necessitate the wind turbines have the capability of low voltage ride through (LVRT). The operation characteristics of DFIG under LVRT condition have a huge influence on the fault characteristics of voltage and current. It means that the increase penetration of DFIGs bring many new problems as well as challenges to the traditional relaying protection of the power grid, since the relaying protection identify and isolate the fault element base on the modify characteristics of electrical quantities (or nonelectrical quantities). In order to address the relaying protection issues of the power grid with penetrations of DFIGs, the fault current characteristics of the DFIG should be considered. In cases of severe faults which happen close to DFIG as well as cause the stator voltage of DFIG to drop gravely, in order to ensure the safety of the DFIG, the crowbar protection will be activated to short circuit the rotor windings with divert the surge current from the rotor-side converter (RSC).

On the other hand, in cases of non-severe faults which occur far away from the DFIG (meanwhile, the stator voltage of DFIG is large enough), the crowbar protection will not be activate and the rotor windings are still energized by the ac/dc/ac converter. The fault current characteristics of the DFIG, such as transient components with damping time constant, are much different under the two conditions. Therefore, it is necessary to study the fault current characteristics of the DFIG under these two conditions separately. For the fault current characteristics of the DFIG on condition that a severe fault happens and the crowbar protection is activated, lots of research works have been carried out. Whereas, under non-severe fault conditions, the dynamic response of the ac/dc/ac converter results in much more complicated fault current characteristics of the DFIG which are difficult to analyze. For the sake of simplicity, the fault current of the DFIG is studied based on the assumption that the excitation current will keep constant before and after the fault occurrence or rise rapidly to the maximum value and then keep constant during the grid faults.

As a consequence, In the fault current characteristics of the DFIG considering the dynamic response of the RSC are studied qualitatively. Nevertheless, the research results are based on simulation analysis, and there are no analytical expressions of the fault current. Accordingly, the research results presented in cannot completely meet the requirements of the study of relaying protection. Hence, the further research works should be implemented to study the fault current characteristics of the DFIG under non-severe fault conditions. In order to fill this gap, a theoretical analysis method for the fault current characteristics of the DFIG under non-severe fault conditions is proposed. Since the rotor windings are still excited by the ac/dc/ac converter, the dynamic response of the ac/dc/ac converter during non-severe fault conditions has a large influence on the characteristics of the stator fault current.

II. WIND ENERGY IN ELECTRICAL SYSTEM

Utility companies increasingly buy back surplus electricity produced by small domestic turbines.

Grid connected wind electric generators (WEG) employing (i) Squirrel Cage Induction Generator (SCIG) and (ii) Doubly Fed Induction Generator (DFIG) have been carried separately. Their dynamic responses to disturbances such as variations in wind speed, occurrence of fault etc. have been studied, separately for each type of WEG.

A. Power from Wind

The power that can be captured from the wind with a wind energy converter with effective area *Ar* is given by

$$P = \frac{1}{2}\rho_{air} C_p A v_w^3 \qquad (1)$$

Where *pair* is the air mass density [kg/m3], *vw* is the wind speed and *Cp* is the so-called power coefficient which depends on the specific design of the wind converter and its orientation to the wind direction. Its theoretical maximum value is 16/27 = 0.593 (Betz limit). For a wind turbine with given blades it can be shown that the power coefficient *Cp* basically depends only on the tip speed ratio *l*, which equals the ratio of tip speed *vt* [m/s] over wind speed *vw* [m/s] and the so-called blade pitch angle *q* [deg]. This pitch angle is defined as the angle between the cord of the blade and the plane of the wind rotor. So, for a wind rotor with radius *r*, (1) can be rewritten as:

$$P = \frac{1}{2}\rho_{air} C_p(\lambda,\theta)\pi r^2 v_w^3 \qquad (2)$$

As an example, Fig. 2 shows the dependency of the power coefficient *Cp* on the tip speed ratio *l* and the blade pitch angle *q* for a specific blade. For this blade maximum energy capture from the wind is obtained for *q* =0 and *l* just above 6. To keep *Cp* at its optimal value for varying wind speed, the rotor speed should be proportional to the wind speed. In practice both constant *l* (variable speed) and constant speed operation is applied.

B. ELECTRICAL SYSTEM

Currently used Generator Systems

As stated before two types of wind turbines can be distinguished namely variable speed and constant speed turbines. For constant speed turbines one applies induction generators that are directly connected to the grid. For variable speed turbines a variety of conversions systems is available. The three most commonly used generator systems applied in wind turbines are depicted in figure 1 and discussed below.

a) Constant speed wind turbine with squirrel cage induction generator (CT)

Between the rotor and the generator, there is a gearbox so that a standard (mostly 1500 rpm) squirrel cage induction generator can be used. The generator is directly connected to the 50 Hz or 60 Hz utility grid.

b) Variable speed wind turbine with doubly-fed (wound rotor) induction generator (VTDI)

Between the rotor and the generator, there is a gearbox so that a standard (mostly 1500 rpm) doubly-fed induction generator can be used. The stator is directly connected to the utility grid. The rotor is connected to a converter. A speed range from roughly 60% to 110 % of the rated speed is sufficient for a good energy yield, that is achieved by using the variable speed capability to keep the tip speed ratio l at the value resulting in optimal energy capture.

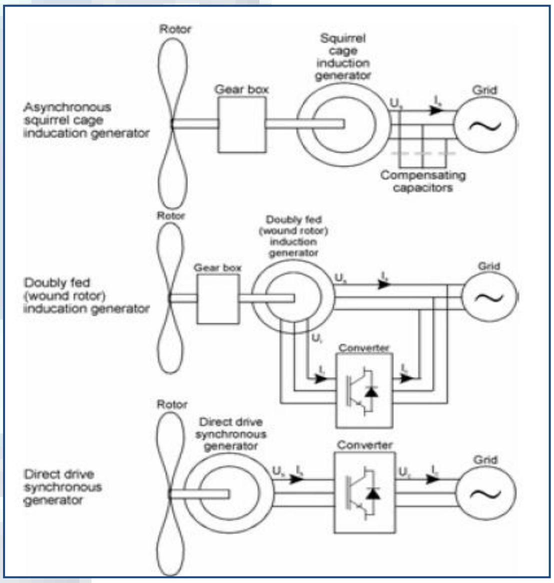


Fig.1 The three commonly used generator systems.

c) Variable speed wind turbines with direct-drive synchronous generator (VTDD)

In this system, no gearbox is necessary, because the generator rotates at very low speed, typically 10 to 25 rpm for turbines in the MW range. Standard generators can therefore not be used and generators have to be developed specifically for this application.

Grid faults

The three concepts behave differently in case of a grid fault causing a voltage dip.

In case of a fault, constant speed wind turbines can deliver the large fault currents, necessary for activating the protection system. However, when the voltage comes back, they consume a lot of reactive power and thus impede the voltage restoration after the dip. In addition both the fault and the reconnection results in large torque excursions that may damage the gear box.

III. DOUBLE FED INDUCTION GENERATOR

A. Introduction:

As the penetration of large scale wind turbines into electric power grids continues to increase, electric system operators are placing greater demands on wind turbine power plants. One of the most challenging new interconnection demands for the doubly fed induction generator (DFIG) architecture is its ability to ride through a short-term low or zero voltage event at the point of common coupling (PCC), resulting from a fault on the grid. During extreme voltage sags high per unit currents and shaft torque pulsations occur unless mitigating measures are taken.

Low voltage ride through requirements were first proposed by German electric transmission operators a stipulates that the wind turbine must remain connected to the grid and provide fault clearing current in the event that the voltage at the high side of the step up transformer to the transmission system drops to zero volts for a maximum of nine cycles, as the result of a three phase fault .Similar low/zero voltage ride through requirements have evolved in most European countries, each with varying specifications on minimum voltage level and requiring provisions of real or reactive power during fault events While many grid codes also stipulate ride through of single and two-phase faults, only balanced faults are considered in this paper. In a conventional DFIG wind turbine the machine stator windings are connected to the grid PCC via collection and/or transmission transformers and excited at the grid frequency.

The rotor windings of the DFIG are connected to an ac–converter commonly referred to as the machine side converter (MSC). The ac side of a second dc–ac converter, commonly referred to as the grid side converter (GSC), is connected in parallel with the machine stator windings and PCC.Severe voltage sags and the resulting stator flux response place significant electrical stress on the MSC and mechanical stress on the gearbox. In the stationary frame the stator flux is equal to the integral of the stator voltage minus stator resistive drop. An abrupt stator voltage change produces a constant dc component of stator flux in proportion to the voltage drop.

B. Double fed induction generator:

DFIG is an abbreviation for Double Fed Induction Generator, a generating principle widely used in wind turbines. It is based on an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with brushes for access to the rotor windings. It is possible to avoid the multiphase slip ring assembly (see brushless doubly-fed electric machines), but there are problems with efficiency, cost and size. A better alternative is a brushless wound-rotor doubly-fed electric machine.

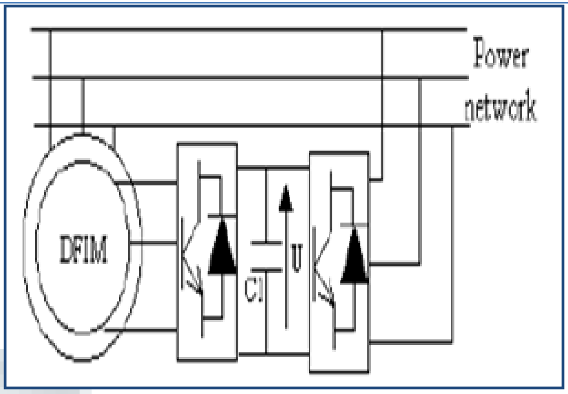


Fig:2 Double Fed Induction Generator.

C. Principle of a Double Fed Induction Generator connected to a wind turbine:

The principle of the DFIG is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converter that controls both the rotor and the grid currents. Thus rotor frequency can freely differ from the grid frequency (50 or 60 Hz). By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed. The control principle used is either the two-axis current vector control or direct torque control (DTC). DTC has turned out to have better stability than current vector control especially when high reactive currents are required from the generator.

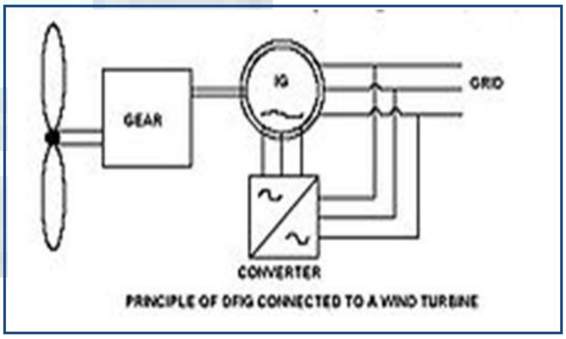


Fig: 3 Principal of DFIG

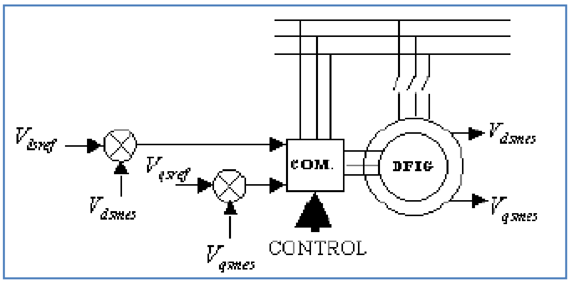
The doubly-fed generator rotors are typically wound with 2 to 3 times the number of turns of the stator. This means that the rotor voltages will be higher and currents respectively lower. Thus in the typical ± 30 % operational speed range around the synchronous speed, the rated current of the converter is accordingly lower which leads to a lower cost of the converter. The drawback is that controlled operation outside the operational speed range is impossible because of the higher than rated rotor voltage. Further, the voltage transients due to the grid disturbances (three- and two-phase voltage dips, especially) will also be magnified. In order to prevent high rotor voltages - and high currents resulting from these voltages - from destroying the IGBTs and diodes of the converter, a protection circuit (called crowbar) is used.

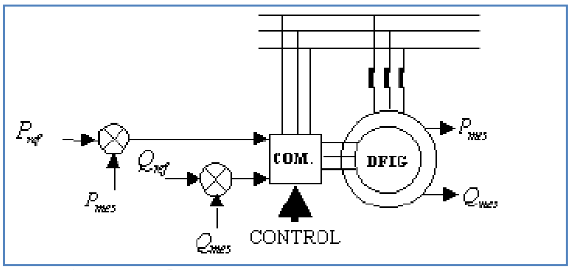
The crowbar will short-circuit the rotor windings through a small resistance when excessive currents or voltages are detected. In order to be able to continue the operation as quickly as possible an active crowbar has to be used. The active crowbar can remove the rotor short in a controlled way and thus the rotor side converter can be started only after 20-60 ms from the start of the grid disturbance. Thus it is possible to generate reactive current to the grid during the rest of the voltage dip and in this way help the grid to recover from the fault.

A doubly fed induction machine is a wound-rotor doubly-fed electric machine and has several advantages over a conventional induction machine in wind power applications. First, as the rotor circuit is controlled by a power electronics converter, the induction generator is able to both import and export reactive power. This has important consequences for power system stability and allows the machine to support the grid during severe voltage disturbances (low voltage ride through, LVRT). Second, the control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the wind turbine speed varies. A variable speed wind turbine utilizes the available wind resource more efficiently than a fixed speed wind turbine, especially during light wind conditions. Third, the cost of the converter is low when compared with other variable speed solutions because only a fraction of the mechanical power, typically 25-30 %, is fed to the grid through the converter, the rest being fed to grid directly from the stator. The efficiency of the DFIG is very good for the same reason.

D. DFIG CONTROL

When the DFIG is connected to an network, connection must be done in three steps which are presented below The first step is the regulation of the stator voltages with the network voltages as reference The second step is the stator connection to this network. As the voltages of the two devices are synchronized, this connection can be done without problem. Once this connection is achieved, the third step, which constitutes the topic of this paper, is the power regulation between the stator and the network.





E. Electronic control:

The electronic controller, a frequency converter, conditions bi-directional (i.e., four quadrant), speed synchronized, and multiphase electrical power to at least one of the winding sets (generally, the rotor winding set). Using four quadrant control, which must be continuously stable throughout the speed range, a wound-rotor doubly-fed electric machine with two poles (i.e., one pole-pair) has a constant torque speed range of 7200 rpm when operating at 60 Hz.

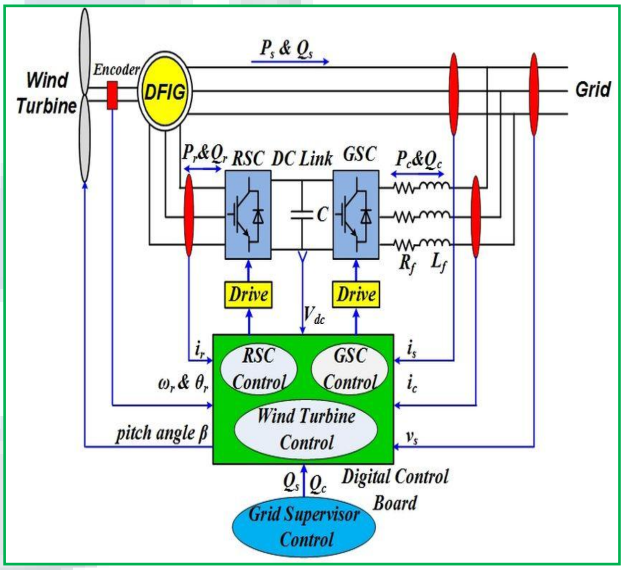


fig:5 Control of DFIG using RSC

However, in high power applications two or three pole-pair machines with respectively lower maximum speeds are common. The electronic controller is smaller, less expensive, more efficient, and more compact than electronic controllers of singly-fed electric machine because in the simplest configuration, only the power of the rotating (or moving) active winding set is controlled, which is less than half the total power output of the electric machine.

IV. PROPOSED SYSTEM

In cases of non-severe faults, the fault current provided by the DFIG consists of the stator fault current and the grid side fault current of the grid side converter (GSC). However, since the capacity of GSC is only 25–30% of the rated capacity of wind turbine, the grid side fault current provided by the GSC is so small that it has limited influence on the fault current provided by the DFIG.

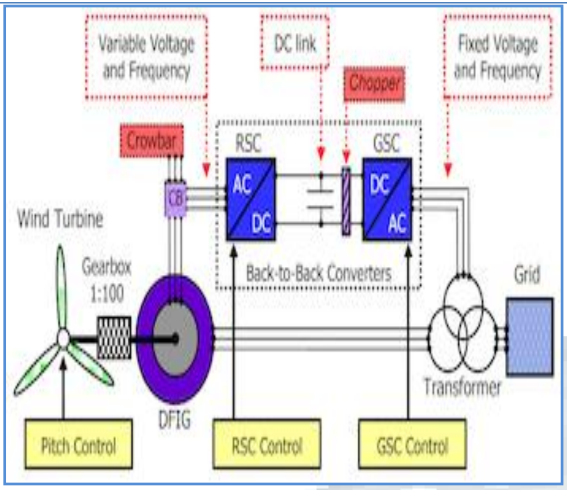


fig: 6 Schematic of DFIG to GRID

Hence, in this paper, only the dynamic response characteristics and stator fault current are taken into consideration. The synchronous *dq* reference frame is chosen to model the DFIG based on the fifth-order two-axis representation, and the model of DFIG is commonly known as “Park model”.

V. SIMULATION RESULTS

The control scheme is implemented using MATLAB software. Simulation parameters are involved to get resultant Waveforms for non severe conditions with different cases implemented for various conditions based on PI controller DFIG fault current characteristics are reduced on rotor side converter on wind energy systems, for dynamic system response.

CASE 1: The dynamic response of the RSC is analyzed on condition that the external power control loop is shut down and the reference signals of the inner rotor current control loop are kept constant.

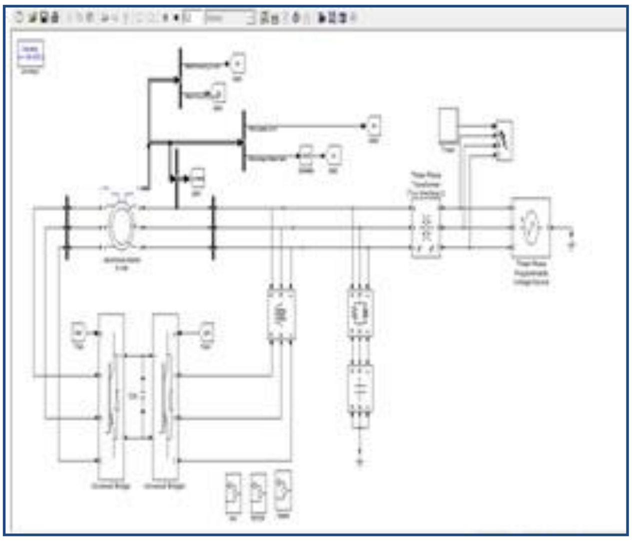


Fig: 7 SIMULATION MAIN CIRCUIT for Case 1

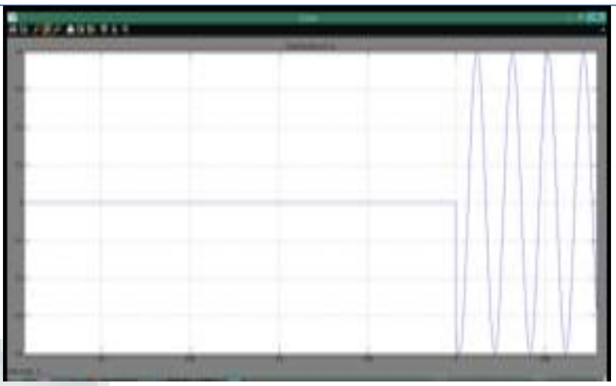


Fig: 7.1 Stator flux linkage (d-axis)

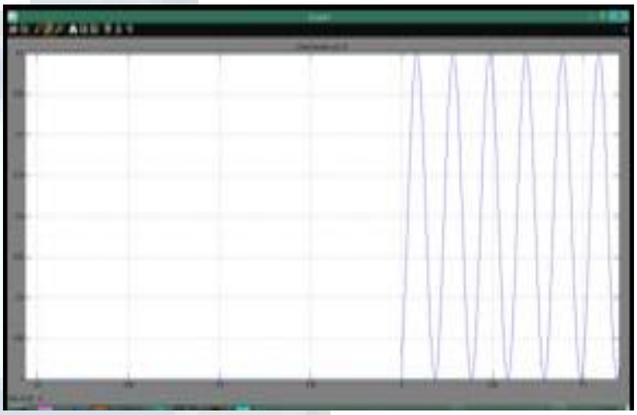


Fig: 7.2 Stator flux linkage in (q-axis)

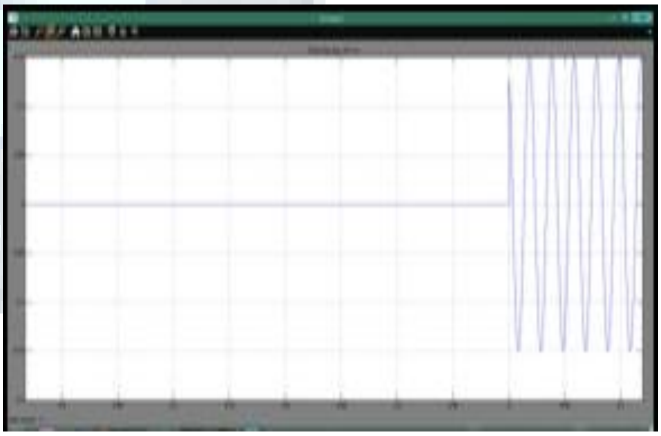


Fig: 7.3 Rotor flux linkage (d-axis)

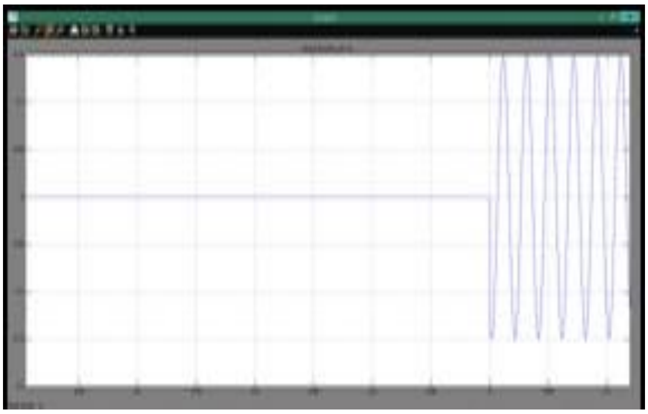


Fig: 7.4 Rotor flux linkage (q-axis)

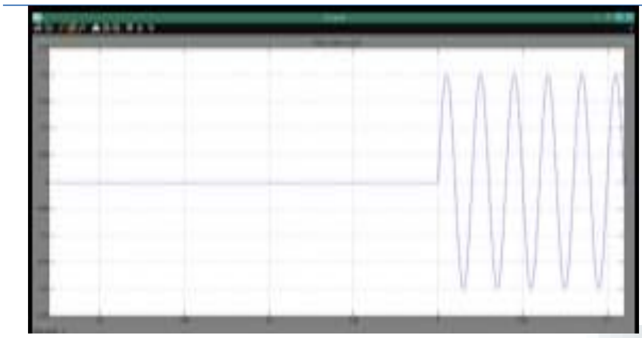


Fig: 7.5 The stator current for a voltage dip down to 60% under condition of the typical first-order system. (d-axis)

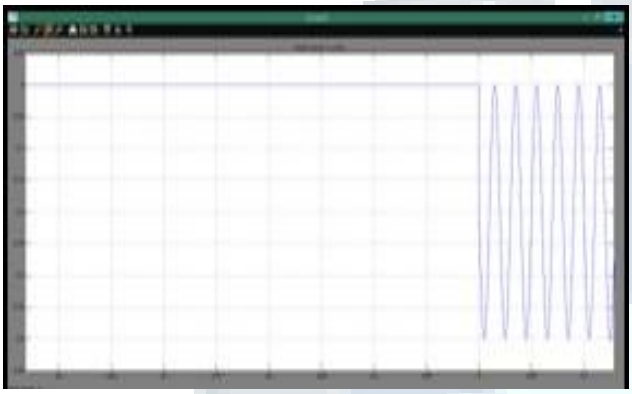


Fig: 7.6 The stator current for a voltage dip down to 60% under condition of the typical first-order system.(q-axis)

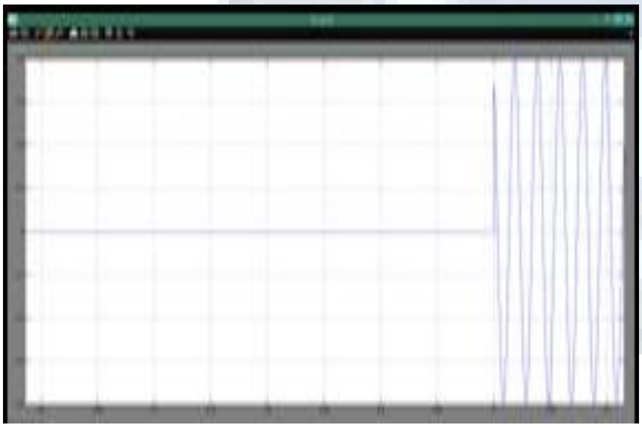


Fig: 7.7 *ed* for a voltage dip down to 60% (d-axis)

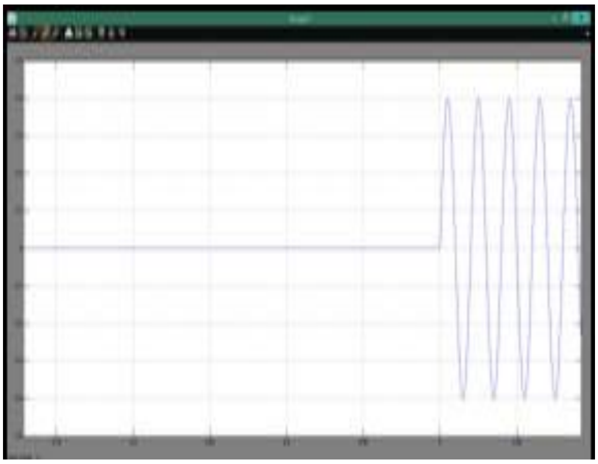


Fig: 7.8 *eq* for a voltage dip down to 60%. (q-axis)

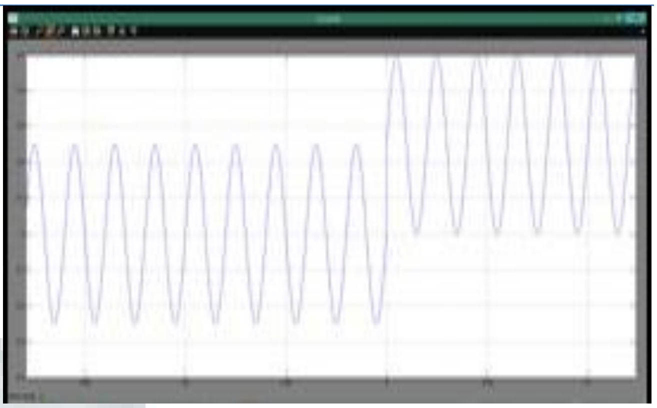


Fig: 7.9 Stator current for a voltage dip down to 60% under condition of the typical first-order system.

Fig: 7.10 The amplitude of the fundamental frequency component (*AMPisa*1) first order.

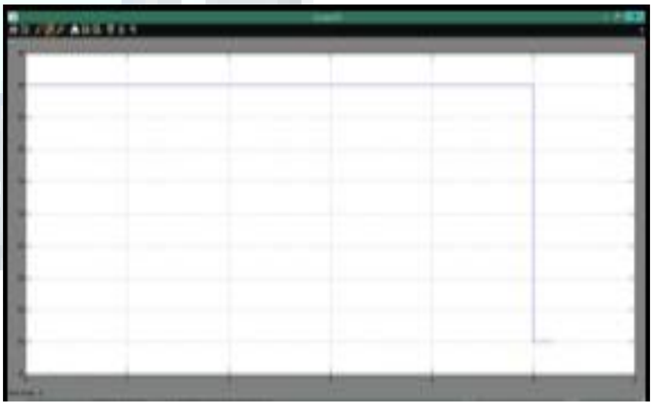


Fig: 7.11 Phase angle of the fundamental frequency component (*PAisa*1) first order

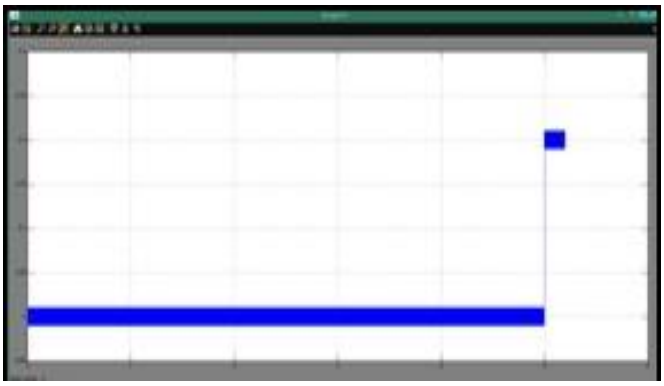


Fig:7.12 Damped dc component (*i*sadc) first order.

Case 2: Second order

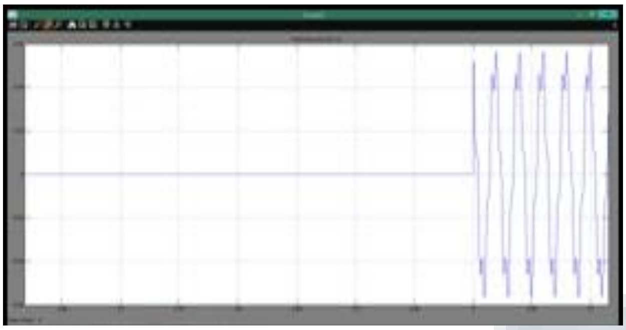


Fig:7.13 *d*-axis fault components of the rotor current for a voltage dip down to 60% under condition of the typical second-order system.

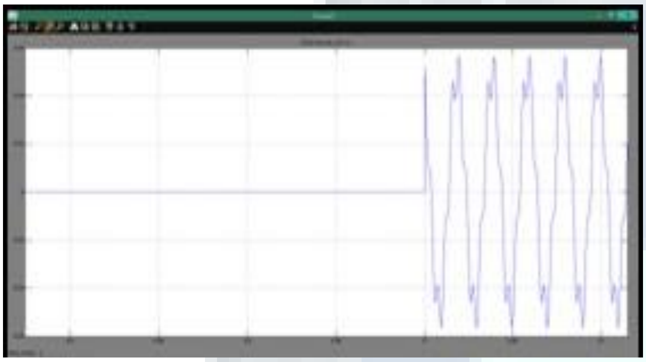


Fig: 7.14 *q*-axis fault components of the rotor current for a voltage dip down to 60% under condition of the typical second-order system.

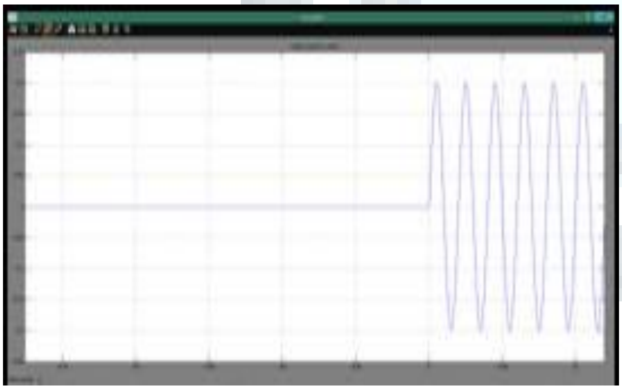


Fig: 7.15 *d*-axis fault components of the stator current for a voltage dip down to 60% under condition of the typical second-order system

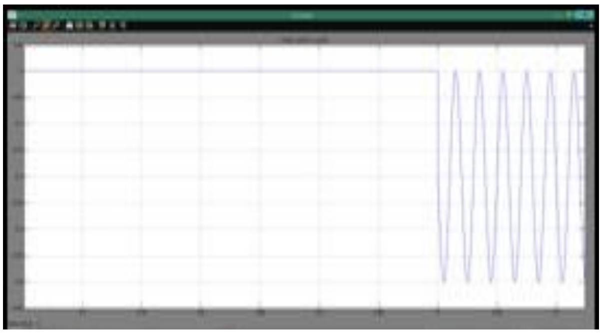


Fig: 7.16 *q*-axis fault components of the stator current for a voltage dip down to 60% under condition of the typical second-order system.

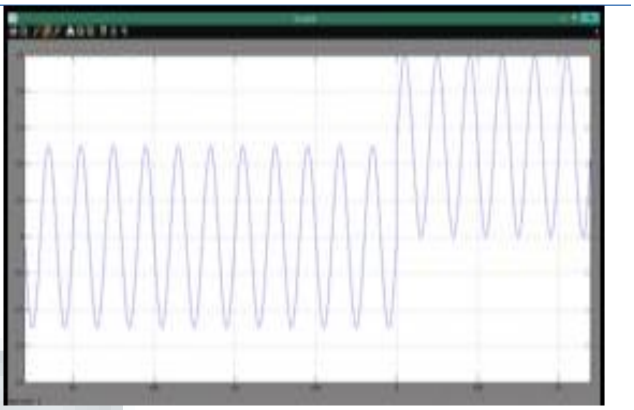


Fig: 7.17 The simulation result of the stator fault current (*isa*) second order

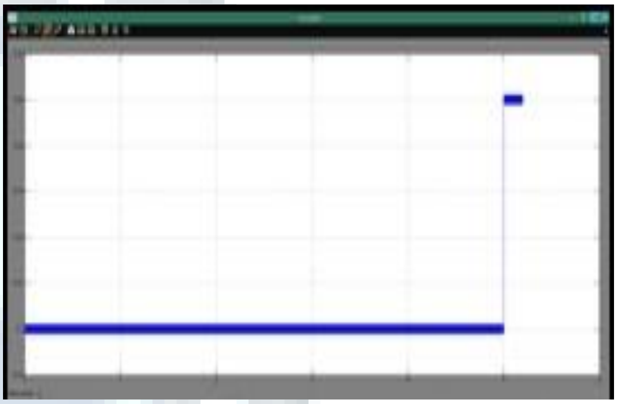


Fig: 7.18 The amplitude of the fundamental frequency component (*AMPisa*1) second order.

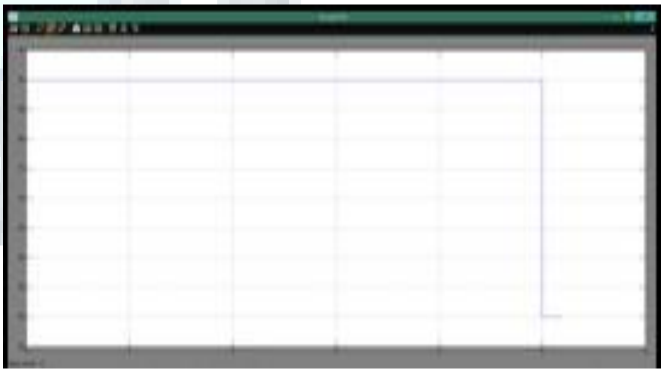


Fig: 7.19 Phase angle of the fundamental frequency component (*PAisa*1) second order

Fig: 7.20 The damped dc component (*isadc)* second order.

The following simulation examples, the output active power of the DFIG is 0.2 p.u. and the grid voltage is 1.0 p.u. before the fault occurs. Additionally, the fault occurs at time t = 5.0s and results in a symmetrical grid voltage dip down to 0.6 p.u. It can be observed that there are damped fundamental frequency components in the d-axis and q-axis components of the stator flux linkage. Meanwhile, the damped fundamental frequency components also exist in ed and eq . There is no dc component in ψsd , but there is a dc component whose amplitude is approximately proportional to the depth of grid voltage dip in though there is no abrupt change in ψsd and ψsq , the grid voltage drops suddenly. Hence, there is an abrupt change in ed , but no abrupt change in eq .

$$\begin{cases} e_d = -\dfrac{\omega_r L_m p\Delta\psi_{sd}}{\omega_s L_s} = -\dfrac{\omega_r L_m\left(\Delta U_s + \omega_s \Delta\psi_{sq}\right)}{\omega_s L_s} \\ e_q = -\dfrac{\omega_r L_m p\Delta\psi_{sq}}{\omega_s L_s} = \dfrac{\omega_r L_m \Delta\psi_{sd}}{L_s} \end{cases}$$

According to different control strategies, different reference signals of the inner rotor current control loop can be obtained. Hence, it needs to discuss the applicability of the proposed analysis method on condition that different control strategies for LVRT of the DFIG are adopted. For the following analysis, the condition under which the inner rotor current controller of the RSC is designed to be a typical first-order system, the fault components of the rotor current reference signals are both zero since the reference signals keep constant before and after the fault occurrence. However, for other control strategies, the fault components of the reference signals may not be zero and can be denoted by $\Delta^{*}ird$ and $\Delta^{*}jrq$, respectively. Under this condition, taking the controller of the d-axis component for example, the control diagram represented in the form of fault component during the fault transient period can be depicted.

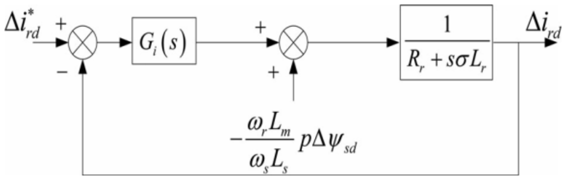


Fig: 8 Control diagram of the d-axis component during fault transient period.

Based on it, the three-phase stator fault currents can be deduced. Likewise, the fault current characteristics of the DFIG with other control strategies for LVRT can also be studied on condition that the inner rotor current controller of the RSC is designed to be a typical second-order system From the aforementioned analysis, it can be concluded that the fault current analysis method proposed in this paper is also applicable for the analysis of the fault current characteristics of the DFIG on condition that other control strategies for LVRT are adopted. Besides, in cases of non severe faults, with the proper control of the GSC or other reasonable measures (for example, installing a converter with UPS in parallel with the dc-link capacitor), the fluctuation of the dc-link voltage can be limited. Under this condition, the influence of the dc-link voltage on the fault current characteristics of the DFIG is so small that it can be neglected. Hence, the influence of the dc-link voltage is not taken into account in this paper.

VI. CONCLUSION

The fault current characteristics of the DFIG under non severe fault conditions are proposed. The dynamic responses of the RSC are analyzed first on condition that the external power control loop is shut down and the reference signals of the inner rotor current control loop are kept constant before and after the fault occurrence. Based on it, the stator fault current characteristics of the DFIG under non severe fault conditions are evaluated. The fault components of the rotor current can be proportional to the differentials of the corresponding fault components of the stator flux linkage when inner rotor can be first order typically, the rotor currents can be considered approximately constant before and after the fault occurrence. With dynamic response of rotor side converter then there is no damping frequency but DC damped and steady state frequency are in the stator fault current. The amplitude dc damped component proportional to the depth of grid voltage dip, and the damping time constant on the stator resistance and inductance, but not affected by the rotor resistance and inductance. The d-axis fault component of the stator fundamental frequency current is zero and the amplitude of the q-axis fault component is approximately proportional to the depth of grid voltage dip. Fault current analysis method proposed in this paper is also applicable for the analysis of the fault current characteristics of the DFIG on condition that other control strategies for LVRT.

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