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An Enhanced Rotor Side Converter Control of DFIG-Based Wind Turbines For Improving LVRT Capability During Balanced Grid Faults

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Abstract

Among variable speed wind turbines the use of doubly-fed induction generator based wind turbines are very common. However, due to their stator direct connection to the grid, they are very sensitive to grid faults. This paper analyzes the low voltage ride-through (LVRT) capability enhancement under the three-phase balanced grid fault. Therefore the variations of 5 parameters during balanced grid fault are Analyzed. These parameters are stator voltage, rotor current, stator current, rotor speed, and the DC link voltage. To improve the LVRT capability an enhanced demagnetization control method is proposed. This method shortens the natural stator current time constant and approximately immunes the system against parameter variations as shown in simulation results. To show the effectiveness of the proposed method, the results are compared with one of the best previous demagnetization control methods.

1. Introduction

Today, wind energy plays an important role in modern renewable energy sources. The advantages of doubly-fed induction generator-based wind turbines (DFIG WTs), such as variable-speed -constant-frequency based operation and decoupled control of active and reactive power has made them one of the most employed WT types at the range of 1 MW and more. Furthermore, the rotor power is managed only by its converter which can be rated at about one-third of the whole generator rating [1-3], which brings the advantages of being light, low cost with small losses compared to WTs with a full-scale converter. However, the Direct DFIG Stator connection to the grid is its main disadvantage, which makes it very sensitive to any voltage disturbances such as low voltage and fault. At the beginning of wind energy employment, the generator unit was disconnected from the grid as soon as occurring a fault. By increasing the penetration of wind turbine systems, during occurring a fault it is required that wind farms to remain connected to the grid for certain time duration and under special criteria (to help the power system stability by supplying reactive power), which is called Low Voltage Ride Through (LVRT) requirement [4].

To prevent the disconnection of wind farms during network disturbances, The grid code requirements for LVRT are imposed by many countries. To define the requirements on the LVRT capability of grid-connected wind farms, China Electric Power Research Institute (CEPRI) developed revising technical rule for connecting wind farms to the power system (GB/T 19963-2005) via inserting specific necessities on the LVRT curve. This rule has been applied since 30 June 2012 [5]. Fig. 1 shows the LVRT requirements for wind farms. According to this new standard, WTs should be able to preserve operating for 625 mS when the voltage of PCC falls to 20% of the nominal voltage. Also in the new standard, WTs should stay connected to the power grid and keep on operating when 90% of the nominal PCC voltage is retrieved in 2 seconds [5].

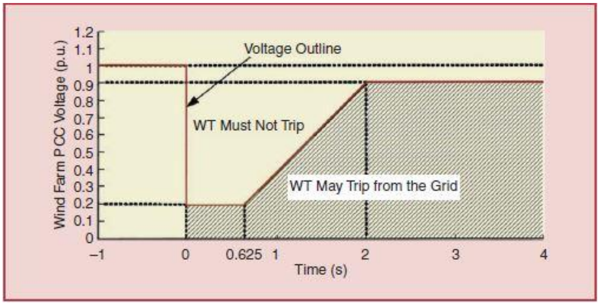

Fig. 1. LVRT requirements for wind farms [5]

Among different proposed methods for improving LVRT capability, the employment of a crowbar [6] is very common. On detecting of the rotor overcurrent, the crowbar short circuits the rotor terminal and the trigging signal of the Rotor Side Converter (RSC) is blocked simultaneously, to be protected. But, it changes the DFIG right into an induction generator which absorbs reactive power, also deteriorating the grid fault. As a result, dynamic VAR compensators are occasionally installed at the DFIG terminals to provide reactive power for the duration of grid faults [7]. Instead of using the crowbar, other methods based on extra power electronic equipment are proposed, such as suggesting the schemes with an additional grid side converter (GSC) [8], [9], dynamic voltage restorer [10], [11] and energy storage system [12]. However, the high cost and control complexity discourages their utilization. The implementation of a stator side passive impedance network [13], rotor side dynamic resistor [14] and rotor side reactor [15] are also proposed. On this manner, the wind turbine can stay connected to the grid during occurring voltage dips. But, sizing of the impedance is made either experimentally or via simulation, and therefore it is quite difficult to optimize the whole system.

In some references, due to easy implementation, solutions based on advanced control methods are suggested. It's been confirmed that Feed-Forward Transient Current Control (FFTCC) can restrict transient rotor current during the low voltages and faults, Resulting in a minimum incidence of crowbar interruptions [16], [17]. But, the torque is constant to zero and the reactive power needs to be drawn from the grid. to counteract the natural and negative sequence components of the stator flux, demagnetization control is proposed in [18]. And it's been verified that the control should promote natural stator flux damping [19]. An aggregate of demagnetization control and active crowbar is proposed to make the crowbar activation time shorter [20]. But, the demagnetization control in the aforementioned researches is sensitive to system parameter variation since stator resistance information is wanted, in spite that the sensitivity can be decreased when demagnetization control is blended with virtual resistance [21]. When a fault occurs, natural stator flux is produced and in an unbalanced fault, extra negative sequence stator flux is added. The two aforementioned fluxes induce a very high electromotive force (EMF) in the rotor circuit leading to a large transient rotor current and finally the destruction of the converter and disconnection of the system.

This paper deals about balanced grid faults and its effects on RSC converter. Therefore, an improved demagnetising control method is proposed to compensate for the harmful effects of the high EMF and large currents in the rotor circuit. In this method, during the fault, the variations of the five parameters of stator terminal voltage (V_t), stator current (I_s), rotor current (I_r), rotor speed (ω_r) and dc-link voltage (V_{dc}), are analysed to see the effectiveness of the proposed method for improving the LVRT capability. Finally, the proposed method is compared to the proposed method in [22] and the effect of changing machine parameters on the LVRT capability in the proposed method is analysed at the end.

This paper is organized as follows. Section 2 analyzes system behaviour during a balanced grid fault. It shows that the natural EMF produced during the fault is influenced by fault duration and stator flux time constant. Section 3 introduces the proposed demagnetization control method, and the influence on the LVRT performance is discussed in Section 4 through simulation results..It is proved that system LVRT capability can be improved by reducing the time constant of the natural stator current during a balanced grid fault. The conclusion is presented in section 5.

2. The Behaviour of the DFIG Under Symmetrical Grid Faults

Concerning the stator reference frame, the stator voltage space vector v_s is expressed as

$$v_s = r_s i_s + \frac{d}{dt}\psi_s \qquad (1)$$

Where v_s, r_s, i_s and ψ_s represent the stator voltage, resistance, current and flux space vector, respectively and $\frac{d}{dt}$ is the derivative operator. In the case of symmetrical three-phase grid faults, the stator voltage vector can be expressed as

$$v_s = V_p e^{j\omega_s t} \qquad (2)$$

where V_p is the amplitude of positive sequence components and ω_s is the synchronous speed. If r_s is neglected, according to (1) and (2), the steady-state component of the stator flux during grid faults can be expressed as

$$\psi_{ss} = \frac{V_p e^{j\omega_s t}}{j\omega_s} \quad (3)$$

where ψ_{ss} is the steady-state component of the stator flux. Due to the continuous variation of the flux from its initial state to its steady-state, the total stator flux includes the transient component and steady-state component during grid faults is expressed as

$$\psi_s = \psi_{ss} + \psi_{st} = \frac{V_p e^{j\omega_s t}}{j\omega_s} + \Psi_{st} e^{-\frac{t}{\tau}} \quad (4)$$

where ψ_{st} and Ψ_{st} are the transient component of the stator flux and its initial value, respectively, and τ is the time constant.

Moreover,

$$\psi_s^r = \psi_s e^{-j\omega_r t} \quad (5)$$

where superscript “r” denotes that the equations are expressed in the rotor reference frame and ω_r is the angular velocity of the rotor.

The rotor circuit EMF, induced by a stator flux, can be expressed as

$$E = \frac{L_m}{L_s} \cdot \frac{d}{dt} \psi_s^r \quad (6)$$

where L_s and L_m are the stator self-inductance and the mutual inductance between the stator and rotor, respectively.

Based on (4), (5) and (6), the EMF E during the grid fault can be derived as

$$E = \frac{L_m}{L_s} sV_p e^{js\omega_s t} + \frac{L_m}{L_s} (\frac{1}{\tau} + j\omega_r) \Psi_{st} e^{-\frac{t}{\tau}} e^{j\omega_r t} \quad (7)$$

where s is the slip rate. By neglecting $\frac{1}{\tau}$ [18], (7) is simplified to (8).

$$E = \frac{L_m}{L_s} sV_p e^{js\omega_s t} + \frac{L_m}{L_s} (1 - s) j\omega_s \Psi_{st} e^{-\frac{t}{\tau}} e^{j\omega_r t} \quad (8)$$

According to equation (8), E consists of two parts. the first part and the second part, are induced by positive and dc components of the stator flux, respectively. Because of small s, the second term induced by the DC component of the stator flux during the faults can cause overvoltages/overcurrents at the rotor side. under symmetric fault, the second term of the stator flux consists of exponentially decayed dc component is added compared to the pre-fault state. The decayed dc component is static concerning to stator windings and rotates at rotor speed concerning to rotor windings; according to the second term in (8), the EMF induced by the dc flux component is proportional to (1−s): this EMF is much higher than the EMF corresponding to the normal operation which is proportional to s; so the total EMF is much higher than that in normal operation and it may exceed the maximum voltage of the rotor converter. The induced large voltages in the rotor windings result in large currents into the rotor circuit, which causes severe damage to RSC and the large increase of the dc-link voltage. Thus, the proposed method in this paper is intended to limit rotor overvoltage and consequently rotor current or decrease the instability rate during the fault. In the next part, the proposed method is introduced.

3. Proposed LVRT Capability Enhancement Method

Though the vector control is commonly used to control the DFIG [23-25], the control method in this paper is focused only on the RSC and nor the GSC. In the following subsection, the proposed demagnetizing method is described. The advantage of this method compared to previous demagnetizing control methods is its lower dependence on machine parameter changes. To show this independence, the comperative simulation results are presented in section 4.

3.1. Control Method Based On Enhanced Demagnetizing Current

The traditional method according to [18-20], was based on mitigating the influence of natural stator flux through decreasing the amplitude of natural stator flux. The main drawback of this method is its sensitivity to the system parameter variation. To lessen this sensitivity, in this paper an improved demagnetization control method is suggested which does not need the system parameter information. In this method, instead of decreasing the natural stator flux amplitude, the time constant of natural stator current is decreased to cause the faster decay of the natural stator flux. Note that, the stator current is proportional to the stator flux, and any changes in the current cause the same effect on the flux. According to equations (9-11), the relation between the natural stator current and the natural stator flux is obtained.

Based on the DFIG model the stator flux is described as

$$\psi_s = L_s i_s + L_m i_r \quad (9)$$

Where, i_r represents the rotor current. The layout of the control approach is shown in Fig. 2. Demagnetizing rotor current, which opposes the natural stator current, is injected into the rotor circuit during the occurence of a balanced three-phase grid fault.

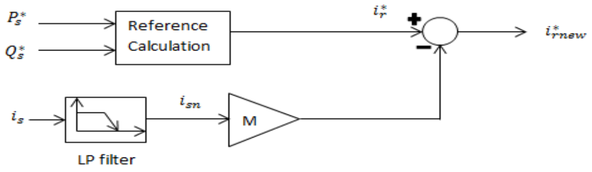

Fig.2. The block diagram of the proposed demagnetization control.

The reference is given as

$$i_{rn} = -Mi_{sn} \tag{10}$$

where M is a positive demagnetization coefficient and i_{rn}, i_{sn}, are natural rotor current and natural stator current respectively. By combining (9) and (10), equation (11) is written as

$$i_{sn} = \frac{\psi_{sn}}{L_s - ML_m} \tag{11}$$

the expression of natural stator flux is given as

$$\psi_s = \psi_{n0} e^{-\frac{t}{\tau}} \tag{12}$$

where ψ_{n0} is the initial value of natural stator flux and $\tau_s = \frac{L_s - ML_m}{r_s}$ is the stator flux time constant with improved demagnetization control. It is clear that the damping of natural stator flux is accelerated with positive M. To have a small time constant, the coefficient M is tuned as large as possible. Therefore a demagnetizing method is obtained without depending on system parameters. The decreasing time constant can have the same effect compared to the traditional demagnetizing method, except that its dependence on system parameters is decreased. The effectiveness of this method is shown in the simulation results. Also in the simulation results section, the proposed method in this paper is compared with one of the best demagnetizing control methods in [22]. According to [22] forcing demagnetization control (FDC) modelling (shown in Fig. 3) is enhanced for LVRT capability of DFIG-based wind farm.

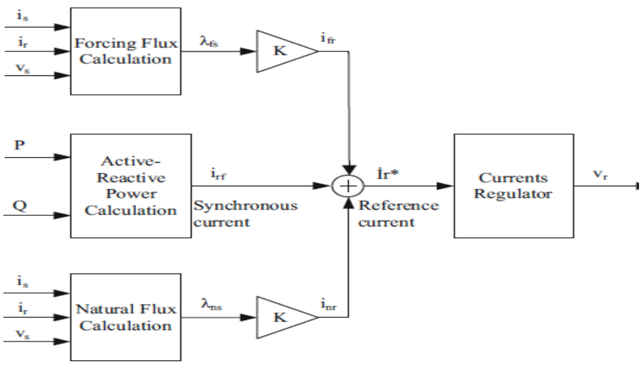

Fig.3. The block diagram of the proposed demagnetization control in [22].

3.2. Fault Identification

On the way to hastily switch the normal operation controller to the LVRT operation controller, quickly identifying of voltage dip may be very critical [26]. In [27] the fault occurrence time is identified through a suggested fuzzy logic controller. Another way for the identification of voltage dip in symmetric dips may be realized with the aid of the usage of transforming three-phase voltage variables in a natural reference frame to a synchronous d–q reference frame. The transformed d–q variables are proportional to the magnitude of the stator voltage; therefore, as compared to the values of d–q variables before voltage dip with ones after voltage dip, voltage dip may be recognized.

4. Simulation Results

The basic configuration of a DFIG-based wind turbine under the symmetric fault which is used in this paper is presented in Fig. 4. The understudy system in Fig. 4, is a wind farm which includes six 1.5 MW wind turbines. The three-phase fault depth is about 85 percentage and happens at second 1 with a duration of 0.3 S. The X/R ratio of the 1 Km cable is 3.4. The wind farm works in the maximum power point tracking (MPPT) mode with the 12 m/s wind speed. The grid frequency is 60 Hz and the DC link capacitor is 10000 micro Farad. Other DFIG parameters are presented in Table (1).

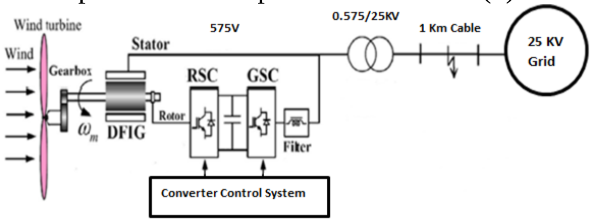

Fig.4. The general schematic of the DFIG-based wind turbine under the symmetric fault

In this part, the proposed demagnetizing method is simulated on the 9 MW wind farm and the results are compared to the proposed method in [22]. To see the effectiveness of the proposed method for improving the LVRT capability, the variations of the five parameters of stator terminal voltage (V_t), stator current (I_s), rotor current (I_r), rotor speed (ω_r) and dc-link voltage (V_{dc}), are analysed during the three-phase fault. The results are presented in Figs. (5-9).

Table 1. The DFIG parameters

Parameter	Values
Rated power	1.5 MW
Rated stator voltage	575 V
Rated frequency	60 Hz
Stator resistance	0.023 pu
Rotor resistance	0.016 pu
Stator leakage inductance	0.18 pu
Rotor leakage inductance	0.16 pu
Magnetizing inductance	2.9 pu
Pole pairs	3
Turns ratio	3.4

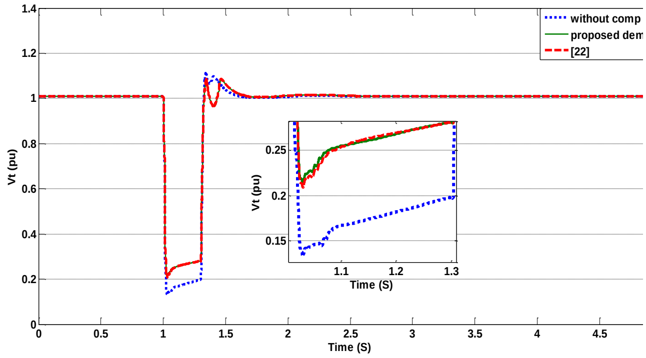

Fig.5. Stator voltage comparison

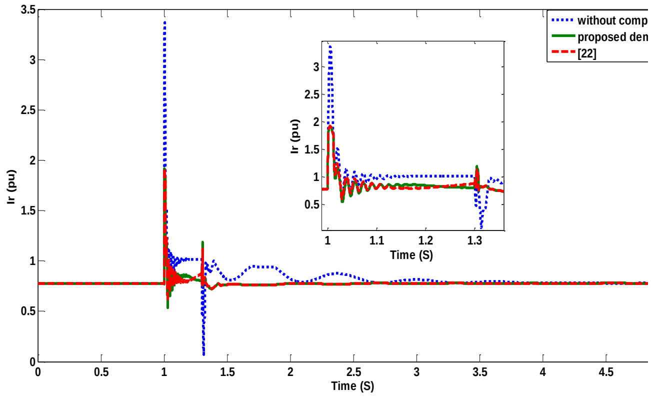

Fig.6. Rotor current comparison

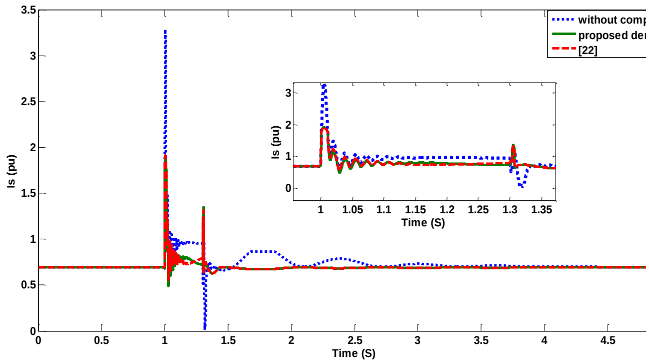

Fig.7. Stator current comparison

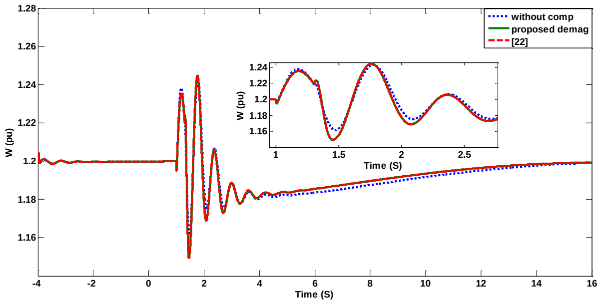

Fig.8. Rotor speed comparison

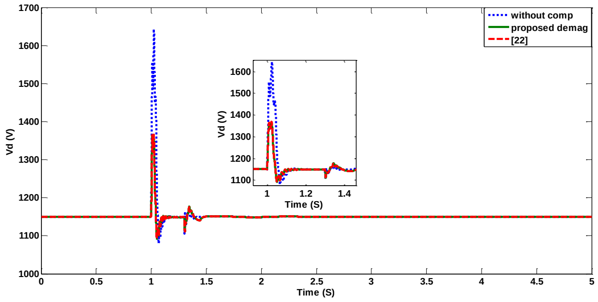

Fig.9. DC link voltage comparison

As seen in Fig. 5, according to LVRT criteria in Fig. 1, the LVRT capability is enhanced and compared to the proposed method in [22], the results are very similar. In Figs 6 and 7, the rotor and stator current is limited below 2.5 per unit, which is acceptable compared to the case which is without any demagnetizing control. In Fig. 8, although the rotor speed oscillations are more than the case without any demagnetizing control its oscillation range is acceptable. In Fig. 9, the peak of the DC-link voltage has decreased by about 20 percentage, which is below the danger zone. Despite acceptable results for improving LVRT capability, it is important to see if the proposed method works correctly in machine parameter changes or not. To check the dependence of the proposed demagnetizing control method on machine parameters, the effect of an increase in rotor resistance to 1.5 times greater (when the machine becomes warmer) and the decrease of magnetizing characteristics of machine to 0.5 times lower (due to machine ageing) is analysed in next part.

4.1. Rotor resistance increment

In this part, the effect of rotor resistance increase (to 1.5 times greater) on the performance of the proposed demagnetizing control method is analyzed and compared to the one proposed in [22]. The simulink results are presented in Fig. 10.

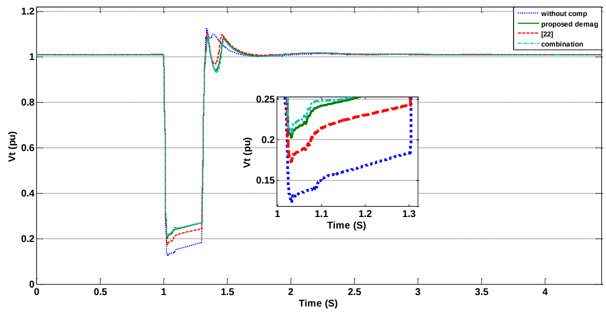

Fig. 10. Rotor resistance increase effect on stator voltage

As shown in Fig.10, the rotor resistance increase causes more voltage dip during fault duration. The voltage dip in the proposed method in [22] is more than 0.8 pu, which means that according to LVRT enhancement criteria in Fig. 1, a wind turbine must be disconnected from the grid. In contrast with the proposed method in [22], the voltage dip in the proposed method and the combination of the proposed method and the method proposed in [22], is less than 0.8 pu, which means that LVRT requirement is satisfied and improved. Therefore, it is proved that the dependency of this paper proposed method on rotor resistance increase is less than previous methods and still the LVRT capability is enhanced.

4.2. Magnetizing inductance decrement

In this part, the effect of magnetizing inductance decrease (to 0.5 times lower) due to machine ageing on performance of proposed demagnetizing control method is analyzed and compared to the one proposed in [22]. The simulink results are presented in Fig. 11.

As shown in Fig.11, the magnetizing inductance decrease causes more voltage dip during fault duration. The voltage dip in the proposed method in [22] is more than 0.8 pu, which means that according to LVRT enhancement criteria in Fig. 1, a wind turbine must be disconnected from the grid.

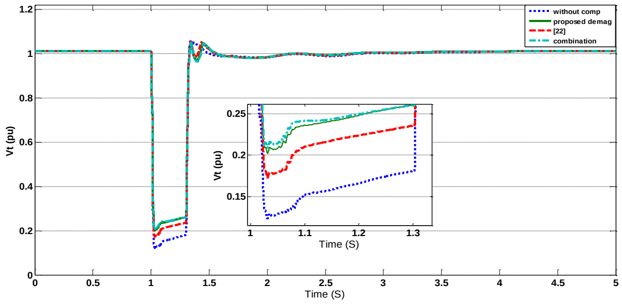

Fig. 11. Magnetizing inductance decrease effect on stator voltage

In contrast with the proposed method in [22], the voltage dip in the proposed method and the combination of the proposed method and the method proposed in [22], is less than 0.8 pu, which means that LVRT requirement is satisfied and improved. Therefore, it is proved that the dependency of this paper proposed method on magnetizing inductance decrease is less than previous methods and still the LVRT capability is enhanced.

4.3. Rotor resistance increment and magnetizing inductance decrement

According to Fig. 12, the effect of rotor resistance increase and simultaneously magnetizing inductance decrease on the performance of the proposed demagnetizing control method is analyzed and compared to the one proposed in [22].

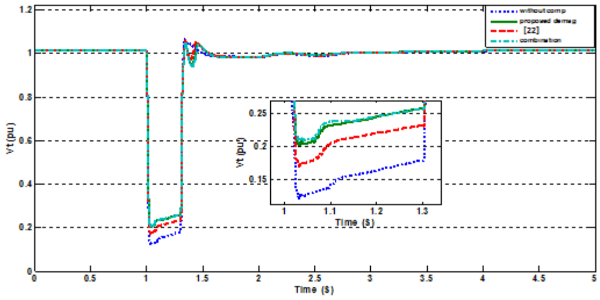

Fig. 12. Effect of increased rotor resistance and decreased magnetizing inductance on stator voltage

As shown in Fig.12, the two aforementioned machine parameter changes cause more voltage dip during fault duration compared to the last two cases. The voltage dip in the proposed method in [22] is more than 0.8 pu, which means that according to LVRT enhancement criteria in Fig. 1, a wind turbine must be disconnected from the grid.

In contrast with the proposed method in [22], the voltage dip in the proposed method and the combination of the proposed method and the method proposed in [22], is still less than 0.8 pu, which means that LVRT requirement is satisfied and improved. Therefore, it is proved that the dependency of this paper proposed method on simultaneously rotor resistance increase and magnetizing inductance decrease is less than previous methods and still the LVRT capability is enhanced.

5. Conclusion

In this paper, an enhanced LVRT control method on the rotor side Converter is proposed, which is based on demagnetizing natural stator current. The idea of this kind of demagnetizing control method is based on decreasing natural stator current time constant compared to decreasing natural stator flux magnitude. In this study, five important parameters which are stator voltage, rotor current, stator current, rotor speed, and DC link voltage were improved during a severe balanced three-phase fault and the results were analyzed. By using the proposed control method, the most important parameter which is the stator voltage was improved according to the LVRT criteria. The rotor and stator current and the dc-link voltage were improved too. Although the rotor speed was not improved through the proposed method, the oscillations are Limited. The previous methods were unable to enhance the LVRT capability in situations like rotor resistance increase or magnetizing inductance decrease. In contrast, the proposed method not only satisfies the LVRT requirement shown in Fig.1 but also has a good performance when the machine parameters change. Therefore the capability of the proposed method in this paper can enlarge the control range for deeper faults compared to the previous demagnetizing control methods.

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