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Ride-through of PMSG Wind Power System Under the Distorted and Unbalanced Grid Voltage Dips

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Abstract – This paper presents a ride-through skill of PMSG wind turbine system under the distorted and unbalanced grid voltage dips. When voltage dips occur in the grid, pitch control and generator speed control as well as a parallel resistor of DC-link help to keep the turbine's safety. Modern grid code requires a wind turbine to supply reactive currents to help voltage recovery after grid faults clearance. In order to supply reactive currents to the grid in case of the distortedly unbalanced grid voltage dips, a special PLL is needed to control the grid side converter and to regulate the grid voltages symmetrically. The proposed method is applied to 2MW multi-pole PMSG wind turbine system, and verified by simulation.

Keywords: Low voltage ride-through, PMSG wind turbine, Distorted grid voltage, Unbalanced grid voltage, PLL

1. Introduction

In many contries in the world, energy policies are focused on the increased utilization of wind energy due to the fact that wind power can provide a considerable input to electricity production. With an increasing amount of wind turbines installed, the behavior of wind turbines during grid faults becomes more important. Currently, most of the grid code specifications require that the turbines must be able to ride-through grid faults that bring voltages down to very low levels.

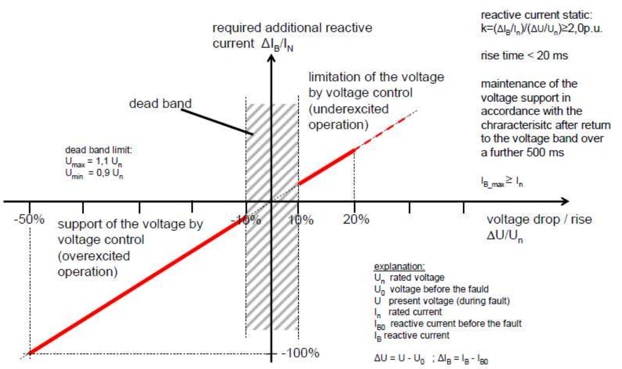

Fig. 1. Voltage support requirement from E.On Netz during grid faults.

Furthermore, some conturies such as Germany and Denmark ask that a wind turbine supports the grid voltage with additional reactive current during a voltage dip [1, 2]. The voltage control in this case acts as shown in Fig. 1. A wind turbine should provide a reactive current on the low voltage side of the transformer equal to at least 2% from the rated current for each percent of the voltage dip. If necessary, the wind turbine shall be able to provide full rated reactive currents.

A control scheme to improve LVRT capability of the variable speed wind turbine under the unbalanced and distroted grid voltages is presented in this paper. Many kinds of methods for LVRT under the distortedly unbalanced grid voltages have been presented. PLL using positive grid voltages to control the grid side converter under the unbalanced grid voltages [3], PLL using 120Hz Notch filter to filter the negative current components [4], and dual currents controller which controls each positive components and negative components of the currents [5] belong to this. Besides, in order to compensate distorted components low pass filter in the d-axis voltage as an input of PLL has been used. But this method could make the control response slower. Inverse compensation of 5^{th}, 7^{th} harmonic currents also has been used. However, This method needs additional harmonic currents to compensate which make the controller more complicated.

If the voltage includes harmonics, the controlled current would have harmonics. Therefore regulating the current and reducing the harmonics are necessary. A low pass filter can be used to reduce the harmonics. However, this mothod may cause the converter to reduce the dynamics during the grid fault. In this paper, a method to reduce the current harmonics by correcting current reference values is presented.

In this paper the LVRT method to improve the control response under the distortedly unbalanced grid voltages using currents correction is propesed. The proposed method is verified by simulation with two cases, below rated blade rotational speed and rated blade rotational speed.

This paper is organized as following contents. The simplified wind turbine characteristics are presented in

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Section 2. Some strategies to improve LVRT capability are reviewed in Section 3. Phase Locked Loop scheme to control the grid side converter under the distortedly unbalanced grid voltages is proposed in Section 4. Simulation results with the turbine specfications and the analysis are illustrated in Section 5. Some conclusions are given.

2. Wind Turbine Characteristics

The complete system of a wind turbine including the mechanical components, the electrical generator and the power electronic converters is a complicated electro-mechanical system. The energy extracted from the wind is commonly expressed as follows.

$$P = \frac{1}{2}\rho\pi r^2 v^3 C_p(\lambda,\beta) \quad (1)$$

where, P is the extracted wind power, ρ the air density, r the blade radius, v the wind speed, λ the tip speed ratio, β the blade pitch angle C_p the power coefficient as a function of λ and β.

The tip speed ratio λ is then defined by

$$\lambda = \frac{r\omega}{v} \quad (2)$$

Where, ω is the rotational speed of the turbine.

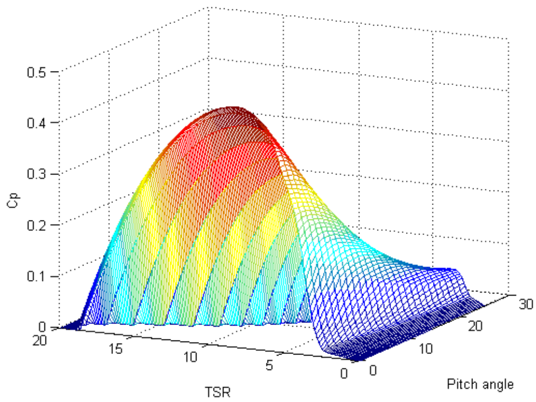


Fig. 2. Power coefficient curves versus TSR and Pitch-angle

The energy efficiency C_p changes according to the tip speed ratio and the blade pitch angle. Therefore, the energy extracted from the wind can be controlled by controlling TSR and the pitch angle. The relationship among the tip speed ratio, pitch angles and power efficient is as shown in Fig. 2. In order to produce the maximum power from the wind, the rotational blade speed has to track the optimal tip speed ratio. And the pitch angle is necessary to be set to the specific angle to produce the maximum power.

On the other hand, the pitch angle can be controlled to reduce the power in such case as over the rated wind speed or grid faults. Because a wind turbine is inherently a non-linear system which the operating point is decided by three variables, v, β, and ω, gain scheduling is necessary to control the pitch angle well [8].

3. Ride-through Strategies

When a fault occurs in the grid, a voltage dip occurs at the AC output terminals of the wind turbine. During the fault, the active power flows into the grid is reduced because of the reduced terminal voltage. As the generator side converter is decoupled to the grid, the wind turbine generator continues generating the active power. Therefore there occurs an energy imbalance in the back-to-back converters as shown in Fig. 3. This energy imbalance will cause the DC-link voltage of the back-to-back converter to increase uncontrollablly [9]. In order to protect and to control the converter stably, a parallel resistor to the DC-link can be added to dissipate the imbalanced energy.

This may cause an excessive heat occurrence of the parallel resistor because the energy dissipated can be significantly high in the case of a large scale of wind turbines.

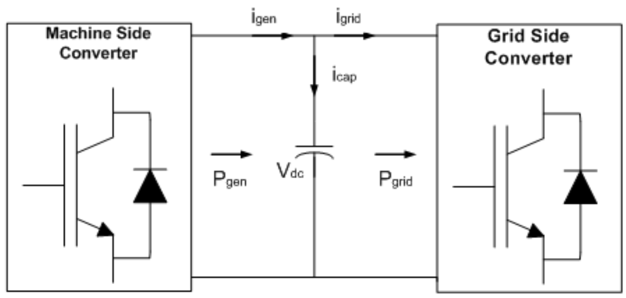


Fig. 3. DC link over voltage

Therefore, it is necessary to reduce the extracted power from the wind during a grid fault.

Two predictable methods [10] are as follows.

a) Pitch Control to reduce the power coefficient

b) Increase the rotational blade speed to change TSR [11].

From the Eq. (1), it is recognizable that the power coefficient C_p which is only possible to control is related to the pitch angle β and the tip speed ratio λ.

When a grid fault occurs, the pitch angle can be controlled keeping the change ratio of 8~10°. However, the control of pitch angle has difficulty as a solution for the low voltage occurrence of a short time period due to a very slower mechanical response than an electrical response. The rotational blade speed also can be adjusted to change the tip speed ratio from the optimal operation point.

Increasing the rotational blade speed takes an advantage of saved energy in the rotor inertia. The considerable point is to increase the speed properly because the excessive increase in the rotational speed causes the DC-link voltage down below the low voltage limit.

4. PLL and Current References Correction

The accurate phase angle information of utility voltage is essential when current or voltage reference is synchronized with the phase of the utility voltage during a grid fault to control the active and reactive power and for the harmonic current regulation. When the low voltage occurs over a short time period, fast dynamics of the converter responses are required. Conventionally, to reduce the current harmonics the second order low pass filter has been used for the input signal of PLL. This may cause the converter dynamics to be slower during a fault. For the distortedly unbalanced grid voltage dips PLL using positive sequence voltage components and current reference correction are presented in this section.

4.1 Pll for the unbalanced grid voltages

Several PLLs have been used for the control of currents under the unbalanced grid conditions. One of them is to use positive components of the grid voltages [3] and the other one is to use 120Hz notch filter to filter the negative components of the voltages [4]. Dual currents control method [5], which control positive components and negative components of the currents respectively can belong to one of them. This method has the advantage that the positive sequence current and the negative sequence current can be controlled respectively. But it has complicated schemes. In this paper, positive sequence components of the phase voltages are used as inputs of the PLL system to simply detect the phase angle for the control. Using the block suggested in Fig. 4, the effect of negative sequence components that cause 2ω ripple to E_{de} and E_{qe} can be eliminated. The positive sequence components of utility can be expressed as

$$\begin{bmatrix} E_{ap} \\ E_{bp} \\ E_{cp} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ a^2 & 1 & a \\ a & a^2 & 1 \end{bmatrix}\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} = \begin{bmatrix} \frac{1}{2}E_a - \frac{1}{2\sqrt{3}j}(E_b - E_c) \\ -(E_{ap} + E_{cp}) \\ \frac{1}{2}E_c - \frac{1}{2\sqrt{3}j}(E_a - E_b) \end{bmatrix} \quad (3)$$

where, $a = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$

By using all-pass 90° shifter and constant gain, the implementation of the PLL for the unbalanced grid voltages. The block diagram of the phase voltage detection is presented in Fig. 4.

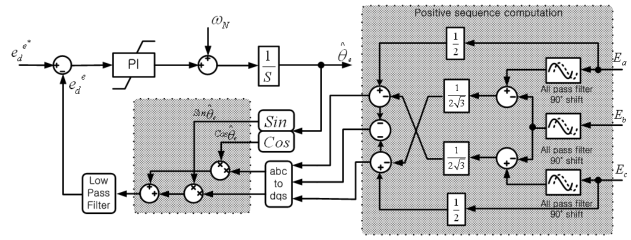


Fig. 4. The phase voltage detection under unbalanced utility

4.2 Current references correction

To eliminate the current harmonics due to the distorted grid voltages, second order low pass filter can be used [3]. In the case of LVRT fast response is very important fact to cope with the grid faults. But this method causes the response of the PLL to be slower. The other method which usually used is to inversely compensate 5th, 7th harmonic currents which are relatively higher than other order harmonics [6]. But this method also has a problem that the control system can be complicated when needed to compensate much higher order harmonic currents.

In this paper, the current references correction is introduced to reduced current harmonics due to the distorted grid voltages [7]. In order to detect an accurate phase angle, two synchronous reference frame PLL systems are used. One is for the phase angle $\theta + \Delta\theta$ with distortion components and the other is for the phase angle using a low pass filter.

By using the original current references i_d^{e*}, i_q^{e*} and the distortion components of the phase angle, the corrected current references i_d^{e**}, i_q^{e**} can be obtained as

$$\begin{aligned} \begin{bmatrix} i_d^{e**} \\ i_q^{e**} \end{bmatrix} &= \begin{bmatrix} \cos(\theta+\Delta\theta) & \sin(\theta+\Delta\theta) \\ -\sin(\theta+\Delta\theta) & \cos(\theta+\Delta\theta) \end{bmatrix}^{-1}\begin{bmatrix} i_d^{e*} \\ i_q^{e*} \end{bmatrix} \\ &= \begin{bmatrix} \cos(\theta+\Delta\theta) & \sin(\theta+\Delta\theta) \\ -\sin(\theta+\Delta\theta) & \cos(\theta+\Delta\theta) \end{bmatrix}\begin{bmatrix} i_d^{e*} \\ i_q^{e*} \end{bmatrix} \\ &= \begin{bmatrix} \cos(\theta+\Delta\theta) & \sin(\theta+\Delta\theta) \\ -\sin(\theta+\Delta\theta) & \cos(\theta+\Delta\theta) \end{bmatrix}\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} i_d^{e*} \\ i_q^{e*} \end{bmatrix} \\ &= \begin{bmatrix} \cos\Delta\theta & \sin\Delta\theta \\ -\sin\Delta\theta & \cos\Delta\theta \end{bmatrix}\begin{bmatrix} i_d^{e*} \\ i_q^{e*} \end{bmatrix} \end{aligned} \quad (4)$$

Where, $\Delta\theta$ is the angle difference between a filtered and distorted phase angle.

For the implementation of this method the phase angle with distortion components is used to improve the converter dynamics. A detailed diagram for the current correction is shown as Fig. 5.

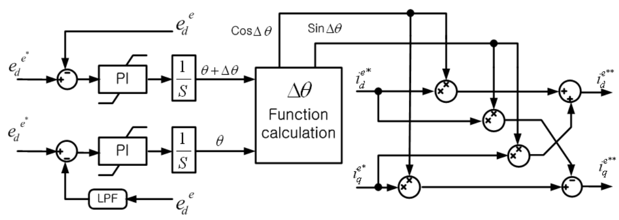


Fig. 5. A detailed diagram for the current correction

This method is useful in the grid connected conversion system because the realization algorithm can be simply implemented by software and requires a smaller interface inductance than the other PLL methods to achieve the same harmonic requirements.

4.3 Current references correction under the unbalanced grid voltages

If the grid voltage is distortedly unbalanced, current references correction with a PLL using positive sequence voltages can be used to regulate the distorted currents maintaining the fast dynamics without a low pass filter. The implementation of this correction is possibly realized as shown in Fig. 6.

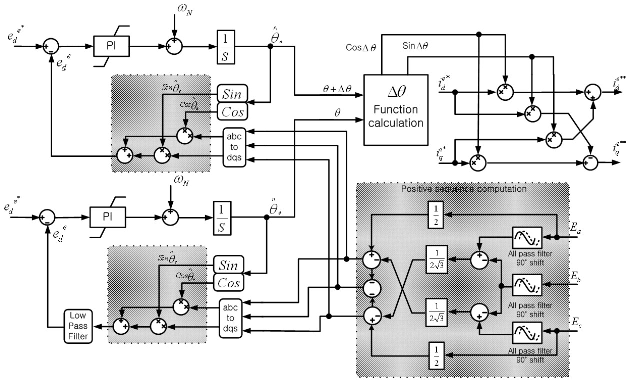


Fig. 6. Current references correction under the unbalanced grid voltages using positive sequence voltages

This method has merits that the realization is simple and futher order currents harmonics are easily eliminated.

5. Simulation and Results

In this section, simulation results and the analysis are illustrated. The specifications of the wind turbine and the generator utilized in this research is listed in Table 1 and Table 2, respectively. The ride-through strategies below the rated rotor speed and at the rated rotor speed are simulated and a detailed analysis is studied.

Table 1. The specifications of the Blades

	Value	Unit
Rated power	2	[MW]
Rated wind speed	11.8	[m/s]
Rated blade speed	1.7453	[rad/s]
Blade radius	40	[m]
Power coefficient	0.4412	
Blade inertia	6816250	[kg·m^2]
Optimal Tip speed ratio	6.908	
Air density	1.225	[kg/m^3]
Cut-in wind speed	4	[m/s]
Cut-out wind speed	25	[m/s]

Table 2. The specifications of the generator

	Value	Unit
Rated power	2.088	[MW]
Rated voltage	659.0V	[V]
Rated current	1952.5	[A]
Rated speed	16.66	[rpm]
Number of poles	120	
Armature resistance	8.278	[mΩ]
Armature inductance	1.285	[mH]
Back-EMF constant	4.813983273	[V/(rad/s)]
Generator inertia	200	[kg·m^2]

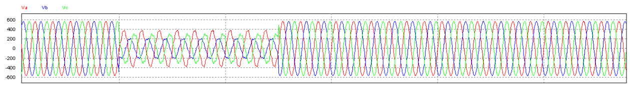
5.1 Below the rated rotor speed

At the below rated rotor speed, it is possible to remain the DC-link voltage by increasing the rotor speed properly. Besides, it is necessary to supply reactive currents into the grid to help voltage recovery. The pitch controller works to reduce the over power flow into the grid by the energy saved in the blade inertia after the recovery.

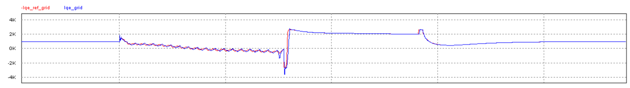
The simulation of LVRT below the rated rotor speed is implemented during 0.15s. From 1s to 1.15s, The grid fault occurs with 50, 40 and 60 percents of voltage sags in the each phase including 5% of fifth harmonics and 7% of seventh harmonics occur.

The simulation results are shown as Fig. 7.

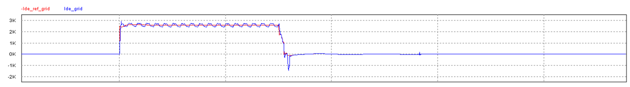
It is confirmed that (b) and (c) from Fig 7. Show the currents tracking the references. (c) also shows the reactive current is supplied to the grid during grid faults. When grid faults occur, the pitch set to 0 to extract the maximum power from the wind is controlled to reduce the power as (f) and TSR is changed by increasing the rotational rotor speed so that the power extracted from the wind is reduced during the grid faults. (d) shows the increasing rotor speed and the changed TSR according to the rotor speed change is seen from (e). the increase in the rotational speed of the blade suppresses DC-link over voltage and works as an energy saving system after the fault recovery. The distorted and unbalanced grid voltages cause the oscillation of the d-q axis grid voltages. This makes the currents into the grid distorted and unbalanced and the distorted-unbalanced currents cause the distortedly unbalanced grid voltages again. Therefore, the control to compensate for the symmetric currents is necessary. (j) shows the currents controlled by using positive sequence components PLL and currents correction method.



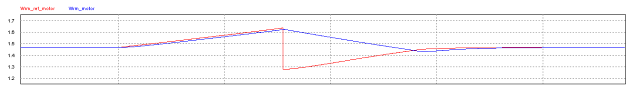
(a) Grid voltages



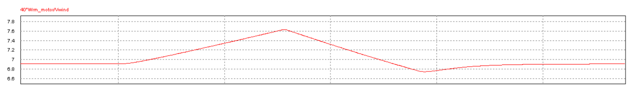
(b) q-axis grid current



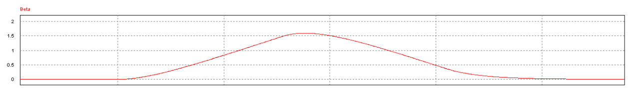
(c) d-axis grid current



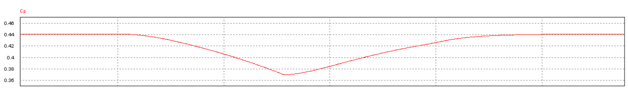
(d) Blade rotational speed



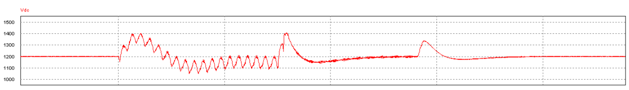
(e) Tip speed ratio



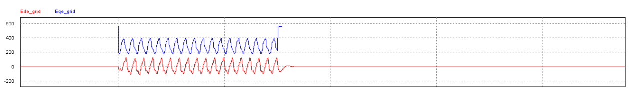
(f) Collective pitch angle



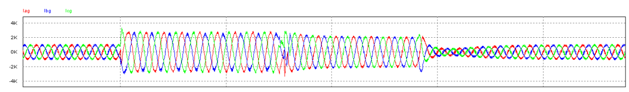
(g) Power coefficient



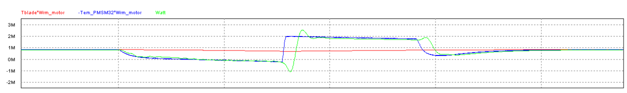
(h) DC-link voltage



(i) d-q axes grid voltages



(j) Three phase grid currents



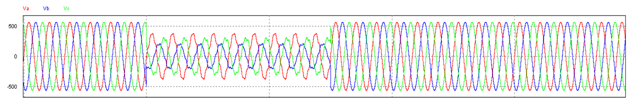
(k) Blade power, Generator power, and Grid power

Fig. 7. System performance under the distortedly unbalanced grid voltages below the rated rotor speed

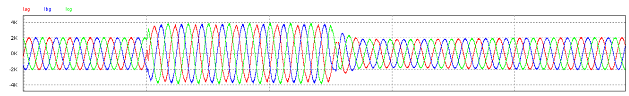
5.2 At the rated rotor speed

When the rotor rotates at the rated speed, because it can be risky to increase the rotor speed the unbalanced energy extracted from the wind is dissipated by the parallel resistor of DC link without increasing the rotational speed. To reduce the heat by the dissipation, pitch control is implemented.

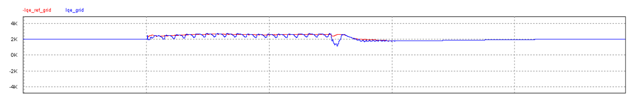
The simulation is implemented assuming that he grid voltage dips occur during 0.15s as below the rated speed as shown in Fig. 8.



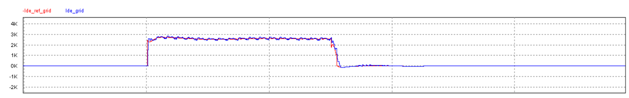
(a) Grid voltages



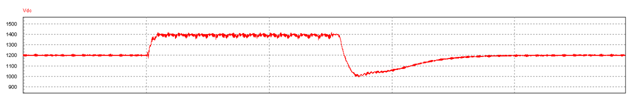
(b) Three phase grid currents



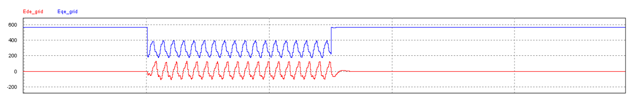
(c) q-axis grid current



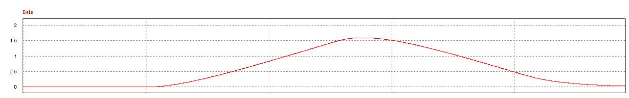
(d) d-axis grid current



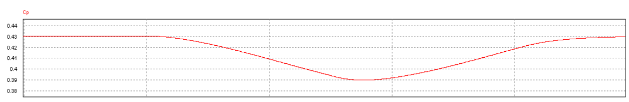
(e) DC-link voltage



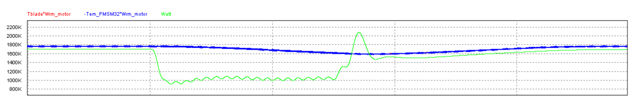
(f) d-q axes grid voltages



(g) Collective pitch angle



(h) Power coefficient



(i) Blade power, Generator power, and Grid power

Fig. 8. System performance under the distortedly unbalanced grid voltages at the rated rotor speed

(d) shows the reactive currents to help the voltage recovery is supplied. DC-chopper works to dissipate the unbalanced energy when the DC link voltage excesses 1400V that is higher than allowed.

Reactive currents are well controlled under the distortedly unbalanced grid voltages as (b). The difference between below the rated rotational speed and at the rated rotational speed is that the energy to the grid flows without as reduced as the energy dissipated in the DC link.

The pitch speed change rate during LVRT is about 10deg/s.

This proposed method is simple and can be easily realized. From the simulation, it is shown the ride-through method is quietly well controlled under the distorted and unbalanced grid voltages. Furthermore, it can be analyzed that the pitch control has much lower response than that of the electrical controller. Therefore the electrical protection and control are obviously necessary.

6. Conclusion

This paper proposes the ride-through strategies under the distortedly unbalanced grid voltages. In the proposed method, the grid voltage phase is detected with positive sequence voltages and current reference correction is used to reduce the harmonics of the active and reactive currents to the grid. This introduced method for LVRT is easily realized and simpler than other methods such as dual currents control with high order harmonics compensation. Besides, two methods to reduce the energy from the wind during the grid fault were implemented. Because the mechanical responses are much lower than that of the electrical responses, the electrical control and protection are required for a short time grid fault. The fact that ride-through strategies which are these days focused in wind power system have to be studied in the both electrical and mechanical sides is obvious. Possible studies can be done with a variety of cases of grid faults including two-mass drive train modeling because the dynamics of two-mass drive train may cause the generated power to be oscillated.

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