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A Novel Method on Fault Ride-Through of a DFIG Wind Turbine using a Dynamic Voltage Restorer During Symmetrical and Asymmetrical Grid Faults

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***Abstract* — The application of a dynamic voltage restorer (DVR) connected to a wind-turbine-driven doubly fed induction generator (DFIG) is investigated. The setup allows the wind turbine system an uninterruptible fault ride-through of voltage dips. The DVR can compensate the faulty line voltage, while the DFIG wind turbine can continue its nominal operation as demanded in actual grid codes. Simulation results for a 2 MW wind turbine and measurement results on a 22 kW laboratory setup are presented, especially for asymmetrical grid faults. They show the effectiveness of the DVR in comparison to the low-voltage ride-through of the DFIG using a crowbar that does not allow continuous reactive power production.**

***Keywords* — Doubly fed induction generator (DFIG), dynamic voltage restorer (DVR), fault ride-through and wind energy.**

I. INTRODUCTION

THE INCREASED amount of power from decentralized renewable energy systems, as especially wind energy systems, requires ambitious grid code requirements to maintain a stable and safe operation of the energy network. The grid codes cover rules considering the fault ride-through behavior as well as the steady-state active power and reactive power production. The actual grid codes stipulate that wind farms should contribute to power system control like frequency and voltage control to behave similar to conventional power stations. A detailed review of grid code technical requirements regarding the connection of wind farms to the electrical power system is given in [1]. For operation during grid voltage faults, it becomes clear that grid codes prescribe that wind turbines must stay connected to the grid and should support the grid by generating reactive power to support and restore quickly the grid voltage after the fault. Among the wind turbine concepts, turbines using the doubly fed induction generator (DFIG) as described in [2] and [3] are dominant due to its variable-speed operation, its separately controllable active and reactive power, and its partially rated power converter.. Conventionally, a resistive network called crowbar is connected in case of rotor over currents or dc-link over voltages to the rotor circuit, and the rotor side converter (RSC) is disabled as described in [6], [7] and [8]. But the machine draws a high short circuit current when the crowbar is activated, as described in [9], resulting in a large amount of reactive power drawn from the power network, which is not acceptable when considering actual grid code requirements. Thus, other protection methods have to be investigated to ride-through grid faults safely and fulfill the grid codes. There are other proposed solutions using additional hardware for fault ride-through of a DFIG using additional hardware like a series dynamic resistance in the rotor in [10] or in the stator in [11] or using a series line side converter (LSC) topology as in [12].Other approaches focus on limiting the rotor currents during transient grid voltage by changing the control of the RSC in order to avoid additional hardware in the system. The RSC can be protected by feed forward of the faulty stator voltage [13], by considering the stator flux linkage [14] or by using the measured stator currents as reference for the rotor current controllers [15]. Other publications focus on the improved performance during unsymmetrical grid voltage conditions [16]–[19]. The advantages of such an external protection device are thus the reduced complexity in the DFIG system. The disadvantages are the cost and complexity of the DVR. Note that a DVR can be used to protect already installed wind turbines that do not provide sufficient fault ride-through behavior or to protect any distributed load in a micro grid. A DVR is used to provide fault ride-through capability for a squirrel cage induction generator in [26]. A DVR to protect a DFIG wind turbine has been presented in [27], but only symmetrical voltage dips have been investigated, and in [28], but the reactive power is not considered and measurement results do not cover transient grid faults. In this paper, the application of a DVR that is connected to a wind-turbine-driven DFIG to allow uninterruptible fault ride through of voltage dips fulfilling the grid code requirements is investigated.

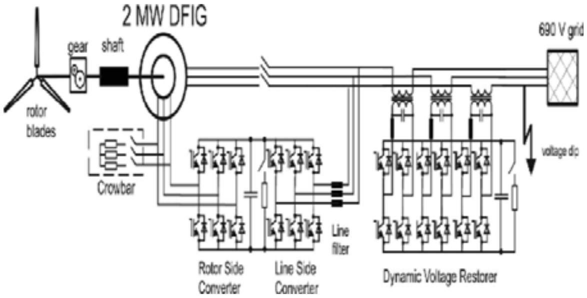


Fig.1. Schematic diagram of DFIG wind turbine system with DVR

The structure is as follows. In Section II, the wind turbine system using a DFIG is described. An analysis of rotor voltage dynamics during transient symmetrical voltage dip and a description of the control structure and conventional crowbar protection are given. In Section III, the DVR electrical system and control using resonant controllers is described. Simulation results for a 2MWwind turbine in Section IV and measurement results on a 22 kW laboratory test bench in Section V show the effectiveness of the proposed technique in comparison to the low-voltage ride-through of the DFIG using a crowbar. A conclusion closes the analysis.

II. DFIG

The investigated wind turbine system, as shown in Fig. 1, consists of the basic components like the turbine, a gear (in most systems), a DFIG, and a back-to-back voltage source converter with a dc link. A dc chopper to limit the dc voltage across the dc capacitor and a crowbar are included. The back-to-back converter consists of a RSC and a LSC, connected to the grid by a line filter to reduce the harmonics caused by the converter.

A. Rotor Voltage Dynamics

A precise knowledge about amplitude and frequency of the rotor voltage is necessary to design and control the RSC. Therefore, equations for the rotor voltage in normal operation and under symmetrical stator voltage dip are derived in the following as in [4].

$$\vec{v}_s = R_s\vec{i}_s + \frac{d\vec{\Psi}_s}{dt} \qquad (1)$$

$$\vec{v}_r = R_r\vec{i}_r + \frac{d\vec{\Psi}_r}{dt} - j\Omega\vec{\Psi}_r \qquad (2)$$

$$\vec{\Psi}_s = L_s\vec{i}_s + L_h\vec{i}_r \qquad (3)$$

$$\vec{\Psi}_r = L_r\vec{i}_r + L_h\vec{i}_s ,4 \qquad (4)$$

where $\_\psi$, $\_v$, and $\_i$ represent the flux, voltage, and current vectors, respectively. Subscripts s and r denote the stator and rotor quantities, respectively. $L_s = L_{s\sigma} + L_h$ and $L_r = L_{r\sigma} + L_h$ represent the stator and rotor inductance, L_h is the mutual inductance, R_s and R_r are the stator and rotor resistances, and Ω is the electrical rotor frequency. By introducing the leakage factor $\sigma = 1 - (L_2\ {}_h/L_sL_r)$, the rotor flux can be described in dependence of the rotor current and the stator flux

$$\vec{\Psi}_r = \frac{L_h}{L_s}\vec{\Psi}_s + \sigma L_r\vec{i}_r \qquad (5)$$

By substituting (5) in (2), an equation for the rotor voltage can be obtained

$$\vec{v}_r = \frac{L_h}{L_s}\left(\frac{d}{dt} - j\Omega\right)\vec{\Psi}_s + \left(R_r + \sigma L_r\left(\frac{d}{dt} - j\Omega\right)\right)\vec{i}_r \qquad (6)$$

which consists of two parts. The first part is caused by the stator flux $\_\psi_s$ that is given in normal operation by the constantly rotating vector

$$\vec{\Psi}_s = \frac{V_s}{j\omega_s}e^{j\omega_s t} \qquad (7)$$

The second part of (6) is caused by the rotor current $\_i_r$. The rotor resistance R_r and the leakage factor σ are often small, so the rotor voltage does not differ considerably from the part caused by the stator flux. Thus, the amplitude of the rotor voltage in normal condition V_{r0} can be calculated as

$$V_{r0} \approx V_s\frac{L_h}{L_s}\frac{\omega_r}{\omega_s} = V_s\frac{L_h}{L_s}s \qquad (8)$$

where $s = 1 - (\Omega/\omega_s) = \omega_r/\omega_s$ describes the slip and ω_r the slip frequency. The rotor voltage induced by the stator flux increases the most during a full symmetrical stator voltage dip. Under a symmetrical voltage dip, the stator voltage is reduced from normal amplitude V_1 to the faulty amplitude V_2 as described in (9)

$$v_s = \begin{array}{ll} V1e^{j\omega s\ t}, & \text{for } t < t0 \\ V2e^{j\omega s\ t}, & \text{for } t \geq t0 \end{array} \qquad (9)$$

Since the stator flux is a continuous value, it cannot follow the step function of the voltage. The evolution of the stator flux can be derived by solving the differential equation (11) (from (1) and (3), assuming $\_i_r = 0$ due to its low influence on the rotor voltage)

$$\frac{d\vec{\psi}_s}{dt} = \vec{v}_s - \frac{R_s}{L_s}\vec{\psi}_s \qquad (11)$$

The solution consists of two parts. The first part is the steady state stator flux after the voltage dip that is described by $\_\psi_{s2}$ and the second part is the transition of the flux from $\_\psi_{s1}$ to $\_\psi_{s2}$ that is described by (12)

$$\vec{\psi}_s = \vec{\psi}_{s0}e^{-tR_s/L_s} = \vec{\psi}_{s0}e^{-t/T_s} \qquad (12)$$

where $\_\psi_{s0}$ is the difference of the stator flux before and after the voltage dip, described by $(V_1 - V_2)/j\omega_s$.

Summarizing, the stator flux is given by the sum of the two parts

$$\vec{\psi}_s(t) = \frac{V_2}{j\omega_s}e^{jw_s t} + \frac{V_1 - V_2}{j\omega_s}e^{-t/T_s} \qquad (13)$$

When the dynamic stator flux from (13) is considered in the rotor voltage equation of (6) (neglecting_i_r and $1/\tau_s$), the dynamic behavior of the rotor voltage under symmetrical voltage dip is described by (15)

$$\vec{v}_r = \frac{L_h}{L_s}\left(\frac{d}{dt} - j\Omega\right)\left(\frac{V_2}{j\omega_s}e^{j\omega_s t} + \frac{V_1 - V_2}{j\omega_s}e^{-t/T_s}\right) \quad (14)$$

$$= \frac{L_h}{L_s}\left(sV_2 e^{j\omega st} - (1-s)(V_1 - V_2)e^{-t/T_s}\right) \quad (15)$$

In a reference frame rotating at rotor frequency, the following rotor voltage is obtained:

$$= \frac{L_h}{L_s}\left(sV_2 e^{j\omega_r t} - (1-s)(V_1 - V_2)e^{-t/T_s}\right) \quad (16)$$

The maximum rotor voltage during symmetrical voltage dip will occur at the beginning of the fault ($t = 0$) and for a full dip
($V2 = 0$)

$$V_{r,\max} \approx \frac{L_h}{L_s}(1-s)V_1 \quad (17)$$

Note that (17) is an approximation of the maximum rotor voltage under the given circumstances. The RSC of a DFIG is rated for a part of the stator power, because the rotor power is approximately Proportional to the slip $Pr \approx sPs$ that is chosen usually between ±0.3. The required amplitude of the rotor voltage is probably determined [with $Lh/Ls \approx 1$ in (8)] by

$$V_r = \frac{sV_s}{N_{sr}} \quad (18)$$

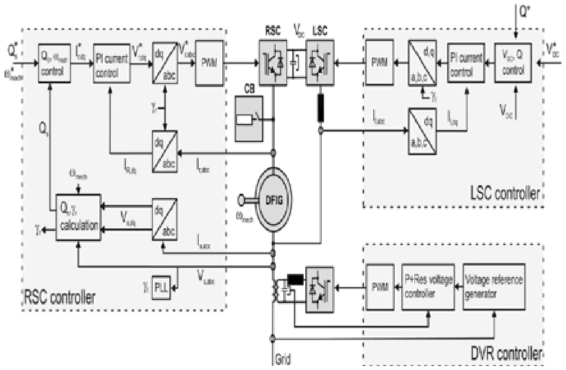
where Nsr is the stator to rotor turns ratio. The turns ratio is usually set at 1/2 or 1/3 in practical wind-turbine-driven DFIGs to make full use of the dc-link voltage and reduce the converters current rating. The required dc-link voltage can be determined by

$$m\frac{V_{dc}}{2} = V_r \quad (19)$$

where m is the modulation index of the pulse width modulation (PWM) technique. The value of the modulation index is 1.0 for the carrier-based sinusoidal PWM and 1.15 for the space vector modulation, both without over modulation techniques [30]. The findings of the section enhance the understanding of rotor over currents during symmetrical grid voltage dip.

B. Crowbar Protection

To protect the RSC from tripping due to over currents in the rotor circuit or overvoltage in the dc link during grid voltage dips, a crowbar is installed in conventional DFIG wind turbines, which is a resistive network that is connected to the rotor windings of the DFIG. The crowbar limits the voltages and provides a safe route for the currents by bypassing the rotor by a set of resistors.



to the mechanical components of the system as the shaft and the gear.

C. RSC Control

The RSC provides decoupled control of stator active and reactive power. The overall control structure is shown in Fig. 2. Neglecting the stator resistive voltage drop, the stator output active and reactive powers are expressed as

$$P_s \approx \frac{3}{2}\frac{L_h}{L_s}V_{sd}I_{rd} \quad (20)$$

$$Q_s \approx -\frac{3}{2}\frac{V_{sd}}{L_s}\left(\frac{V_{sd}}{\omega_s} + L_h I_{rq}\right) \quad (21)$$

thus, the stator active and reactive power can be controlled independently, controlling the d and q components of the rotor current. Based on (20) and (21), the outer power control loops are designed.

D. LSC Control

The LSC controls the dc voltage V_{dc} and provides reactive power support. A voltage-oriented cascade vector control structure with inner current control loops is applied [see Fig. 2(right)]. The line current I_l can be controlled by adjusting the voltage drop across the line inductance L_l giving the following dynamics:

$$V_s = R_l I_l + L_l\frac{dI_l}{dt} \quad (22)$$

which is used to design the current controller, while the dc voltage dynamics can be expressed by

$$C_{dc}\frac{dV_{dc}}{dt} = I_{dc} - I_{load} \quad (23)$$

which is used to design the outer dc voltage control loop, where C_{dc} is the dc capacitance and I_{dc} and I_{load} are the dc currents on LSC and RSC side, respectively.

III. DVR

A. Electrical System

A DVR is a voltage source converter equipped with a line filter (usually LC type). For voltage sags or swells with zero-phase angle jump, the requirement of active power of the DVR is simply given by

$$P_{DVR} = \left(\frac{V_1 - V_2}{V_1}\right)P_{load} \quad (24)$$

where V_1 is the nominal and V_2 the faulty line voltage.

B. DVR Control

For control of the DVR system, a closed-loop control in a rotating *dq* reference frame is introduced in [22], but identified as unsuitable for the compensation of unsymmetrical grid faults.

Table i
Simulation and experimental parameters

Symbol	Quantity	Value
	Simulation Parameters	
U_{line}	low voltage level (phase-to-phase, rms)	690 V
ω_s	Line angular frequency	2 π 50 Hz
P_{DFIG}	Wind turbine rated power	2 MW
i	stator to rotor transmission ratio	1
n	Rated mechanical speed	1800 r/min
L_h	mutual inductance	3.7 mH
R_s	stator resistance	10 mΩ
$R_{crowbar}$	crowbar resistance	0.3 Ω
	Experimental Parameters	
Symbol	Quantity	Value
U_{line}	grid voltage (phase-to-phase. rms)	330 V
P_{DFIG}	DFIG rated power	22 kW
n_{mech}	Mechanical speed	1800 r/min
N_{sr}	stator to rotor transmission ratio	1.5
L_h	mutual inductance	37.13 mH
R_s	stator resistance	112 mΩ
$R_{crowbar}$	crowbar resistance	2.7 Ω
V_{DC}	DVR DC voltage	560 V
n	series transformer ratio (DVR to line)	$\sqrt{3}$
C_{DC}	DVR DC link capacitance	7.5 mF

The controller transfer function expressed in terms of inverter voltage reference $u*_i$, measured filter capacitor voltage u_c, and filter capacitor voltage reference $u*_c$ is given by

$$u_i^*(s) = u_c(s) + G_{P+\mathrm{Res}(s)} \cdot \left(u_c^*(s) - u_c(s)\right) \quad (25)$$

where a feed forward of the measured filter capacitor voltage is used. The transfer function of the P+Res voltage controller is defined as

$$G_{P+\mathrm{Res}(s)} = K_P + K_I \frac{s}{s^2 + \omega_0^{\,2}} \quad (26)$$

which has been implemented in the discrete form leading to the following transfer function:

$$G_{P+\mathrm{Res}(z)} = K_P + K_I \frac{zT_S - T_S}{z^2 + z\left(T^2{}_S\omega_0^{\,2} - 2\right) + 1} \quad (27)$$

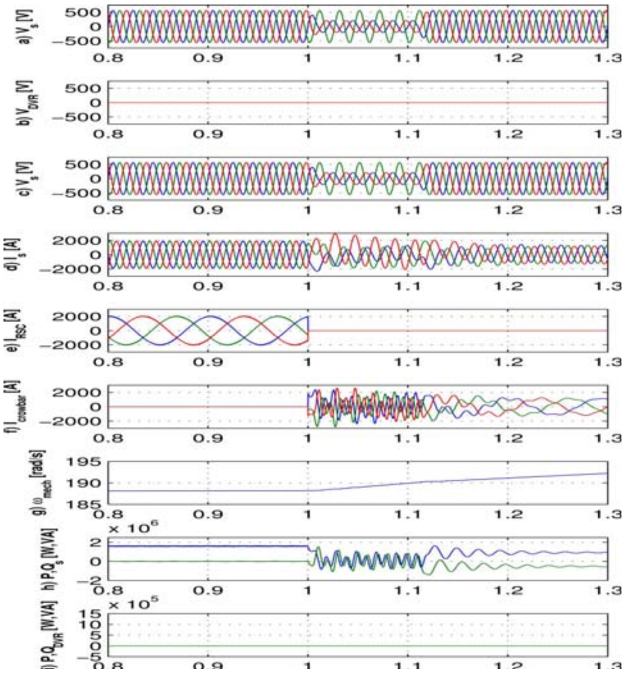


Fig.3. Simulation of DFIG performance with crowbar protection during 37 % two-phase voltage dip. (a) Line voltage. (b) DVR voltage. (c) Stator voltage. (d) Stator current. (e) RSC current. (f) Crowbar current. (g) Mechanical speed. (h) Active and reactive stator power. (i) Active and reactive DVR power.

IV. SIMULATION RESULTS

To show the effectiveness of the proposed technique, simulations have been performed using MATLAB/Simulink and PLECS for a 2 -MW DFIG wind turbine system and a DVR, as shown in Fig. 1. The simulation parameters are given in Table I. The control structure, as shown in Fig. 2, is implemented in Simulink, while all power electronic components are modeled in PLECS. The system performance of the DFIG is shown in Fig. 3, protected by the conventional passive crowbar, and in Fig. 4, protected by the DVR during a two-phase 37 % voltage dip of 100 ms duration [see Figs. 3(a) and 4 (a)].

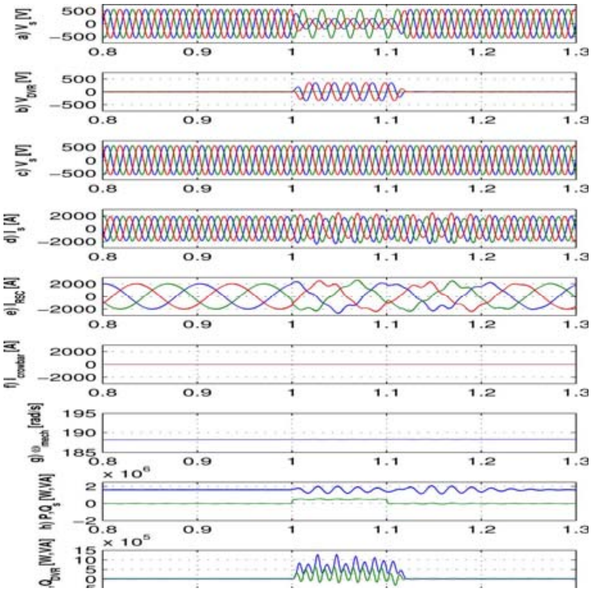
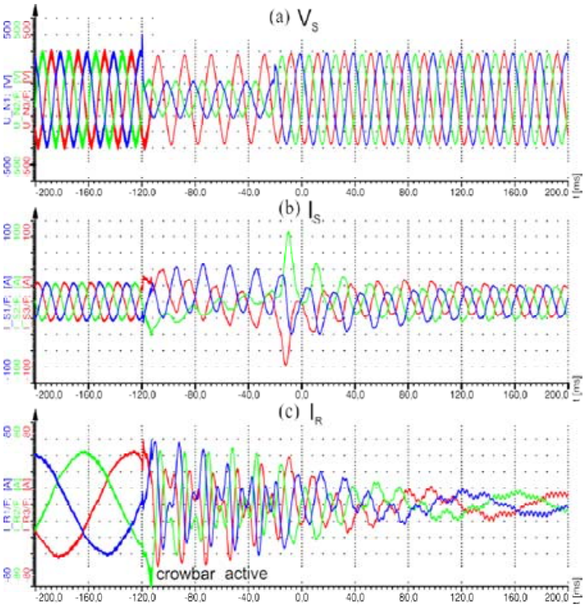


Fig.4. Simulation of DFIG performance with DVR protection during 37 % two-phase voltage dip. (a) Line voltage. (b) DVR voltage. (c) Stator voltage. (d)\ Stator current. (e) RSC current. (f) Crowbar current. (g) Mechanical speed. (h) Active and reactive stator power. (i) Active and reactive DVR power.



V. MEASUREMENT RESULTS

Measurement results are taken at a 22 kW test bench and a 30 kVA DVR connected in series to the grid. The schematic diagram of the laboratory setup is similar to the one shown in fig 1.

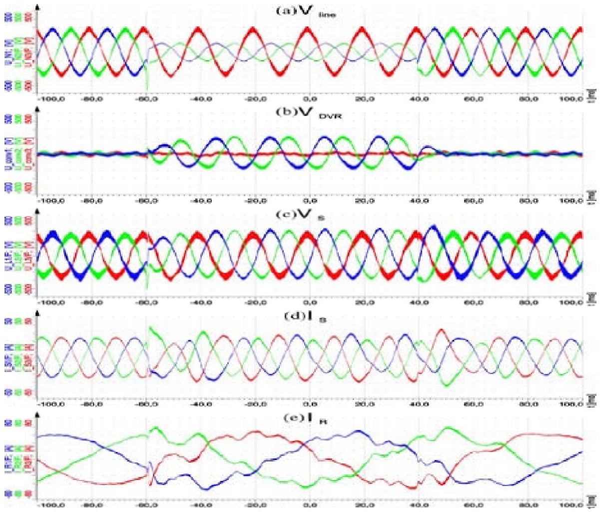


Fig.6. Measurement results for DFIG with DVR protection: (a) line voltages,(b) DVR voltages, (c) stator voltages, (d) stator currents, and (e) rotor currents.

In all laboratory tests, the grid voltage level has been lowered to 330 V (line to line) by a separate transformer to avoid saturation problems in the series-connected transformers of the DVR. One can conclude that the DVR can compensate voltage dips and swells of symmetrical and asymmetrical nature to allow a low- or high voltage ride-through for any distributed load.

VI. CONCLUSION

The application of a DVR connected to a wind-turbine-driven DFIG to allow uninterruptible fault ride-through of grid voltage faults is investigated. The DVR can compensate the faulty line voltage, while the DFIG wind turbine can continue its nominal operation and fulfill any grid code requirement without the need for additional protection methods. The DVR can be used to protect already installed wind turbines that do not provide sufficient fault ride-through behavior or to protect any distributed load in a micro grid. Simulation results for a 2 MW wind turbine under an asymmetrical two-phase grid fault show the effectiveness of the proposed technique in comparison to the low-voltage ride through of the DFIG using a crowbar where continuous reactive power production is problematic. Measurement results under transient grid voltage dips on a 22 kW laboratory setup are presented to verify the results.

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