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Improvement Fault-ride Through of DFIG Based Wind Turbines by Using a Series Compensation Technology with Emphasis Put on the Mitigation of Voltage Dips

Mustafa Jawad Kadhim, D.S.Chavan

Abstract__Low Voltage Ride Through is an important feature for wind turbine systems to fulfill grid code requirements. In case of wind turbine technologies using doubly fed induction generators the reaction to grid voltage disturbances is sensible. Hardware or software protection must be implemented to protect the converter from tripping during severe grid voltage faults. In this paper the Dynamic Voltage Restorer (DVR) solution for LVRT of DFIG wind turbines is investigated by simulation results using a detailed converter model considering the switching and appropriate 2 MW wind turbine system parameter. To show the effectiveness of the proposed method the results are compared to a conventional fault ride through of the DFIG using a crowbar circuit. Measurement results on a 22 kW laboratory DFIG test bench show the effectiveness of the proposed control technique.

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

I. INTRODUCTION

Due to high depletion of conventional energy sources and increasing environmental concern, more efforts are put in electricity generation from renewable energy sources. Among various renewable energy source, wind power is the most rapidly growing one since the 20th century due to its reproducible, resourceful and pollution-free characteristics. Among the wind turbine concepts, turbines using the doubly fed induction generator (DFIG) are dominant due to its variable-speed operation, its separately controllable active and reactive power, and its partially rated power converter. But the reaction of DFIGs to grid voltage disturbances is sensitive, for symmetrical and unsymmetrical voltage dips, and requires additional protection for the rotor side power electronic converter [1].Conventionally a resistive network called crowbar is connected, as described in [2],[3],[4] and [5]. once the crowbar is applied it cannot be removed until its current reaches zero. During the period the crowbar is applied, the machine behaves as a conventional FSIG, losing control of the active and reactive power.

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Therefore the time taken for the crowbar current to reach zero is crucial as it determines when the RSC can regain power control and how soon the AC voltage can recover. It is seen that the crowbar current can take a long time to decrease to zero and that this has a significant impact on the voltage recovery after fault. The larger the crowbar resistor and the further the generator is from synchronous speed, the shorter the crowbar current transient is. Power and energy dissipation through the crowbar resistor are also considered, and it is observed that the power varies in accordance with the maximum power transfer theorem. It is seen that reactive power control during fault clearance can assist AC voltage recovery. This is not acceptable when

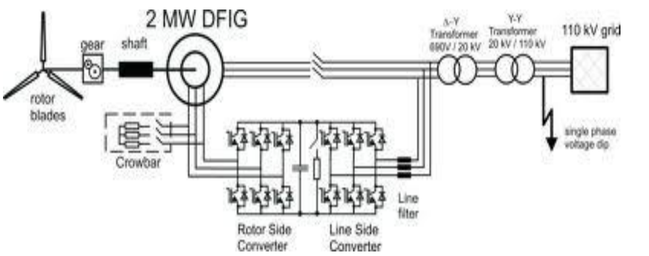

Fig 1: Schematic diagram of DFIG wind turbine system considering grid code requirements [6]? Thus other protection methods have to be investigated to ride through grid faults safely and fulfill the grid codes.

If an external power electronic device is used to compensate the faulty grid voltage, any protection method in the DFIG system can be left out. Such a system is introduced in [7] and is called a dynamic voltage restorer (DVR).The dynamic voltage restorer is a series connected device, which by voltage injection can control the load voltage. In the case of a voltage dip the DVR injects the missing voltage and it avoids any tripping the load. Fig. 2 illustrates the operation principle of a DVR.

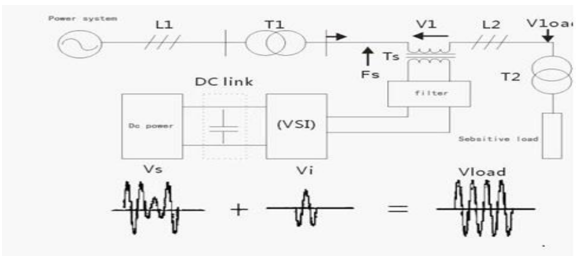

Fig. 2: operation principle of a DVR.

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The application of a dynamic voltage restorer (DVR)connected to a wind-turbine-driven doubly fed induction generator(DFIG) is investigated and compared to aconventional fault ride through of the DFIG using a crowbar circuit.

The paper is structured as follows. In section 2 the DFIG wind turbine system and its control structure are described. The DVR control anddesign described in section 3. Simulation results for a 2 MW wind turbine in section 4 in section 5 shows the effectiveness of the proposed techniquein comparison to the low voltage ride through of the DFIG using a crowbar. A conclusion closes thepaper.

II. DFIG

For variable-speed systems with limited variable-speed range, e.g. 30% of synchronousspeed, the DFIG can be an interesting solution [8]. As mentioned earlier the reason forthis is that power electronic converter only has to handle a fraction (20–30%) of the totalpower [9, 10]. This means that the losses in the power electronic converter can be reducedCompared to a system where the converter has to handle the total power.

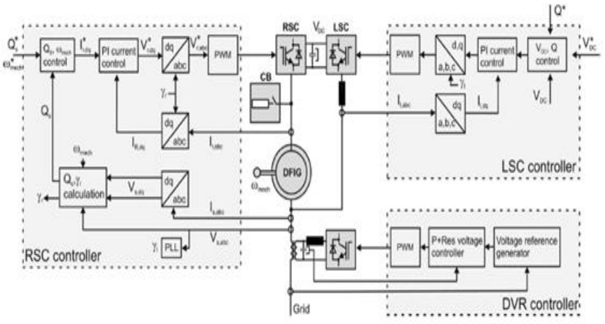

Fig 3: Schematic diagram of DFIG wind turbine control structure.

In addition, the costof the converter becomes lower. The stator circuit of the DFIG is connected to the grid whilethe rotor circuit is connected to a converter via slip rings, see Fig. 1. Amore detailed picture of the InvestigatedDFIG system with a back-to-back converter can be seen in Fig. 1. The back-to-back converter consists of two converters, i.e., machine-side converter and grid-side converter that are connected "back-to-back." Between the two converters a dc-link capacitor is placed, asenergy storage, in order to keep the voltage variations (or ripple) in the dc-link voltage small. With the machine-side converter it is possible to control the torque or the speed of the DFIG and also the power factor at the stator terminals, while the main objective for the grid-side converter is to keep the dc-link voltage constant. The speed–torque characteristics of the DFIG system. The DFIG can operate both in motor and generator operation with a rotor-speed range of ±Δωmaxr around the synchronous speed, ω1.

The overall control structure is shown in Fig.3

The mathematical model of the DFIG will only briefly be discussed here. From the per-phase equivalent circuit of the DFIG in an arbitrary reference frame rotating at synchronous angular speed ws the following stator and rotor voltage and flux equations can be derived.

$$V_s = R_s I_s + L_s \frac{d\psi_s}{dt} + j\omega_s \psi_s \quad (1)$$

$$V_r = R_r I_r + L_r \frac{d\psi_r}{dt} + j\omega_{slip} \psi_r \quad (2)$$

$$\psi_s = L_s I_s + L_h I_r \quad (3)$$

$$\psi_r = L_r I_r + L_h I_s \quad (4)$$

Where ψ, U and I represent the flux, voltage and current vectors respectively. Subscripts s and r denotethe stator and rotor quantities respectively. $L_s = L_{s\sigma}+L_h$ and $L_r = L_{r\sigma}+L_h$represent the statorand rotor inductance, L_h is the mutual inductance, R_s and $R_r$are the stator and rotor resistances andw_{slip} is the slip angular frequency $w_{slip} = w_s - w_{mech}$.The rotor currents are controlled by the rotor side voltage source converter. Substituting Is $=\psi_s/L_s-(L_h/L_s)I_r$ from (3) in (2) and assuming the stator flux to be constant ($d_{\psi s}/d_t = 0$) yieldsthe rotor voltage equation:

$$V_r = R_r I_r + \sigma L_r \frac{dI_r}{dt} + j\omega_{slip} \psi_r \quad (5)$$

that is used to design the inner current loop controllers, where $jw_{slip}\psi_r$ is used as decoupling term.The stator active and reactive power can be controlled independently by the outer control loops.The line side converter controls the DC voltage V_{DC} and provides reactive power support. The linecurrent I_l can be controlled by adjusting the voltage drop across the line inductance $L_l$giving thefollowing dynamics:

$$V_s = R_1 L_1 + L_1 \frac{dI_1}{dt} \quad (6)$$

used to design the current controller, while the DC voltage dynamics can be expressed by:

$$C_{DC} \frac{dV_{DC}}{dt} = I_{DC} - I_{load} \quad (7)$$

used to design the outer DC voltage control loop, where *CDC* is the DC capacitance and *IDC* and $I_{load}$are the DC currents on LSC and RSC side, respectively.

III. DFIG PROTECTION

3.1 Crowbar:

To protect the rotor side converter fromtripping due to overcurrents 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. When the crowbar is activated the rotor side converters pulses are disabled and the machine behaves like a squirrel cage induction machine directly coupled to the grid. The magnetization of the machine that was provided by the RSC in nominal condition is lost and the machine absorbs a large amount of reactive power from the stator and thus from the network [6], which can further reduce the voltage level and is not allowed in actual grid codes.

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Triggering of the crowbar circuit also means high stress to the mechanical components of the system as the shaft and the gear. Detailed analyses on the DFIG behavior during voltage dip and crowbar protection can be found in [2] and [6]. Thus, from network and from machine mechanical point of view a crowbar triggering should be avoided. Anyway, to compare the presented technique here with a conventional DFIG wind turbine system protected by a crowbar circuit, simulation results including crowbar protection are examined. Therefore the crowbar resistance is designed. The value of the crowbar resistance should be chosen carefully.There are two requirements that give an upper and a lower limit to the crowbar resistance. Itshould be high enough to limit the short circuit rotor current and it should be low enough to avoid toohigh voltage in the rotor circuit. If the voltage across the crowbar terminals rises above the DC-linkvoltage of the RSC high currents will flow through the antiparallel diodes of the converter. Appropriate
Crowbar resistances are designed in [6] and [5]. A crowbar resistance of *Rcrow*= 150*Rr* isused in the simulations. There are approaches limiting the operation time of the crowbar to returnto normal DFIG operation with active and reactive power control as soon as possible. A hysteresis
Control triggered by the rotor current is presented in [4] and also applied here.When the absolute value of the rotor current reaches a maximum threshold value the crowbar is fired and the RSC is blocked. When the rotor transients have died out and the absolute value of the rotor current is below a minimal threshold value the crowbar is switched off and the RSCs control is restarted. A reset of the integral values of the RSCs current and power control before restart is necessary to avoid overcurrents.

3.2 DVR Protection:

The DVR is a powerful controller that is commonly used forvoltage sags mitigation at the point of connection. Fig. 4 shows the basic configuration ofDVR.

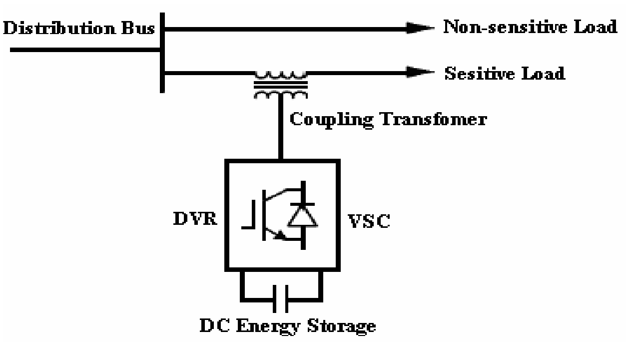

Fig 4: Basic configuration of DVR.

The VSC generates a three-phase ac output voltage which iscontrollable in phase and magnitude. These voltages areinjected into the ac distribution system in order to maintain theload voltage at the desired voltage reference.
in [11]. The rating of the DVR system depends mainly on thedepth of the voltage fault that should be compensated. For voltagesags or swells with zero-phase angle jump, the requirementof active power of the DVR is simply given by:

$$P_{DVR} = \left(\frac{V_1 - V_2}{V_1} \right) P_{load} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

where *V*1 is the nominal and *V*2 the faulty line voltage. Note thatspecial focus must be taken on voltage faults with phase angle jump that can lead to a higher power rating [12].When the DVR compensates a voltage sag, the active power of the DFIG is partly fed into the grid and the DVR system that is dependent of the remaining grid voltage. The active power flowing into the DVR charges its dc link. The excess energy must either be delivered to an energy storage system or transformed into heat by a dc chopper. Note that for full compensation of a full voltage dip, the DVR must be rated for the power of the wind turbine, making the solution in economical. Thus, the solution will probably be implemented to fully compensate the line voltage during partial voltage dip or swell and to assist during full voltage dip.
The injection transformers have a great impact on the DVR design. To adapt the DVR dc voltage to the compensating voltage, an adequate transformer ratio must be chosen. The design of the injection transformers differs from normally used shunt transformers. They must be higher rated to avoid possible saturation effects and lower the risk of high inrush currents that must be handled by the converter. Rating and design issues for the injection transformer are given in [13]. In practical applications, several security issues must be considered. Since the DVR is connected in series to the load, bypass switches across the transformers must be included to disconnect the DVR from the load, to protect the converter from damage in overload situations.

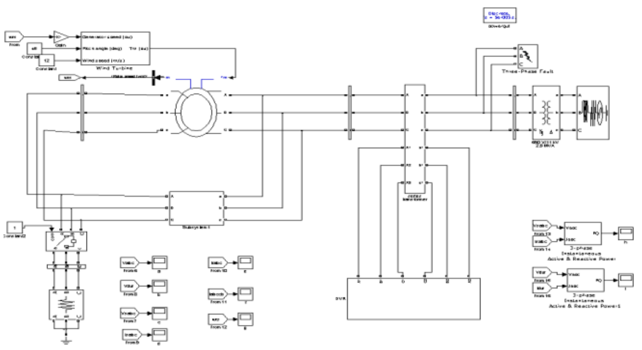

Fig 5: Matlab/Simulink for the proposed model

III. 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 control structure, as shown in Fig. 3, is implemented in Matlab/Simulink as show in fig 5, while all power electronic components are modeled in PLECS. The system performance of the DFIG is shown in Fig. 6, protected by the conventional passive crowbar, and in Fig. 7, protected by the DVR during a two-phase 37 % voltage dip of 100 ms duration [see Figs. 6(a) and 7 (a)]. The DFIG reacts with high stator currents *Is*, and thus, high rotor currents are induced in the rotor circuit. When the rotor currents exceed the maximum level, the crowbar is triggered to protect the RSC from overcurrents *I*RSC [see Fig. 6(e) and (f)]. When the voltage level has been reestablished and transients have decayed, the crowbar can be deactivated, which is not shown here.

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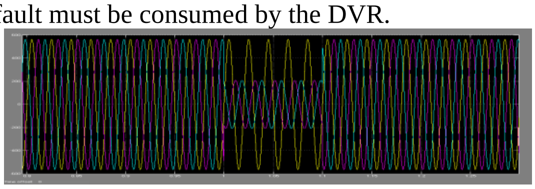
When the RSC is in operation, the machine magnetization is provided by the rotor, but when the crowbar is triggered, the RSC is disabled and the machine excitation is shifted to the stator. Thus, reactive power control cannotbe provided during the voltage dip [see Fig. 6(h)], which is not acceptable when considering the grid codes. The machine cannot generate enough torque so that the rotor accelerates, which can lead to disconnection of the turbine due to overspeed. The DVR is not activated in the simulations, as shown in Fig. 6. When the wind turbine system is protected by the DVR, as shown in Fig. 7, the voltage dip can almost be compensated [see Fig. 7(c)]. The DFIG response is much less critical, which means that lower stator overcurrents and rotor overcurrents are produced so that the crowbar does not have to be triggered [see Fig. 7(d)–(f)]. Note that although the stator voltage dip is fairly well-compensated, a slight distortion in the stator currents (dc components), and thus, disturbed rotor currents can be observed. Anyway, the RSC remains in operation and can control stator active and reactive power independently. Thus, the speed is kept constant and a reactive power production (Qs = 0.5Mvar) during grid fault as demanded in grid codes is performed. Note that a communication between DVR and DFIG is necessary. In Fig. 7(i), the DVR power to compensate the voltage dip is shown. It becomes clear that the active and reactive power that cannot be fed into the faulty grid during grid fault must be consumed by the DVR.



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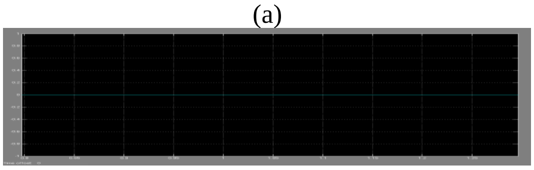

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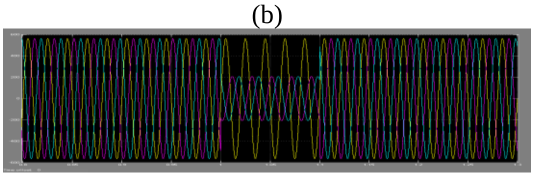

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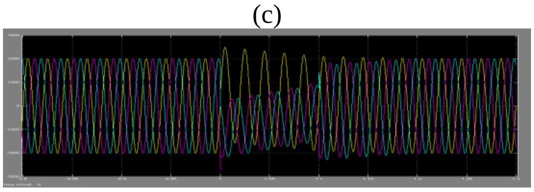

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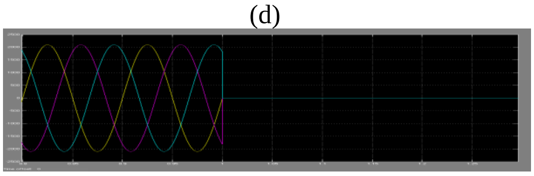

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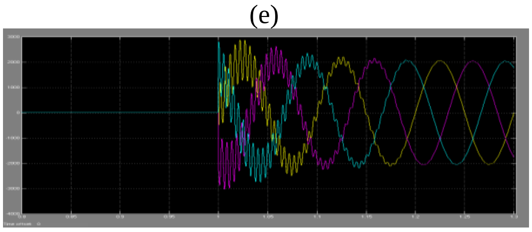

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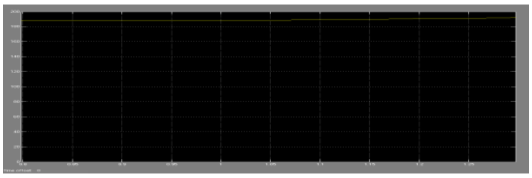

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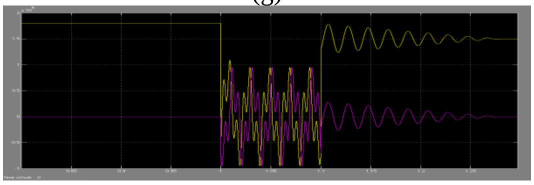

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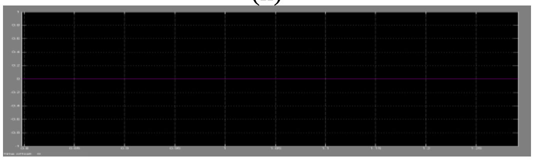
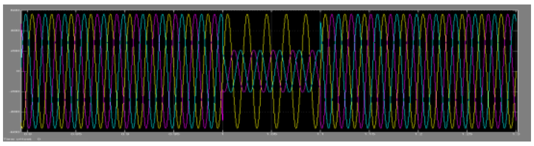


(i)

Fig 6: 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.



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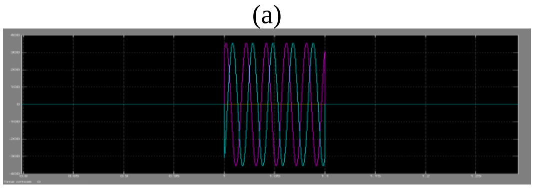

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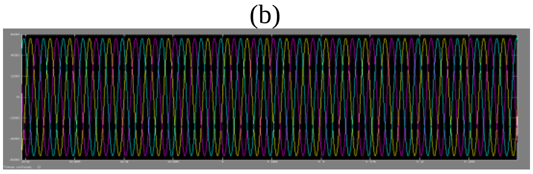

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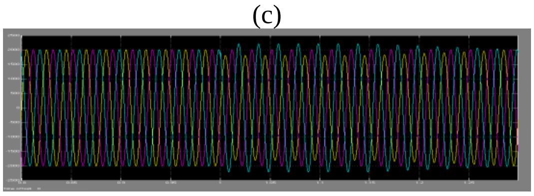

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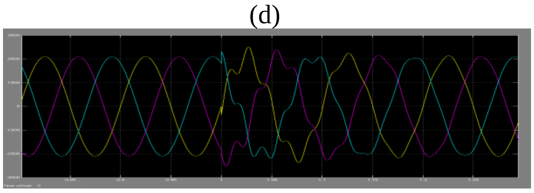

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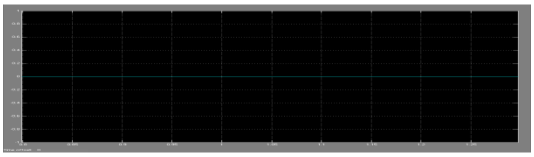

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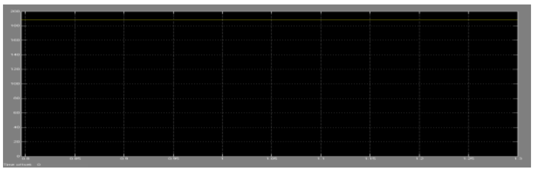

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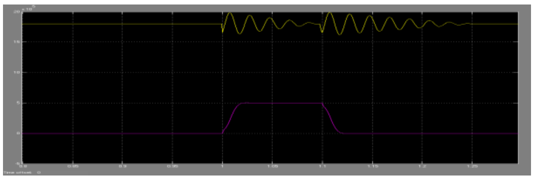

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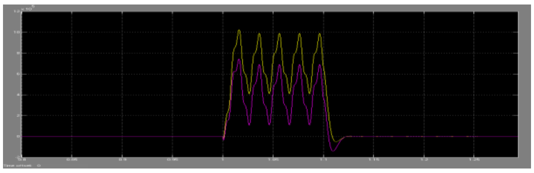

(i)

Fig 7: 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.

IV. CONCLUSION

Through this project the investigation of the application of the DVR has shown the ability of the DVR connected to a wind-turbine-driven DFIG to provide uninterruptible fault-ride-through of grid voltage disturbance/ faults compared to the system under the crowbar protection. The DVR can improve the faulty line voltage, while the DFIG wind turbine can continue its complete nominal operation and fulfill any grid code requirement without the need to extra 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.

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V. APPENDIX:

Simulation parameters

Symbol	Quantity	Value
V_{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

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