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Fault Ride-Through of a DFIG Wind Turbine Using a Dynamic Voltage Restorer during Symmetrical and Asymmetrical Grid Faults

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ABSTRACT: This paper introduces a new solution for doubly fed induction generators to stay connected to the grid during Faults. The main idea is to increase the stator voltage to a level that creates the required flux to keep the rotor side converter current below its transient rating. To accomplish this goal, a series compensator is added to inject voltage in series to the stator side line. The Dynamic Voltage Restorer can compensate the faulty line voltage while the DFIG wind turbine can continue its nominal operation as demanded in actual grid codes. Fuzzy Logic controller is used as a controller in order to control the dc link voltages and to reduce the harmonics. Simulation results for a 2 MW wind turbine 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.

INTRODUCTION

The increased amount of power from decentralised, 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 behaviour 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. From the physical setup viewpoint, there are horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). Initially, vertical axis designs were considered due to their expected advantages of omni-directionality (hence do not need yaw-system) and having gears and generating equipments at the tower base. In HAWT, the wind turbine blades rotate about an axis parallel to the ground and wind flow. Almost all the larger turbines employed in modern wind farms are HAWT because they are more suitable for harnessing more wind energy. However, HAWT are subjected to reversing gravitational loads (structural load is reversed when the blade goes from upwards to downwards position) which impose a limit on the size of such turbines. The rotation of both HAWT and VAWT can be powered primarily by lift or drag force depending on the design of the blade. An easy way to protect the converter is to disconnect the generator during low-voltage conditions. But many regulations have been developed and are under development to support the grid during short circuits with reactive power and prevent disconnection to deliver power when the voltage is restored. Recently, many researchers have focused on different techniques to overcome the low-voltage ride-through (LVRT) issue. There are many different methods to mitigate voltage sags and swells, but the use of a custom Power device is considered to be the most efficient method. Switching off a large inductive load or Energizing a large capacitor bank is a typical system event that causes swells [1]. When short circuit occurs on the grid side, the rotor currents rise and if the converter is not protected against these high currents, it will be damaged. The system has two modes of operation which are: the series voltage compensation using DVR. In this mode of operation, the voltage sags are mitigated but not completely. In this method the voltage sags are completely mitigated. The use of the Clarke transform, the real (Ids) and imaginary (Iqs) currents can be identified. The Park transform can be used to realize the transformation of the Ids and the Iqs currents from the stationary to the moving reference frame and control the spatial relationship between the stator vector current and rotor flux vector. In this paper, the application of a DVR that is connected to a wind-turbine-driven DFIG to

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allow uninterruptible fault ride through of voltage dips fulfilling the grid code requirements is investigated. The DVR can compensate the faulty line voltage, while the DFIG wind turbine can continue its nominal operation as demanded in actual grid codes. Here, asymmetrical faults are investigated and measurement results under transient grid voltage dips on a 22 kW Matlab is implemented. The structure is as follows. In Section II, the wind turbine system using a DFIG is described. In Section III, the DVR electrical system and control using resonant controllers is described. Fuzzy Logic controller is explained in the section IV Simulation results for a 2MWwind turbine in Section V. and the entire system is Implemented using Matlab/Simulink Software.

MODELLING OF DFIG

The Simulink discrete-time WT_DFIG model, presented here, is based on the Wind Turbine Doubly-Fed Induction Generator (Phasor Type) available in version 4.0 of Matlab/ SimPowerSystems library The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings. The control system generates the pitch angle command and the voltage command signals Vr and Vgc for Crotor and Cgrid respectively in order to control the power of the wind turbine, the DC bus voltage and the voltage at the grid terminals. An average model of the AC/DC/AC converter is used for real-time simulation [6]. In the average model power electronic devices are replaced by controlled voltage sources. Vr and Vgc are the control signals for these sources. The DC bus is simulated by a controlled current source feeding the DC capacitor. The current source is computed on the basis of instantaneous power conservation principle: the power that flows inside the two AC-sides of the converter is equal to the power absorbed by the DC capacitor. With the average model, the high frequency components of the voltage, generated by the PWM switching of electronic devices, are not simulated. The Matlab Circuit is implemented based on the fig 1 mentioned below

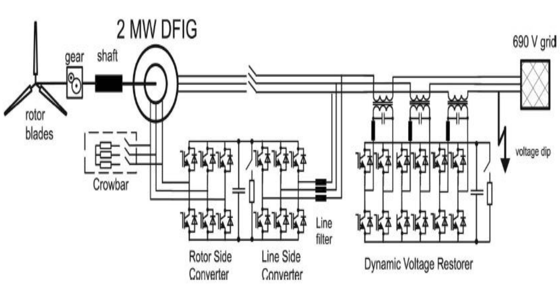

Fig. 1. Schematic diagram of DFIG wind turbine system with DVR.

A. RSC Control:

The RSC provides decoupled control of stator active and reactive power. A cascade vector control structure with inner current control loops is applied. The overall control structure is shown in Fig. 2. When adopting stator-voltage-oriented (SVO) control, a decomposition in d and q components is performed (Vsq = 0). Neglecting the stator resistive voltage drop, the stator output active and reactive powers are expressed as

$$Ps = \frac{3}{2} * \frac{Lh}{Ls} * Vsd * Ird \text{ ---- } (1)$$

$$Qs = -\frac{3}{2} Vsd/Ls(\frac{Vsd}{Ws} + LhIrq)(2)$$

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.

B. LSC Control:

The LSC controls the dc voltage Vdc 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 Il can be controlled by adjusting the voltage drop across the line inductance Ll giving the following dynamics:

$$Vs = Rl * Il + LlDil/dt(3)$$

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

$$Cdc * \frac{dVdc}{dt} = Idc - Iload \, (4)$$

Which is used to design the outer dc voltage control loop, where Cdc is the dc capacitance and Idc and Iload are the dc currents on LSC and RSC side, respectively.

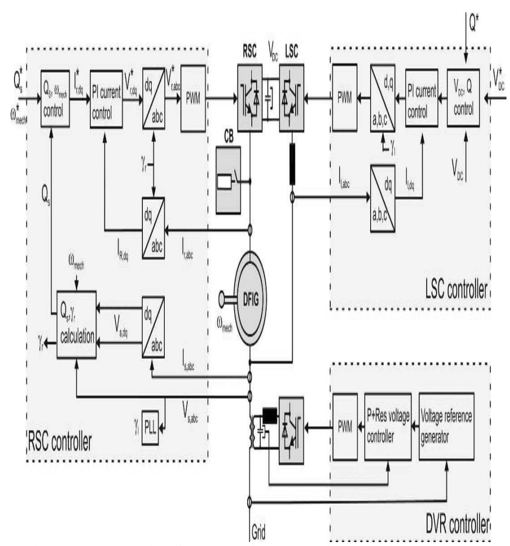

Fig. 2. Schematic diagram of DFIG wind turbine and DVR control structure.

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DYNAMIC VOLTAGE RESTORER AND ITS OPERATING PRINCIPLE

A. Dynamic voltage Restorer:

Dynamic voltage is one of the custom power device which is used for voltage sag/swell elimination and it consists of a VSC (Voltage Source Converter), storing device (Battery), Passive Filters, Injection transformer also known as Coupling transformer, In DVR VSC is made up with 6 IGBT switch which is used for conversion of dc link voltage into ac supply and there a battery which acts as dc link voltage and as well as storing agent and there placed a passive which is elimination of switching harmonics, when voltage source converter converts ac-dc or dc-ac we get ripple in the output supply of VSC and in order to eliminate those ripples passive filters are used and this output of the ripple filter is connected to the injection transformer and which injects the filtered supply into the bus or feeder. When there is no disturbance in the system the injected transformer will be short circuited by the switch to decrease losses and increase cost effectiveness. The o/p of the DVR is completely depending upon the PWM technique and control method. The PWM generates signal by comparing sinusoidal signal with the carrier wave signal and sending appropriate signal to the Inverter.

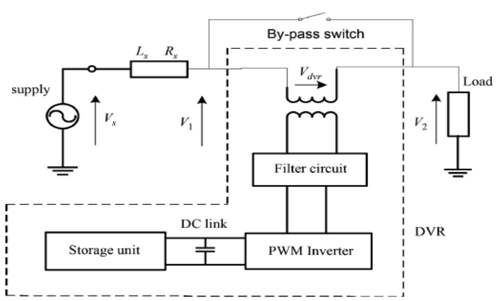

Fig 3: Schematic Circuit of Dynamic Voltage Restorer

B.Working principle of DVR:

When voltage drop occurred at load, DVR will inject a series Voltage through transformer so that the load voltage can be maintained at nominal value, thus equation can be written as

$$Vdvr = Vl + ZthIl - Vth \quad (5)$$

$$Il = [pl + jQl / Vl]^* \quad (6)$$

In most of the sad conditions the DVR injects some active power to the system. Generally the operation of DVR can be categorized into two modes: 1) standby mode, 2) Injection Mode. Therefore the capacity of the storing device can be limiting factor especially during long-term voltage sag. In standby mode, DVR either in short circuit operation or inject small voltage to cover voltage drop due to transformer reactance losses. The DVR is turn into injection mode as soon as sag is detected and injects voltage in Series with the load with required magnitude and phase for compensation.

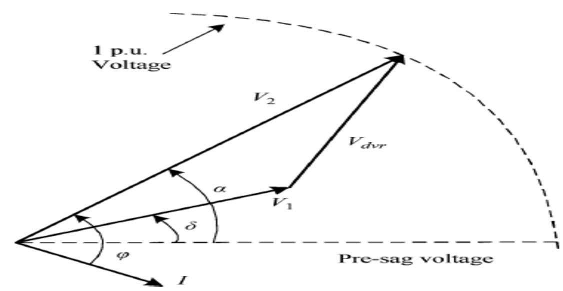

Fig4: Phasor diagram during Voltage sag Condition

The Phasor diagram represents the electrical condition during voltage sag condition for easy analysis one phase is only considered. Voltages V1, V2, Vdvr are source voltage, load voltage and DVR injected voltages, respectively. I, Ø α, δ, represents the load current, load power factor angle, the source phase voltage, and phase angle. The advantage of proposed technique is that less active power will be transferred from storage unit to distribution system. This results in compensation for deep voltage sag in the distribution system. The reference is considered as the source voltage and a carrier frequency is considered and both are compared with a comparator and the gating signals obtained are given to the gate terminals of DVR. The capability of injection of DVR system is 50% of nominal voltage; this allows DVR to succefully provide protection against sag to 50% from durations of up to 0.1sec.

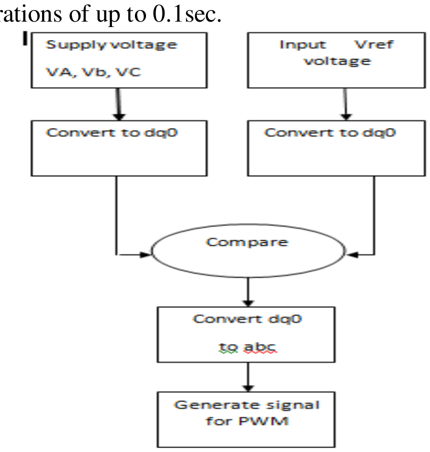

Fig 5: Flow chart for control technique of DVR

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FUZZY LOGIC CONTROLLER

The Fuzzy Logic Controller (FLC) is used as controller in the proposed model. The Fuzzy Logic tool was introduced in 1965, also by Lotfi Zadeh, and is a mathematical tool for dealing with uncertainty. It offers to a soft computing partnership _the important concept of computing with words‘. It provides a technique to deal with imprecision and information granularity. The fuzzy theory provides a mechanism for representing linguistic constructs such as 'many' 'low' 'medium' 'often' 'few'. In general, the fuzzy logic provides an inference structure that enables appropriate human reasoning capabilities. In fuzzy logic, basic control is determined by a set of linguistic rules which are determined by the system. Since numerical variables are converted into linguistic variables, mathematical modelling of the system is not required. The fuzzy logic control is being proposed for controlling the inverter action. FLC is a new addition to control theory and it incorporates a simple, rule based IF X AND Y THEN Z approach to a solving control problem rather than attempting to model a system mathematically

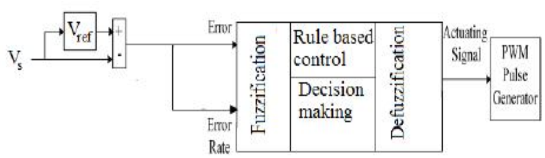

Fig. 6: Block diagram of proposed control system.

A. Error Calculation:

The error is calculated from the difference between supply voltage data and the reference voltage data. The error rate is the rate of change of error.

B. Fuzzification:

Fuzzification is an important concept in the fuzzy logic theory. Fuzzification is the process where the crisp quantities are converted to fuzzy. Thus Fuzzification process may involve assigning membership values for the given crisp quantities. This unit transforms the non-fuzzy (numeric) input variable measurements into the fuzzy set (linguistic) variable that is a clearly defined boundary, without a crisp (answer). In this simulation study, the error and error rate are defined by linguistic variables such as negative big (NB), negative medium (NM), negative small (NM), zero (Z), positive small (PS), positive medium (PM) and positive big (PB) characterized by membership functions given in Fig. 6.

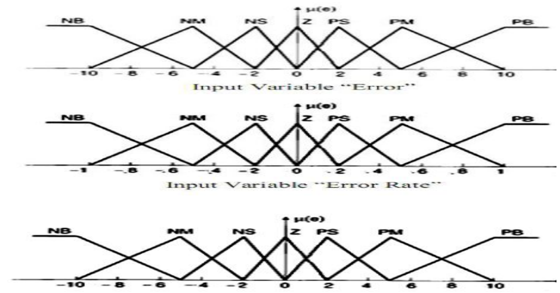

Fig. 7: Membership functions for inputs and output

C. Decision Making:

Fuzzy process is realized by Mamdani method. Mamdani inference method has been used because it can easily obtain the relationship between its inputs and output [11]. The set of rules for fuzzy controller are represented in Table II. There are 49 rules for fuzzy controller. The output membership function for each rule is given by the Min (minimum) operator. The Max operator is used to get the combined fuzzy output from the set of outputs of Min operator .The output is produced by the fuzzy sets and fuzzy logic operations by evaluating all the rules. A simple if-then rule is defined as follows: If error is Z and error rate is Z then output is Z.

Table I

Ce\e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NM	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PM	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PM	PM	PB	PB	PB

D. Defuzzification:

It is the process of converting the controller outputs in linguistic labels represented by fuzzy set to real control (analog) signals. Defuzzification means the fuzzy to crisp conversions. The fuzzy results generated cannot be used as such to the applications, hence it is necessary to convert the

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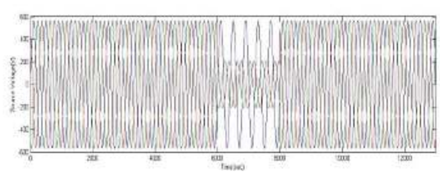
fuzzy quantities into crisp quantities for further processing. This can be achieved by using Defuzzification process. Centroid method is used for Defuzzification in the present studies.

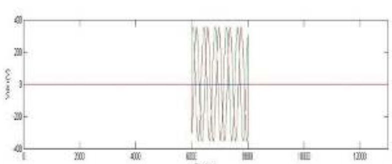
E. Signal Processing:

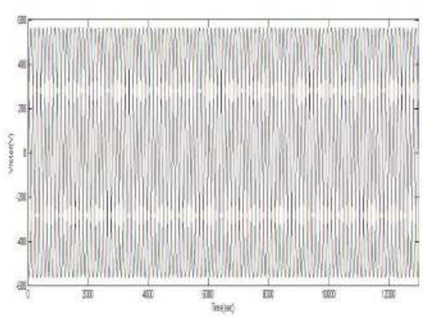
The outputs of FLC process are the control signals that are used in generation of switching signals of the PWM inverter by comparing with a carrier signal.

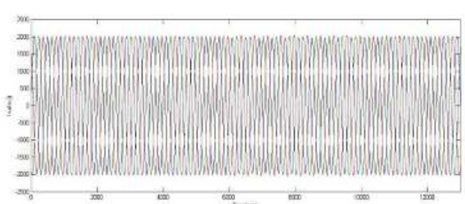
SIMULATION RESULTS

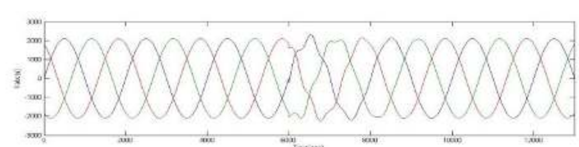
To show the effectiveness of the proposed technique, simulations have been performed using MATLAB/Simulink for a 2 -MW DFIG wind turbine system and a DVR, as shown in Fig. 1. The simulation parameters are given in Table II. The control structure, as shown in Fig. 2, is implemented in Simulink, while all power electronic components are modelled in Matlab. The system performance of the DFIG is shown in Fig. 8, protected by the conventional passive crowbar, and in Fig. 9, protected by the DVR during a two-phase 37 % voltage dip of 100 ms duration [see Figs. 8(a) and 9 (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 over currents IRSC [see Fig.8(e) and (f)]. When the voltage level has been re-established and transients have decayed, the crowbar can be deactivated, which is not shown here. 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 cannot be provided during the voltage dip [see Fig. 8(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 over speed. The DVR is not activated in the simulations, as shown in Fig. 8. When the wind turbine system is protected by the DVR, as shown in Fig. 8, the voltage dip can almost be compensated [see Fig. 9(c)]. The DFIG response is much less critical, which means that lower stator over currents and rotor over currents are produced so that the crowbar does not have to be triggered [see Fig. 9(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. 9(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.

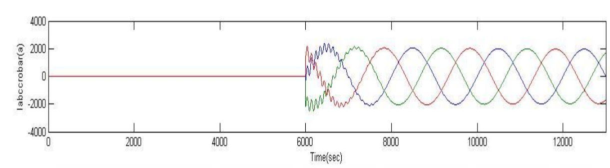


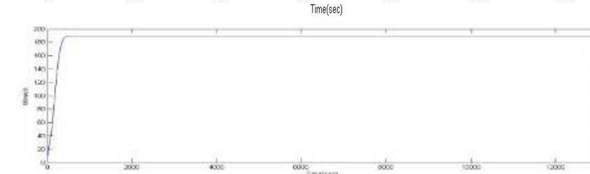












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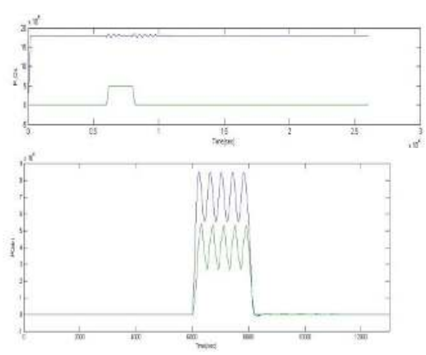
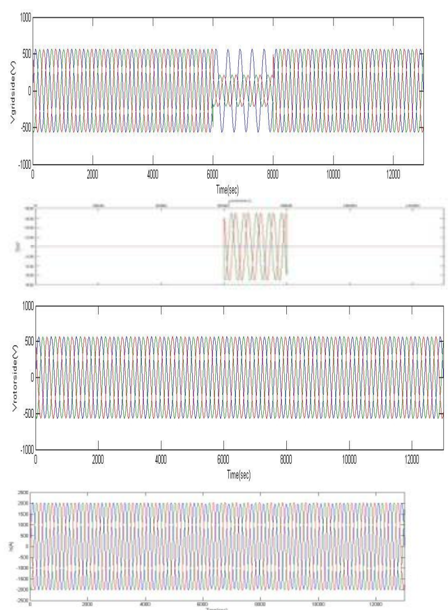


Fig 8:Simulation of DFIG performance with crowbar protection during 37 % two-phase voltage dip. (a) Line voltage. (b) DVR voltage. (c) Stator voltage. (d) Stator current. (e) RSC current. (f) Crowbar current. (g) Mechanical speed. (h) Active and reactive stator power. (i) Active and reactive DVR power.



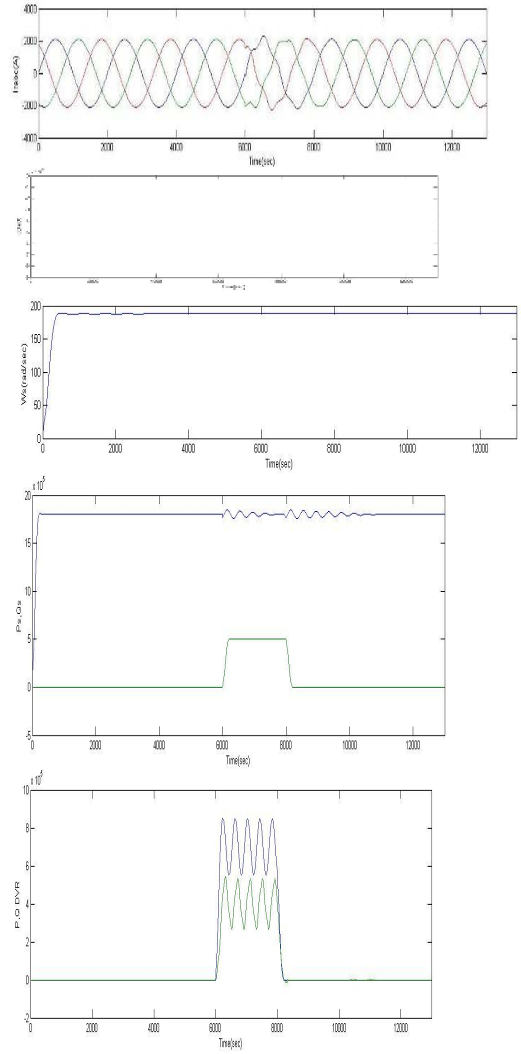


Fig 9:Simulation of DFIG performance with DVR protection during 37 % two-phase voltage dip. (a) Line voltage. (b) DVR voltage. (c) Stator voltage. (d) Stator current. (e) RSC current. (f) Crowbar current. (g) Mechanical speed. (h) Active and reactive stator power. (i) Active and reactive DVR power.

TABLE II
SIMULATION 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	
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

CONCLUSION

This paper has presented an analysis and improved control of a wind-turbine-driven DFIG operating under distorted grid voltage conditions. Simulated studies on a 2 MW DFIG wind power generation system are carried out using fuzzy logic based control of DVR to eliminate voltage sag and to maintain power quality. We can observe from the results that fuzzy logic controller can able to compensate the harmonics in the dc system and has the ability to compensate the harmonics in the system and we can also conclude that wind dfig is able to withstand to fault conditions and further extension can be done using neural network and simulation results shows the effectiveness of comparison of DFIG performance using crowbar and DVR protection.

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