International Journal on Recent and Innovation Trends in Computing and Communication ISSN: 2321-8169
Volume: 3 Issue: 12 6679 - 6685

Voltage Sag Compensation by DVR for DFIG Wind Turbine System

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Abstract – This paper describes the dynamic voltage restorer for maintaining the grid codes to be followed by the doubly fed induction wind turbine system. Because of extended power handling properties of power electronics devices, it is been used widely in the Electrical Devices. The extensive usage of power electronic devices has raised the problem of power quality issues, resulting into the problem of voltage sag/swell etc. The system to be designed will face the problems of voltage sag/swell & will keep the system healthy throughout the symmetrical & unsymmetrical fault conditions. This will also avoid the nuisance tripping of highly sensitive relays & will also maintain synchronism of power system. The use of doubly fed induction generation system is done to maintain the constant voltage to frequency output irrespective of wind velocity.

Keywords – *Voltage Stability, Doubly fed induction generation, dynamic voltage restorer, DVR control.*

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I. Introduction

The recent trends in technology has invented many sophisticated electrical and electronic equipments, such as computers, programmable logic controllers and variable speed drives, which are non-linear loads and are very sensitive to disturbances. The use of recent power electronics devices create power quality problems like voltage sags, swells and harmonics and the purity of sine waveform is lost. Voltage sags are considered to be one of the most severe disturbances to the industrial equipments [1-3].

Power systems, ideally, are bound to provide their customer with an uninterrupted power flow at smooth sinusoidal voltage at the contracted magnitude level and frequency. A momentary disturbance for sensitive electronic devices causes voltage reduction at load end leading to frequency deviations which results in interrupted power flow, scrambled data, nuisance tripping, unexpected plant shutdowns and equipment failure. Voltage lift up at a load can be achieved by reactive power injection at the load point of common coupling (PCC) [4-7].

Use of Dynamic Voltage Restorer (DVR) is an electronic solution to the voltage regulation. DVRs are custom power devices for providing reliable power quality. It has a series of voltage boost technology using solid state switches for compensating voltage sags/swells [8]. The DVR applications are mainly for sensitive loads that may be drastically affected by fluctuations in system voltage level.

The doubly fed induction generation (DFIG) system helps to improve the performance of the power generation system during variable wind velocities [9].

II. Doubly Fed Induction Generation System

The DFIG wind turbine is the wound rotor Induction Generator. The rotor has three phase windings supplied with line supply as feedback. It is useful for generation of electric power during variable wind speeds giving out const voltage & frequency output. The system is so constructed that it has Stator Side Converter (Line Side Converter) & Rotor Side Converter, as shown in fig. 1. The speed of the rotor is always varying depending upon the wind velocity, so if speed is below the rated, then the supply frequency of rotor winding is varied to maintain the constant frequency & output voltage. This special supply arrangement gives us the fulfilment of the grid codes [7].

When DFIG is interconnected to the grid; it has to maintain the certain grid codes so as to be in synchronism with the grid. This can be achieved by the proper triggering of power electronics switches.

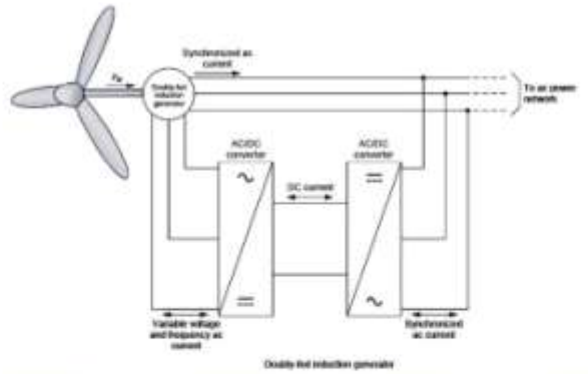


Fig.1 DFIG wind turbine block representation

For DFIG system the output frequency control is done as per the following expression,

$$f_{stator} = \frac{n_{rotor}}{120} \times P + f_{rotor} \quad (1)$$

So, in order to maintain the synchronism of system with the grid, we supply the rotor with the AC supply as per following expression,

$$f_{stator} = \frac{n_{rotor}}{120} \times P - f_{rotor} \quad (2)$$

The construction of DFIG system consists of rotor with the converter unit that is nothing but the back to back connection of the converters separated by the DC link & the capacitor unit so that to reduce the harmonic component produced by the converters.

As the voltage disturbance last for the short duration & there is no any arrangement of increase in the turbine input, which is air, the system should ride through that condition

A. Rotor Voltage Dynamics

As far as rotor voltage dynamic is concerned the main focus comes on the voltage & frequency that is given to the rotor.

Let us consider the equivalent per phase circuit of DFIG stator circuit, the expression for the voltage is given as follows:

$$v_s = R_s i_s + \frac{d\phi_s}{dt} \quad (3)$$

$$v_r = R_r i_r + \frac{d\phi_r}{dt} - jf\phi_r \quad (4)$$

$$\phi_s = L_s i_s + L_h i_r. \quad (5)$$

$$\phi_s = L_r i_r + L_h i_s. \quad (6)$$

Where ϕ, v,i represent the flux, voltage & current respectively. Subscript s & r denote the stator & rotor respectively.

$L_s = L_{s\sigma} + L_h$ & $L_r = L_{r\sigma} + L_h$ represent stator & rotor inductances R_s & R_r are the stator & rotor resistances & f is the electrical rotor frequency.

By introducing the leakage factor $\sigma = 1 - (L_h^2 / L_s L_r)$ the rotor flux can be described in dependence of rotor current & stator flux

$$\phi_r = \frac{L_h}{L_s}\phi_s + \sigma L_r i_r \quad (7)$$

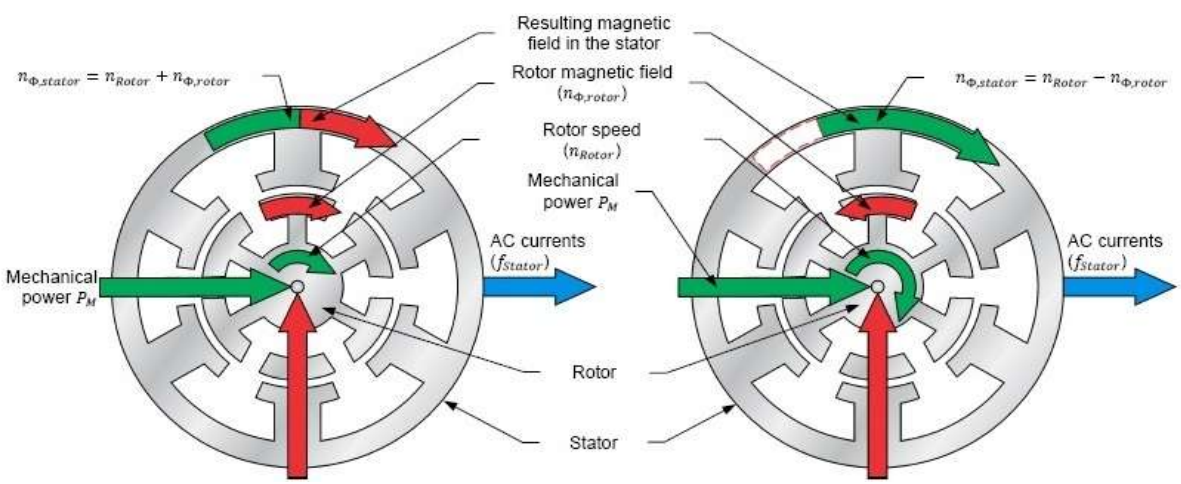


Fig.2 DFIG wind turbine rotating magnetic field representation

By substituting (5) in (2) equation for the rotor voltage can be obtained as follows

$$v_r = \frac{L_h}{L_s}\left(\frac{d}{dt} - jf\right)\phi_s + \left(R_r + \sigma L_r\left(\frac{d}{dt} - jf\right)\right)i_r \quad (8)$$

The expression shows the rotor induced voltage that depends upon the magnitude of the flux of the stator & the rotor induced currents.

B. Rotor Side Converter Control (RSC)

This rotor side converter unit acts as controller to control the amount of active & reactive power flow from the stator. The system is so designed to have stator voltage oriented control, for that purpose, the decomposition in *d* & *q* components is done. i.e. (V_{sq}=0)

Neglecting the stator voltage drop, the stator output active & reactive powers can be expressed as,

$$P_s \approx \frac{3L_h}{2L_s} V_{sd} I_{rd} \quad (9)$$

$$Q_s \approx -\frac{3V_{sd}}{2L_s}\left(\frac{V_{sd}}{\omega_s} + L_h I_{rq}\right) \quad (10)$$

Thus the active & reactive power flow can be controlled with the control on *d* & *q* components of the rotor.

C. Line Side Converter Control (LSC)

The main feature of the line side control is that it provides the required DC voltage V_{dc} along with the reactive power back up to the system. A voltage oriented cascade vector control is shown in the fig. 2. The line current I_l can be controlled by the adjustment of the line inductance L_l as shown below

$$V_s = R_l I_l + L_l \frac{dI_l}{dt} \quad (11)$$

The equation (9) is used to design the current controller, while DC dynamics can be expressed by following expression,

$$C_{dc}\frac{dV_{dc}}{dt} = I_{dc} - I_{load} \quad (12)$$

Where C_{dc} is the DC capacitance while I_{dc} & I_{load} are the DC currents of LSC & RSC respectively.

III. DYNAMIC VOLTAGE RESTORER (DVR)

Dynamic Voltage Restorer is a static VAR device having a voltage source converter along with energy storage device. This is a series compensation device that protects the sensitive electrical loads from the power quality problems like voltage sag, voltage swell, voltage unbalance & distortion. A boosting transformer is used in series to inject the exact amount of voltage to restore the voltage of the load to normal operating value & also performs the function of correction of deteriorated line voltage [10].

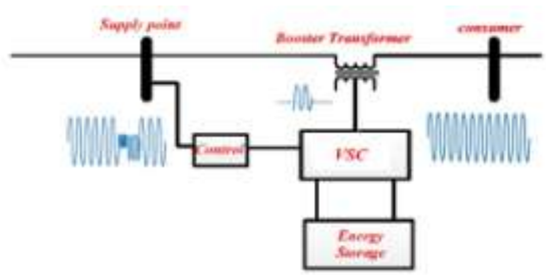


Fig.3 DVR block diagram

Generally the solid state electronic switches are used in pulse width modulation structure. DVR can supply or absorb independently controllable real & reactive power at the load side [11]. In other words, DVR is made up of solid state DC to AC switching power converter that injects a set of three phase AC output voltage line voltages in series & synchronism. The general configuration of DVR consists of following blocks as shown in fig. 3.

A. Injection Transformer/ Boosting Transformer

This transformer is a special purpose transformer that attempts to limit the coupling of noise & transient energy from the primary side to the secondary side. The HV winding of the transformer is connected to the power system that injects the compensating voltages generated by voltage source converter in the transmission line. This transformer must have the higher rating to avoid saturation effects & high inrush current protection.

B. Harmonic Filter

The use of harmonic filter provides the filtration from the distorted waveforms coming out of semiconductor devices present inside the DVR itself. So if Harmonic Filter is not connected in series with DVR, it may add some harmonics in the system instead of removing it.

C. Voltage Source Converter

This is a power electronic switching cum storage device which generates the sinusoidal voltage at required frequency, amplitude & phase angle. The scheme used for voltage generation is PWM technique. It is used for conversion of the DC voltage into sinusoidal AC voltage. It is also possess the control mechanisms so as to have precise control over the energy sent to the network.

D. Control System/ Energy Storage Device

The control system consists of energy storing devices such as DC capacitors, batteries, super capacitors, superconducting magnetic storage device etc. These devices store the energy & supply it with the exact required amount so as to bridge up the gap of voltage Sag/Swell with the reference.

IV. Voltage Injection Methods

The rating of the DVR system depends mainly on the depth of the fault voltage that is to be compensated [12]. For voltage sag & swells with zero phase angle jump, the requirement of active power of the DVR is given by

$$P_{DVR} = \left(\frac{V_1 - V_2}{V_1}\right) P_{load} \quad (13)$$

Where V_1 & V_2 are normal & faulty line voltages respectively. The faults having phase angle jump along with the voltage variation, the active power flowing into DVR charges the DC link. For full compensation of full voltage dip, the rating of the DVR must be as same as that of the DFIG.
There are four voltage injection methods that are normally used as follows.

A. Pre Sag Compensation

This method is constant tracking method, here the supply voltage is consistently kept comparing with the reference set point & if any disturbance in supply voltage is detected, the differential voltage that is equal to difference of the supply voltages & sag voltage is injected, so that the load voltage is restored back as that of pre fault voltage, as shown in fig. 4

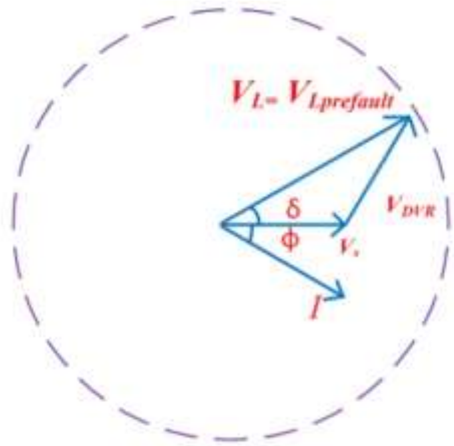


Fig.4 Pre Sag Compensation

Compensation in both phase angle & amplitude sensitive loads is achieved. The amount of voltage fed to the system is determined by following expression

$$V_{DVR} = V_{prefault} - V_{sag} \quad (14)$$

B. In Phase Compensation Method

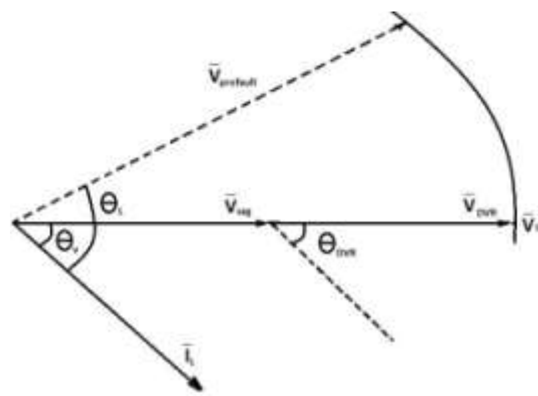


Fig.5 In Phase Compensation Method

The voltage that is to be injected is in phase with the supply voltage irrespective of the pre sag value. By this method the constant amplitude of the load voltage is maintained. The advantage with this method is that, the magnitude of DVR injection voltage is less for the voltage sag condition, as compared with other strategies, as shown in fig. 5

C. In Phase Advanced Compensation

In previous two methods, the active power is injected into system during disturbances where as this method is based on the phase angle compensation. The phase angle of voltage sag & the load current is minimized to control the real power supplied. The active power supplied by the

The energy of DVR is stored in DC link. The values of load current & voltages are fixed the change is done in only phase angle of the voltage sag. It has drawback that, not all voltage sags are mitigated by this system hence it is suitable for only limited range of voltage sags.

D. Voltage Tolerance Method With Minimum Energy Injection

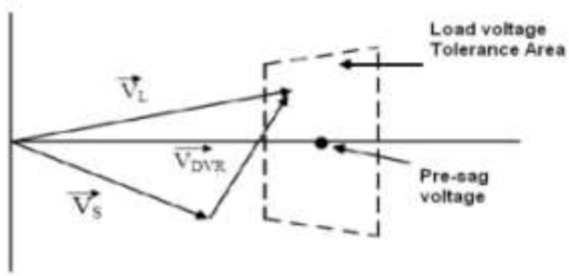


Fig.6 Voltage Tolerance Method

There always exists some tolerable limit in the system. Similarly, small amount of voltage drop & phase angle jump is allowable in the system. If the voltage magnitude lies in between the range of 90-110% of nominal voltage & 5-10% of nominal state that will not affect the performance characteristics of the load [5]. Hence both magnitude & phase are the control parameters, which can be achieved by this method of small energy injection. That means this method of operation of DVR is to control the voltage up to some desired accepted value so that the system will not change the load performance characteristics, as shown in the fig. 6.

V. DVR CONTROL

For the operation of DVR closed loop control in stationary frame reference *d-q* frame is done. This technique provides good positive & negative sequence voltage regulation [7]. This cascade control scheme uses current controllers for DFIG windings & voltage controllers for DVR, as shown in fig. 7.
Transfer function expressed in terms of inverter voltage reference is given by,

$$u_i^*(s) = u_c(s) + G_{P+Res}(s) \cdot (u_c^*(s) - u_c(s)) \quad (15)$$

Where, $u_i^*(s)$ is inverter voltage reference
$u_c(s)$ is the measured filter capacitor voltage &
$u_c^*(s)$ is the reference filter capacitor voltage.
The transfer function of P+Res voltage controller is defined as,

$$G_{P+Res}(s) = K_P + K_I\left(\frac{s}{s^2+\omega_0^2}\right) \quad (16)$$

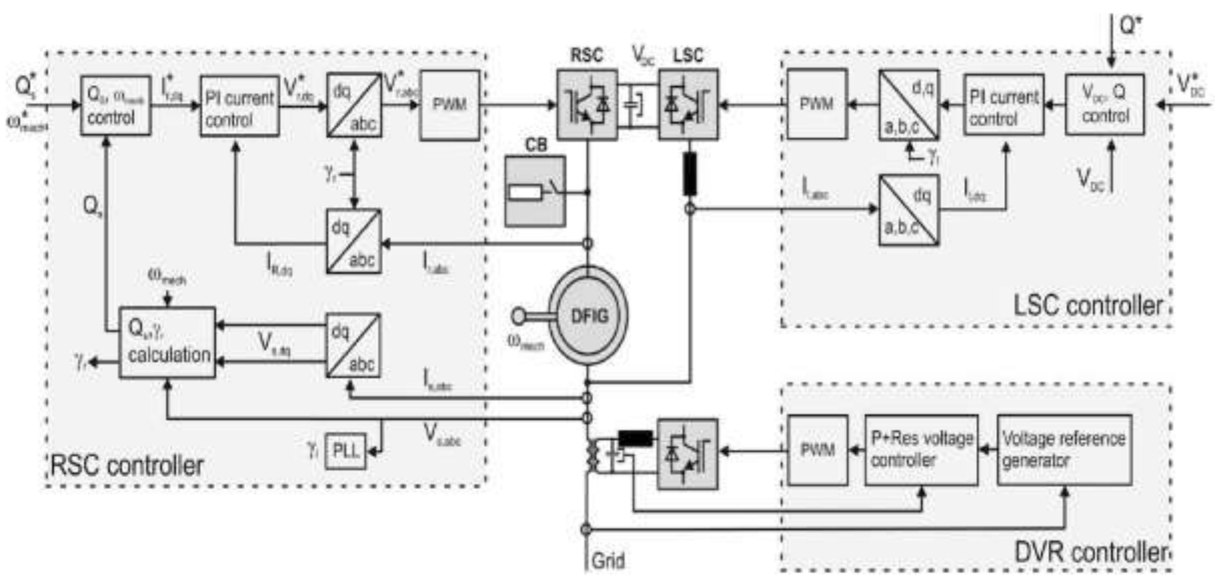
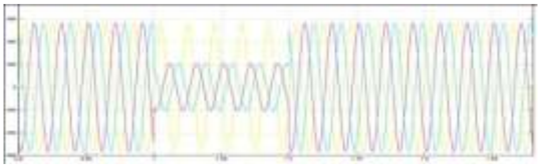
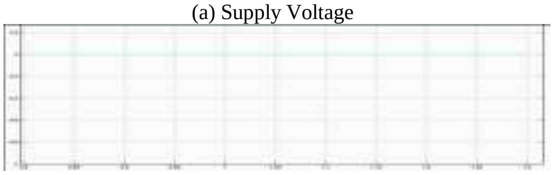


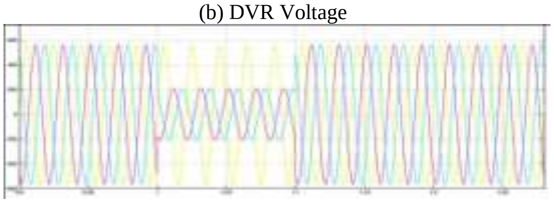
Fig. 7 Control Structure of DFIG & DVR system



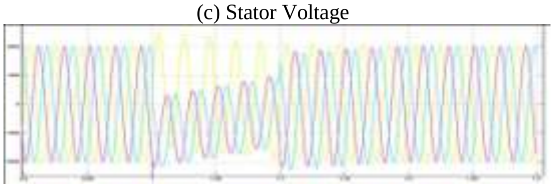
(a) Supply Voltage



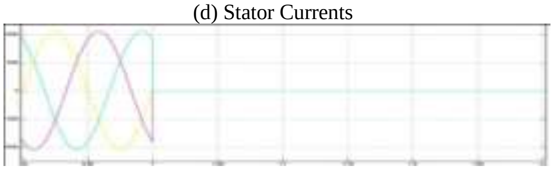
(b) DVR Voltage



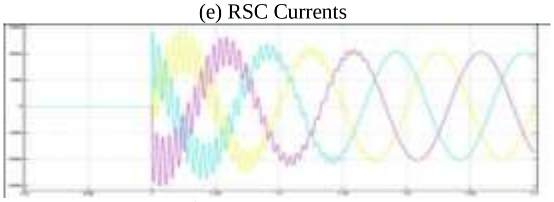
(c) Stator Voltage



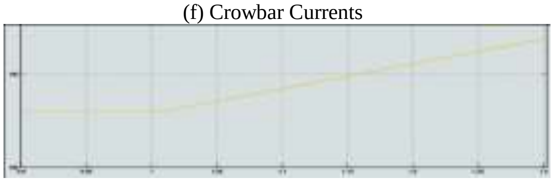
(d) Stator Currents



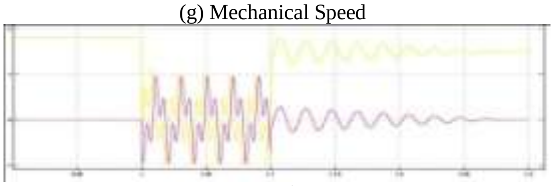
(e) RSC Currents



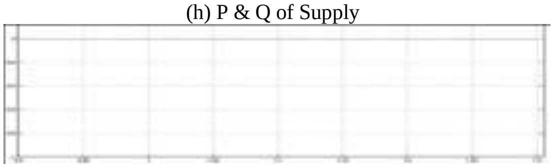
(f) Crowbar Currents



(g) Mechanical Speed

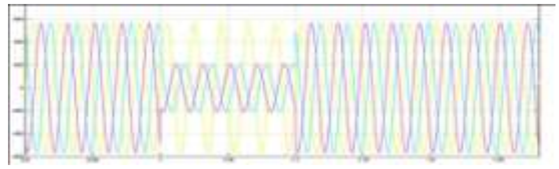


(h) P & Q of Supply

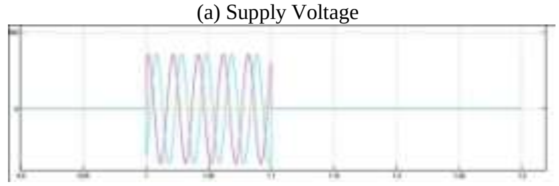


(i) P & Q of DVR

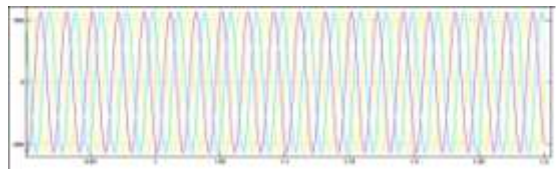
Fig. 8 Simulation results with active Crowbar in network



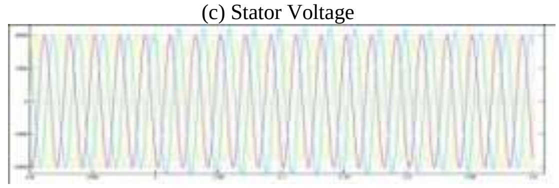
(a) Supply Voltage



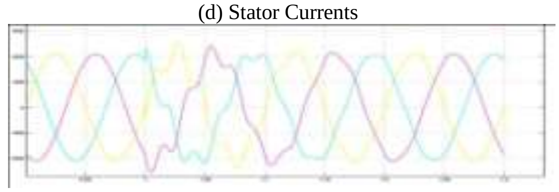
(b) DVR Voltage



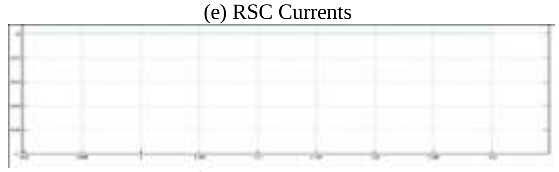
(c) Stator Voltage



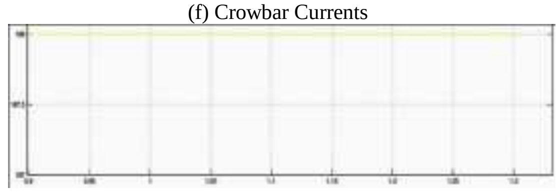
(d) Stator Currents



(e) RSC Currents

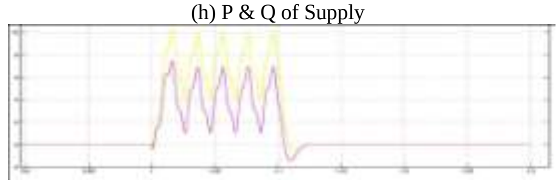


(f) Crowbar Currents



(g) Mechanical Speed

(h) P & Q of Supply



(i) P & Q of DVR

Fig. 9 Simulation results with active DVR in network

VI. SIMULATION RESULTS

The performance of this system is analysed by the MATLAB/Simulink. The use of 2MW Wind turbine system is done for the simulation purpose. Fig. 8 describes the simulation results of the DFIG system with the active operation of Crowbars, while fig. 9 describes the simulation results of DFIG system with active DVR operation.

Fig. 8 (a) & 9 (a) shows the supply voltages, in the both cases, voltage sag has occurred. When crowbar protection is considered, the voltage sag appears as it in the stator voltage output. Voltage sag gives rise to the increased current circulation from the RSC, thus tripping the RSC. At the instant, crowbar is switched, the control triggering of the RSC is deactivated.

Fig. 8 (f) describes the operation of crowbars, at that time DFIG acts like squirrel cage rotor. Disabling of RSC fails to supply the required amount of reactive power; hence acceleration of rotor takes place. Ultimately, the Grid Codes are not satisfied.

Where as, when DVR protection is considered, the DVR injects the required amount of voltage in the form of reactive power injection, satisfying the required grid codes, in terms of voltage limits along with maintaining speed of rotor constant & successfully riding the system through fault.

VII. CONCLUSION

The paper focuses on the fault ride through operation of DFIG wind system during voltage sag. The DVR is proven effective device for enhancing the voltage stability of this system. It supplies the required amount of reactive power to the system so as to maintain the parameters in the limit which are required to satisfy the grid codes. The use of DFIG wind turbine system provides precise control over the voltage & frequency irrespective of the wind speed as compared to the conventional wind turbine. DVR can be employed to the existing wind turbines to develop the fault ride through capabilities.

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