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Behavior of DFIG Based Wind Energy Conversion System Due to Short Circuit of DC-Link Capacitor

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ABSTRACT

The aim of this paper is to present the complete modelling and simulation of wind turbine driven doubly fed induction generator which feeds AC power to the utility grid. For that, two pulse width modulated voltage source converters are connected back-to-back between the rotor terminals and utility grid via common DC-link. The grid side converter controls the power flow between the DC-bus and the AC-side and allows the system to be operated in sub-synchronous and super-synchronous mode of operation. Here, the effect of DC-link electrolytic capacitor malfunction of DFIG based wind energy conversion system (WECS) is investigated. The degradation of electrolytic capacitor can lead to the malfunction of DC-link. As DFIG based WECS utilize low power converter, so there is a requirement to investigate the effects of capacitor short circuit. This breakdown (short circuit of capacitor) leads to the power ullage, high machine currents, high transient currents in rotor circuit, low terminal voltage of the generator and increase in generator speed. All these scenarios have been simulated with the help of the simulation program using MATLAB and its inbuilt components provided in SIMULINK library to study the effects of DC-link capacitor short circuit on different parameters of system.

Keywords : Doubly Fed Induction Generator (DFIG), Wind Energy Conversion System (WECS), Stator Voltage Oriented Control (SVOC)**,** Grid Side Converter (GSC), Rotor Side Converter (RSC).

I. INTRODUCTION

Doubly fed induction generator vindicate itself as one of the successful generator technology for wind energy conversion system due to its compensation of reactive power and variable speed operation along with low power rating of converter. These power converters usually consist of DC-link capacitors as energy storage. Electrolytic type capacitors are preferred due to their large storage capability & low cost. These capacitors are less reliable, temperature and frequency sensitive. The age of electrolytic capacitor is usually shorter than the other components of the converter. Reference [3] reported that 72% of the power supplies failures were due to electrolytic capacitor malfunction. If their capacitance is decreased by more than 25% [4] with the passage of time then capacitor is said to be over. It has been reported in many researches that electrolytic capacitors are the weakest link in power electronic converters [5]. The breakdown of DC-link electrolytic capacitor can lead to either short circuit (SC) or open circuit (OC) of DC-link while remaining the converters is unaffected. The capacitor degradation is due to the effects of temperature, mechanical, environmental stresses and electrical and there can be any cause of its breakdown. There a need to cram the effects of breakdown of DC-link electrolytic [5]. As the DC-linked capacitor converters are installed inside the systems, so they make it difficult to detach the component and measure the degradation of the capacitor. Also it is very difficult to monitor manually of off-shore or on-shore wind turbines having high towers. This paper deals with the study of results of DC-link electrolytic capacitor failure on the DFIG system. High and comparatively low power converters are widely used in DFIG, permanent magnet synchronous generator or induction generator based wind energy conversion systems.

II. WIND ENERGY SYSTEM MODEL

a. Aerodynamic Model of the Wind Turbine

Wind power is dragged through wind turbine blades and then transferred through a mechanical coupling and the rotor hub to the mechanical energy. The shaft drives the generator to convert the mechanical energy to electrical. The turbine model is based on the output power characteristics.

$$P_m = C_p(\lambda, \beta).\frac{1}{2}\rho A v_w^3 \quad (1)$$

$$\lambda = (R_{blade}\omega_r)/v_w \quad (2)$$

Where P_m is the mechanical output power in watt, which depends on performance coefficient C_p, air density ρ, turbine swept area A and wind speed v_w. $\frac{1}{2}\rho A v_w^3$ is equal to the kinetic energy contained in the wind at particular speed v_w. The performance coefficient C_p (λ, β), which depends on tip speed ratio λ and blade pitch angle β, determines how much of the wind kinetic energy can be captured by the wind turbine system.

A nonlinear model describes C_p (λ, β) as:

$$c_p(\lambda, \beta) = c_1(c_2 - c_3\beta - c_4\beta^2 - c_5)e^{-c_6} \quad (3)$$

Where, c_1=0.5, c_2=116/ λi, c_3=0.4, c_4=0, c_5=5, c_6=21/ λi,

$$\frac{1}{\lambda i} = \frac{1}{\lambda + 0.08\,\beta} - \frac{0.035}{\beta^3 + 1} \quad (4)$$

There is an optimum value of λ that leads to maximum power coefficient Cp_{max} .The maximum theoretical value of Cp is approximately 0.59.

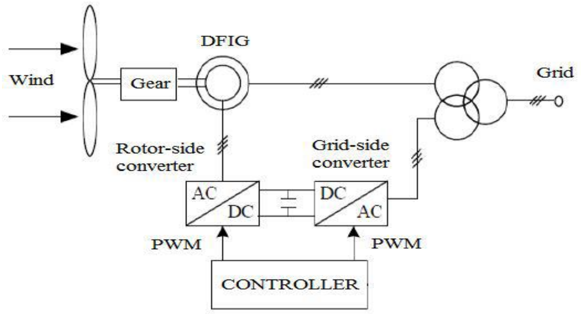

Figure 1. Basic configuration of DFIG wind turbine

b. Modelling of DFIG - dq Reference Frame Model

The dq-axis model of the induction generator can be obtained by decomposing the space-vectors into their corresponding *d*- and q-axis components, that is, Space-vector models for induction generator in the synchronous and stationary reference frames

$$\vec{v_s} = v_{ds} + jv_{qs};\ \vec{i_s} = i_{ds} + ji_{qs};\ \vec{\lambda_s} = \lambda_{ds} + j\lambda_{qs} \quad (5)$$

$$\vec{v_r} = v_{dr} + jv_{qr};\ \vec{i_r} = i_{dr} + ji_{qr};\ \vec{\lambda_r} = \lambda_{dr} + j\lambda_{qr} \quad (6)$$

The dq-axis voltage equations for the induction generator are

$$v_{ds} = R_s i_{ds} + p\lambda_{ds} - \omega\lambda_{qs} \quad (7)$$

$$v_{qs} = R_s i_{qs} + p\lambda_{qs} + \omega\lambda_{ds} \quad (8)$$

$$v_{dr} = R_r i_{dr} + p\lambda_{dr} - (\omega - \omega_r)\lambda_{qr} \quad (9)$$

$$v_{qr} = R_r i_{qr} + p\lambda_{qr} + (\omega - \omega_r)\lambda_{dr} \quad (10)$$

Similarly, substituting the equations, the dq-axis flux linkages are obtained

$$\lambda_{ds} = (L_{ls} + L_m)i_{ds} + L_m i_{dr} = L_s i_{ds} + L_m i_{dr} \quad (11)$$

$$\lambda_{qs} = (L_{ls} + L_m)i_{qs} + L_m i_{qr} = L_s i_{qs} + L_m i_{qr} \quad (12)$$

$$\lambda_{dr} = (L_{lr} + L_m)i_{dr} + L_m i_{ds} = L_r i_{dr} + L_m i_{ds} \quad (13)$$

$$\lambda_{qr} = (L_{lr} + L_m)i_{qr} + L_m i_{qs} = L_r i_{qr} + L_m i_{qs} \quad (14)$$

The electromagnetic torque *Te* in Equation (15) can be expressed by dq-axis flux linkages and currents as well. By mathematical manipulations, several expressions for the torque can be obtained. The most commonly used expressions are given by

$$T_e = \begin{cases} \frac{3P}{2}\left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}\right) \\ \frac{3PL_m}{2}\left(i_{qs}i_{dr} - i_{ds}i_{qr}\right) \\ \frac{3PL_m}{2L_r}\left(i_{qs}\lambda_{dr} - i_{ds}\lambda_{qr}\right) \end{cases} \quad (15)$$

Equations (11) to (14) together with the motion Equation (15) represent the dq-axis model of the induction generator in the arbitrary reference frame. To obtain the dq-axis model in the synchronous and stationary reference frames, the speed of the arbitrary reference frame *w* can be set to the synchronous (stator) frequency ω_s of the generator and zero, respectively.

c. Stator Voltage Oriented Control

In DFIG wind energy systems, the stator of the generator is directly connected to the grid, and its voltage and frequency can be considered constant under the normal operating conditions. It is, therefore, convenient to use stator voltage oriented control (SVOC) for the DFIG. The stator voltage oriented control is achieved by aligning the d-axis of the synchronous reference frame with the stator voltage vector $\vec{v_s}$. The resultant d- and q-axis stator voltages are:

$$v_{qs} = 0\ \&\ v_{ds} = v_s$$

Where v_s is the magnitude of $\vec{v_s}$, (also the peak value of the three-phase stator voltage).

The rotating speed of the synchronous reference frame is given by

$$\omega_s = 2\pi f_s \tag{16}$$

where f_s is the stator frequency of the generator (also the frequency of the grid voltage). The stator voltage vector angle θ_s is referenced to the stator frame, which varies from zero to 2π when $\overrightarrow{v_s}$ rotates one revolution in space. The rotor rotates at speed ω_r. The rotor position angle θ_r is also referenced to the stator frame. The angle between the stator voltage vector and the rotor is the slip angle, defined by

$$\theta_{sl} = \theta_s - \theta_r \tag{17}$$

The DFIG operates with unity power factor, the stator current vector $\overrightarrow{\iota_s}$ is aligned $\overrightarrow{v_s}$ with *but* with opposite direction (DFIG in generating mode). The rotor voltage and current vectors, $\overrightarrow{v_s}$ and $\overrightarrow{\iota_s}$, which are controlled by the converters in the rotor circuit, are also given in the diagram. The rotor voltage and current vectors can be resolved into two components along the dq-axes: v_{dr} and v_{qr} for $\overrightarrow{v_r}$ and i_{dr} and i_{qr} for $\overrightarrow{\iota_r}$.

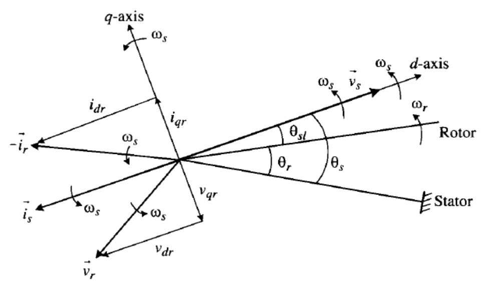

Figure 2. Space-Vector Diagram Of DFIG with SVOC in the Super-Synchronous Mode

These dq-axis components can be controlled independently by the rotor converters. The DFIG wind energy system can be controlled by the electromagnetic torque for speed control or active power. In contrast to the other wind energy systems, the electromagnetic torque *Te* of the generator, the active power P_s and the reactive power Q_s of the stator are controlled by the rotor-side converter. Therefore, it is worthwhile to investigate the controllability of T_e, P_s, and Q_s by the rotor voltage and current. The investigation will also facilitate the analysis of the stator voltage oriented control. The electromagnetic torque of the generator can be expressed as

$$T_e = \frac{3\mathrm{P}}{2}\left(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}\right) \tag{18}$$

where λ_{ds} and λ_{qs} are the dq-axis stator flux linkages, given by

$$\begin{cases}\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \\ \lambda_{qs} = L_s i_{qs} + L_m i_{qr}\end{cases} \tag{19}$$

from which the dq-axis stator currents are calculated to

$$\begin{cases} i_{ds} = \frac{\lambda_{ds} - L_m i_{dr}}{L_s} \\ i_{qs} = \frac{\lambda_{qs} - L_m i_{qr}}{L_s}\end{cases} \tag{20}$$

Substituting Equation (20) into (18)

$$T_e = \frac{3PL_m}{2L_s}(-i_{qr}\lambda_{ds} + i_{dr}\lambda_{qs}) \tag{21}$$

Referring to the induction generator model, the stator voltage vector for the steady-state operation of the generator is

$$\overrightarrow{v_s} = R_s\overrightarrow{\iota_s} + j\omega_s\overrightarrow{\lambda_s} \tag{22}$$

the representation in dq-axis is

$$\left(v_{ds} + jv_{qs}\right) = R_s\left(i_{ds} + ji_{qs}\right) + j\omega_s\left(\lambda_{ds} + j\lambda_{qs}\right) \tag{23}$$

from which the dq-axis stator flux linkages are

$$\begin{cases}\lambda_{ds} = \frac{v_{qs} - R_s i_{qs}}{\omega_s} \\ \lambda_{ds} = \frac{v_{qs} - R_s i_{qs}}{\omega_s}\end{cases} \tag{24}$$

substituting Equation (24) into (21) with $v_{qs} = 0$ for the stator voltage orientation control, the torque equation can be simplified to

$$T_e = \frac{3PL_m}{2\omega_s L_s}(R_s i_{qs} i_{qr} + R_s i_{ds} i_{dr} - i_{dr} v_{ds}) \tag{25}$$

Ignoring the stator resistance from the above equation the electromagnetic torque is a function of d-axis rotor current and stator voltage. The stator active and reactive power can be calculated by

$$\begin{cases} P_s = \frac{3}{2}(v_{ds}i_{ds} + v_{qs}i_{qs}) \\ Q_s = \frac{3}{2}(v_{qs}i_{ds} - v_{qs}i_{qs})\end{cases} \tag{26}$$

Using the stator voltage oriented control ($v_{qs} = 0$, the above equation can be simplified to

$$\begin{cases} P_s = \frac{3}{2}v_{ds}\left[\frac{\lambda_{ds} - L_m i_{dr}}{L_s}\right] \\ Q_s = -\frac{3}{2}v_{ds}\left[\frac{\lambda_{qs} - L_m i_{qr}}{L_s}\right]\end{cases} \tag{27}$$

$$\begin{cases} i_{dr} = -\frac{2L_s}{3v_{ds}L_m}P_s \\ i_{qr} = -\frac{2L_s}{3v_{ds}L_m}Q_s - \frac{v_{ds}}{\omega_s L_m}\end{cases} \tag{28}$$

The above equations indicate that for a given stator voltage, the stator active power P_s and reactive power Q_s can be controlled by the dq-axis rotor currents.

d. Control Strategy for Grid Side Converter

The grid-connected inverter can be controlled with various schemes. One of the schemes is known as voltage oriented control (VOC). To realize the VOC, the grid voltage is measured and its angle θ_g is detected for the voltage orientation. This angle is used for the transformation of variables from the abc stationary frame to the d-q synchronous frame through the abc/dq transformation or from the synchronous frame back to the stationary frame through the dq/abc transformation.

In the voltage orientation control, the grid voltage is measured and its angle θ_g is detected for the voltage orientation. Assuming that the grid voltage v_{ag}, v_{bg}, and v_{cg} are three phase balanced sinusoidal waveforms, θ_g can be obtained by

$$\theta_g = \tan^{-1}\frac{v_\beta}{v_\alpha} \quad (29)$$

Where ,

$$v_\alpha = \frac{2}{3}\left(v_{ag} - \frac{1}{2}v_{bg} - \frac{1}{2}v_{cg}\right) = v_{ag} \quad (30)$$

$$v_\beta = \frac{2}{3}\left(\frac{\sqrt{3}}{2}v_{bg} - \frac{\sqrt{3}}{2}v_{cg}\right) = \frac{\sqrt{3}}{3}\left(v_{ag} + 2v_{bg}\right) \quad (31)$$

For

$$v_{ag} + v_{bg} + v_{cg} = 0 \quad (32)$$

The above equation indicates that there is no need to measure the phase-c grid voltage. In practice, the grid voltage may contain harmonics and be distorted, so digital filters or phase locked loop (PLLs) may be used for the detection of the grid voltage angle θ_g .

To achieve the VOC control scheme, the d-axis of the synchronous frame is aligned with the grid voltage vector, therefore the d-axis grid voltage is equal to its magnitude ($v_{dg} = v_g$) and the resultant q-axis voltage v_{qg} is then equal to zero, from which the active and reactive power of the system can be calculated by

For $v_{qg} = 0$,

$$P_g = \frac{3}{2}\left(v_{dg} i_{dg}\right) \quad (33)$$

$$Q_g = -\frac{3}{2}\left(v_{dg} i_{qg}\right) \quad (34)$$

The q-axis current reference i_{qg}^* can be obtained from

$$i_{qg}^* = \frac{Q_q^*}{-1.5 v_{dg}} \quad (35)$$

Where Q_g^* is the reference for the reactive power, which can be set to zero for unity power factor operation, a negative value for leading power factor operation, or a positive value for lagging power factor operation.

e. Control Strategy for Rotor Side Converter

The main purpose of controlling rotor side converter is to control stator side active and reactive power independently. In order to implement the decoupled control method of active and reactive power, stator flux oriented vector control scheme is adopted. To achieve this stator field oriented scheme, Stator voltage drop across resistance has been neglected as the stator resistance values are quite low in value. The DFIG is connected to stiff grid i.e. the frequency and amplitude of stator and grid voltage is assumed to be constant. The q- axis is rotating 90^0 ahead of d-axis at synchronous speed in the direction of rotation. The stator flux vector is aligned with the d-axis of the stator.

From the SVOC scheme d-axis and q-axis voltages are:

$$v_{qs} = 0 \ \ and \ \ v_{ds} = v_s \quad (36)$$

The angle between the stator voltage vector and the rotor is the slip angle, is defined as:

$$\theta_{sc} = \theta_s - \theta_r \quad (37)$$

The rotor voltage and current is controlled by the converters in the rotor circuit. The DFIG wind energy system can be controlled by the electromagnetic torque speed control or active power. In contrast to the other wind energy system, the electromagnetic torque of the generator, the active power and the reactive power of the stator are controlled by the rotor- side converter.

$$T_e = \frac{3PL_m}{2L_s}\left(-i_{qr}\lambda_{ds} + i_{dr}\lambda_{qs}\right) \quad (38)$$

The above torque equation shows that the T_e is the function of rotor current and stator flux linkages. In this system the stator voltage is constant, since it is directly connected to the grid. To find the relationship between the torque, stator voltage and rotor current referred to the induction generator model. The stator voltage vector for the steady state operation of the generator is-

$$\overrightarrow{v_s} = R_s\overrightarrow{i_s} + j\omega_s\overrightarrow{\lambda_s} \quad (39)$$

It has to represent in d-q-axis is-

$$\left(v_{ds} + jv_{qs}\right) = R_s\left(i_{ds} + ji_{qs}\right) + j\omega_s\left(\lambda_{ds} + j\lambda_{qs}\right) \quad (40)$$

Substituting the value of flux linkage into the electromagnetic torque equation, with $v_{qs} = 0$, for the stator voltage orientated control, and ignoring stator resistance R_s which is normally very low for large DFIG, the torque is simplified

$$T_e = \frac{-3PL_m}{2L_s\omega_s} i_{dr} v_{ds} \quad (41)$$

It can be observed from the above equation that the electromagnetic torque is a function of d-axis rotor current and stator voltage. Using the stator voltage oriented control (v_{qs}= 0), the stator active and reactive power can be calculated

$$\begin{cases} P_s = \frac{3}{2} v_{ds} i_{ds} \\ Q_s = -\frac{3}{2} v_{ds} i_{qs} \end{cases} \text{for} v_{qs} = 0 \quad (42)$$

Substituting the value of current in above equation,

$$\begin{cases} P_s = \frac{3}{2} v_{ds} \left[\frac{\lambda_{ds} - L_m i_{dr}}{L_s}\right] \\ Q_s = -\frac{3}{2} v_{ds} \left[\frac{\lambda_{qs} - L_m i_{qr}}{L_s}\right] \end{cases} \quad (43)$$

The value of active and reactive power in terms of dq-axis rotor current and flux linkages, from which the value of current (neglecting the stator resistance, which is very small) we have

$$\begin{cases} i_{dr} = -\frac{2L_s}{3v_{ds}L_m} P_s \\ i_{qr} = -\frac{2L_s}{3v_{ds}L_m} Q_s - \frac{v_{ds}}{\omega_s L_m} \end{cases} \quad (44)$$

The above equations show that for a given stator voltage, the stator active power *Ps* and reactive power *Qs* can be controlled by the dq-axis rotor currents.

III. DC-LINK CAPACITOR BREAKDOWN

Off-shore or on-shore wind turbines bear unkind environmental conditions. By The application of electrolytic capacitors in DC-link of converter makes it weak to periodic degradation. This degradation of capacitor over the passage of years or loose link may result in short circuit or open circuit of capacitor in the DC-link. If the capacitor is short circuited it will make the DC voltage as zero in the rotor and grid side converter controllers. These controllers depend on Vdc for determining the modulation index for active power, reactive power and DC-link voltage control. In case of DC link short circuit, the GSC will try to charge the capacitor in order to raise the voltage of capacitor; hence it will exchange more power from the grid. On the other hand, the firing sequences of the switches are also dependent upon the DC-link voltage. The modulation indices of rotor side convertor and grid side convertors are determined by taking into account the DC-link voltage. Equation (45) gives the relation that is used for determining the modulation indices of RSC and GSC.

$$m = \frac{1.633 * Vab}{Vdc} \quad (45)$$

From above equation, the converters will try to achieve maximum modulation indices. This will create the fluctuating DC-link voltage in which grid side converter will try to stable the DC-link voltage and rotor side converter will try to generate the sequence for controlling the torque. This breakdown (short circuit of capacitor) leads to the power ullage, high machine currents, high transient currents in rotor circuit, low terminal voltage of the generator and increase in generator speed.

IV. Performance Analysis of DFIG during Short Circuit of DC-Link Capacitor

Wind turbine works in different environmental conditions. The incorporation of array of electrolytic capacitors in DC-link of convertors makes it vulnerable to periodic degradation. Due to this degradation of capacitor for a long years or loose link may result in short circuit or open circuit of DC-link capacitor.

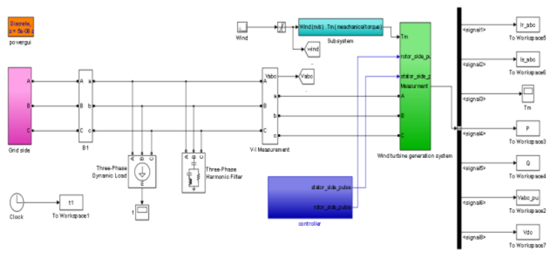

Figure 3. Simulation Model of DFIG during Short Circuit of DC-Link Capacitor

If the capacitor is short circuited it will make the dc voltage as zero in the rotor and grid side convertor controllers. The grid side convertor will try to charge the capacitor in order to raise the voltage of capacitor hence it will exchange more power from the grid. This problem leads to machine instability a machine suffers from power outage, low terminal voltage, high current and high rotor speed.

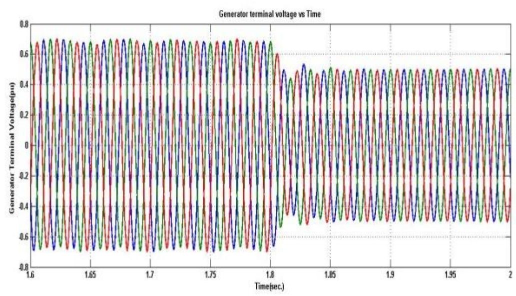

Figure 4. Generator Terminal Voltage at short circuit of DC-link capacitor

Fig. 4 shows generator terminal voltage .the simulation was run with steady state and at t=1.8 sec., short circuit was applied. The voltage of the generator reached to 0.4 pu. While before short circuit it was 0.7 pu.

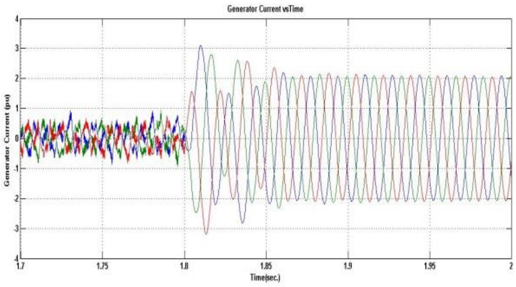

Figure 5. Generator Current at short circuit of DC-link capacitor

Fig. 5 shows the generator current reached up to 2 pu with the transient peak current reaching up to 3 pu the increased generator current will result in increased rotor currents.

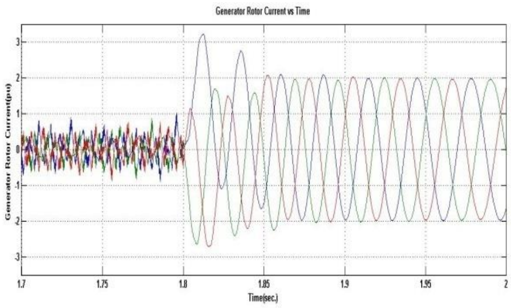

Figure 6. Generator Rotor Current at short circuit of DC-link capacitor

Fig. 6 shows that with the increase of generator current rotor current increases. The rotor current reached up to 2 pu while before fault it was 0.8 pu, with the transient peak touching 3pu.

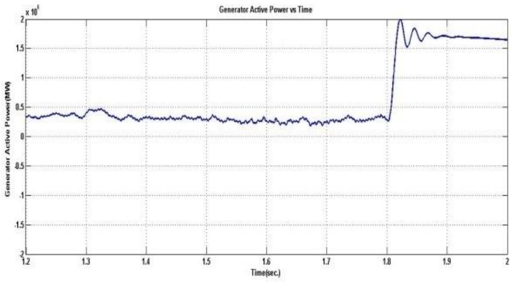

Figure 7. Generator Active power at short circuit of DC-link capacitor

Fig.7 shows generator active power. After the dc-link capacitor short circuit, the generator active power generation increases.

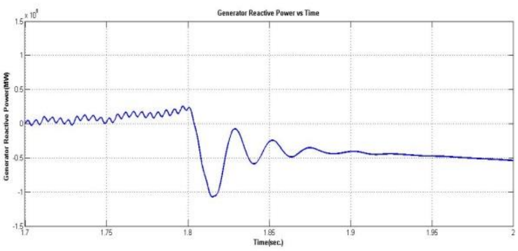

Figure 8. Generator Reactive power at short circuit of DC-link capacitor

Fig. 8 shows that after the DC-link capacitor short circuited, generator reactive power demand increases .this is due to the disturbance in the control of grid side convertor. The rotor speed fluctuates around its rated speed during the short circuiting of capacitor.

Form Fig. 5 to 8 it is seen that dc link capacitor failure leads to low generator terminal voltages, high rotor speed and failure of rotor side and grid side convertors control. Low terminal voltage, high currents, high active and reactive power fluctuations can bring disturbance to the complete system.

V. CONCLUSIONS

The modelling and simulation of DFIG based wind energy power system and control technique SVOC is used for maximum energy extraction and grid synchronization reference frame and conditions. The behaviour of DC link short circuit is simulated in Simulink to observe the output parameters of DFIG based wind energy conversion system. DC-link of DFIG constitutes the array of electrolytic capacitors. Electrolytic capacitors degrade with the passage of long time. DC -link represents the weakest link in converter and is vulnerable to short circuit. During the short circuiting of capacitor, the generator terminal voltage falls, its active power capability is lost with high rotor and stator currents. The grid side converter exchanges high currents than the nominal values. These conditions are serious for other wind turbines in the same wind farm. The disturbance in one generator can make complete wind farm unstable.

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