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Analysis of Converter Connected Synchronous Wind Turbines to Grid Disturbances.

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Abstract- **This paper investigates the performance of synchronous generators to grid voltage unbalance and grid faults. A Model of a synchronous generator with a full converter is implemented in the SimPowerSystems toolbox in Matlab/Simulink. Methods to modify the converter control schemes to improve the synchronous generator systems response to grid voltage unbalance and grid faults are investigated. Grid faults including grid voltage unbalance, and line-to-ground faults are introduced into the model at specific times to analyse the performance of the wind generation system. Improvements in the performance of the synchronous generator WECS to the grid disturbances are illustrated.**

***Index Terms*—Synchronous Generator, Converter, Voltage Unbalance, Grid Faults, Wind Energy**

I. Introduction

There has been a large increase in the installed wind capacity in transmission and distribution systems in Ireland and worldwide in recent years, and this has resulted in the necessity that wind generation systems remains in operation in the event of network disturbances.

In weak networks, the propensity for grid problems including network voltage unbalance is higher [2]. The development of WECS in the period from the early 1990's to the present day was predominantly Double Fed Induction Generators (DFIGs'), however in recent years the trend appears to favour the installation of synchronous generators. These systems are also susceptible to problems associated with grid voltage unbalance and grid faults [4].

The synchronous generator wind turbine in this study is modelled in Matlab/Simulink [1] to analyse its behaviour during grid voltage disturbances. The system under investigation consists of a single synchronous generator connected to a simple network as illustrated in Fig. 1.

II. SYNCHRONOUS GENERATOR

Synchronous generators can be configured as permanent magnet (PM) or electrically excited, and can be connected through a gearbox or directly (direct driven). The model in this paper consists of a wind turbine connected through a gearbox to an electrically excited synchronous generator, with a full converter connected to the stator. The stator of the synchronous generator is connected to an uncontrolled three-phase rectifier, a DC/DC boost converter, dc link and a three-phase IGBT voltage source inverter, illustrated in Fig. 2. The rated power of the generator is 2MW, and the converter is rated accordingly, see Table 1 in the Appendix for details.

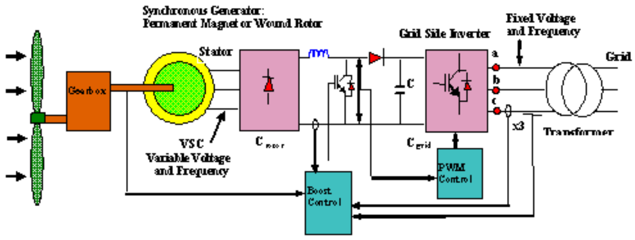


Fig. 1 Synchronous Generator Control

The three-phase diode rectifier converts the synchronous generator AC power into uncontrolled DC power. When the wind speed changes and thus the generator speed, the rectified DC voltage will change. The voltage output of the three-phase rectifier is uncontrolled and therefore to control the DC voltage in the DC link a boost chopper converter is used [9]. The boost converter provides control to smooth the DC link voltage to the grid side inverter. A PI controller is used to control the power difference between the DC power and the reference turbine power, and thus the control of the generated torque and speed is maintained by controlling the boost converter [7].

The voltage output of the boost chopper can be obtained as:

$$V_o = V_s \left[\frac{T}{(T - T_{on})} \right] \qquad (1)$$

And if the duty cycle, $\delta = T_{on}/T$

$$V_o = \frac{V_s}{(1-\delta)} \qquad (2)$$

III. Grid Side Converter Control

The control structure for the grid-side converter is based on the decoupled *dq* vector control method with grid voltage synchronous reference frame. The grid-side converter controls the dc link voltage, converts the DC link voltage to AC and can also control reactive power. The *dq* voltage equations can be obtained in the grid voltage synchronous reference frame with the d_{axis} aligned with the grid voltage as [5]:

$$v_{dqg} = i_{dqg} R_g + L_g \frac{di_{dqg}}{dt} - \omega_e L_g \, i_{dqg} + v_{dqg1} \qquad (3)$$

In normal operation (no grid disturbances), the reference control currents can be obtained form (3). During conditions of network voltage unbalance it is necessary to separate (3) into positive and negative sequence components:

$$v^{+}_{dqg+} = i^{+}_{dqg+}R_g + L_g \frac{di^{+}_{dqg+}}{dt} - \omega_e L_g \; i^{+}_{dqg+} + v^{+}_{dqg1+} \quad (4)$$

$$v^{-}_{dqg-} = i^{-}_{dqg-}R_g + L_g \frac{di^{-}_{dqg-}}{dt} - \omega_e L_g \; i^{-}_{dqg-} + v^{-}_{dqg1-} \quad (5)$$

The apparent power of the converter can be described as:

$$S = P_g + jQ_g = \frac{3}{2} v^{+}_{dqg} i^{+*}_{dqg} \quad (6)$$

where the superscript indicates the positive sequence reference frame.

The real power injected into the grid by the grid side converter in synchronous generator is given as [4, 5]:

$$P_g = v_{dg} i_{dg} + v_{qg} i_{qg} \quad (7)$$

where v_{dq} and i_{dq} are the grid dq voltages and currents respectively.

When an asymmetrical fault occurs, positive and negative sequence components can be introduced into (6) as [4]:

$$S = \frac{3}{2} \cdot \begin{pmatrix} \left(v^{+}_{dqgc+} + v^{-}_{dqgc-}.e^{-j2\omega_e t}\right). \\ \left(i^{+*}_{dqgc+} + (i^{-}_{dqgc-}.e^{-j2\omega_e t})^{*}\right) \end{pmatrix} \quad (8)$$

Multiplying (8) and expanding:

$$\begin{aligned} S = \Big\{ & \left(v^{+}_{dgc+}.i^{+}_{dgc+} - v^{+}_{dgc+}.ji^{+}_{dgc+} + jv^{+}_{qgc+}.i^{+}_{dgc+} + v^{+}_{qgc+}.i^{+}_{qgc+}\right) \\ & + \left(v^{+}_{dgc+}.i^{-}_{dgc-} - v^{+}_{dgc+}.ji^{-}_{dgc-} + jv^{+}_{qgc+}.i^{-}_{dgc-} + v^{+}_{qgc+}.i^{-}_{qgc-}\right)e^{j2\omega_e t} \\ & + \left(v^{-}_{dgc-}.i^{+}_{dgc+} - jv^{-}_{dgc-}.i^{+}_{qgc+} + jv^{-}_{qgc-}.i^{+}_{dgc+} + v^{-}_{qgc-}.i^{+}_{qgc+}\right)e^{-j2\omega_e t} \\ & + \left(v^{-}_{dgc-}.i^{-}_{dgc-} - v^{-}_{dgc-}.ji^{-}_{dgc-} + jv^{-}_{qgc-}.i^{-}_{dgc-} + v^{-}_{qgc-}.i^{-}_{qgc-}\right)\Big\} \end{aligned} \quad (9)$$

Equation (9) can be equated to:

$$P_{acg} = P_{og} + P_{c2g}\cos(2\omega_s t) + P_{s2g}\sin(2\omega_s t)$$

$$Q_{acg} = Q_{og} + Q_{c2g}\cos(2\omega_s t) + Q_{s2g}\sin(2\omega_s t) \quad (10)$$

where:

$$\begin{bmatrix} P_{og} \\ Q_{og} \\ P_{c2g} \\ P_{s2g} \\ Q_{c2g} \\ Q_{s2g} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} v^{+}_{dg+} & v^{+}_{qg+} & v^{-}_{dg-} & v^{-}_{qg-} \\ v^{+}_{qg+} & -v^{+}_{dg+} & v^{-}_{qg-} & -v^{-}_{dg-} \\ v^{-}_{dg-} & v^{-}_{qg-} & v^{+}_{dg+} & v^{+}_{qg+} \\ v^{-}_{qg-} & -v^{-}_{dg-} & -v^{+}_{qg+} & v^{+}_{dg+} \\ v^{-}_{qg-} & -v^{-}_{dg-} & v^{+}_{qg+} & -v^{+}_{dg+} \\ -v^{-}_{dg-} & -v^{-}_{qg-} & v^{+}_{dg+} & v^{+}_{qg+} \end{bmatrix} \begin{bmatrix} i^{+}_{dg+} \\ i^{+}_{qg+} \\ i^{-}_{dg-} \\ i^{-}_{qg-} \end{bmatrix} \quad (11)$$

To control the grid-side inverter real power oscillations to zero, it is necessary to put P_{s2g} and $P_{c2g} = 0$. The reference currents are thus obtained as:

$$i^{-}_{dg-} = \frac{1}{v^{+}_{dg+}}\left[v^{-}_{dg-}\, i^{+}_{dg+} + v^{-}_{qg-}.i^{+}_{qg+}\right] \quad (12)$$

$$i^{-}_{qg-} = \frac{1}{v^{+}_{dg+}}\left[v^{-}_{dg-}.i^{+}_{dg+} - v^{-}_{dg-}.i^{+}_{qg+}\right] \quad (13)$$

The equations for the synchronous generator demonstrate that during conditions of voltage unbalance, whether as a result of voltage unbalance due to unequal single-phase loads in the locality of the generators or as a result of single-phase faults, the synchronous generator grid converter will be affected.

In the grid oriented reference frame, V_{dq} is aligned with the grid voltage and $V_{qg} = 0$ and (7) is then:

$$P_g = v_{dg} i_{dg} \quad (14)$$

During asymmetrical network voltage conditions or single-phase faults the power injected into the grid will reduce according to the ratio of positive sequence voltage to rated voltage [4], and the current i_{dq} is usually controled to a maximum value. The power injetced can therefore be decribed as:

$$P_{gF} = v^{+}_{dg+} i_{dg} = v_{dg} i_{dg} \frac{v^{+}_{dg+}}{v_{dg}} = P_g \frac{v^{+}_{dg+}}{v_{dg}} \quad (15)$$

Where P_{gF} is the power fed to the grid during the disturbance.

Thus when the grid voltage becomes asymmetrical due to single-phase faults or unbalanced loading the power injected into the grid will reduce according to the ratio of positive sequence voltage to rated grid voltage. The power however supplied by the synchronous generator is unchanged and therefore a power unbalance in the DC link bus results.

IV. Control of DC Link Boost Converter

During grid disturbances, grid voltage unbalance and single-phase faults the DC link power $V_d I_d$ becomes greater than the injected power and therefore the DC link voltage will rise, and damage to the converters may result. By controlling the rise in the DC link power of the converter, the LVRT of the system will improve.

If the synchronous generator speed varies, the DC voltage on the DC link will vary. The boost converter is designed to control the DC link voltage supplied to the inverter. The generator speed and torque are controlled by controlling the pulses to the boost converter, and this in turn controls the DC link inductor current [7]. The power fed from the synchronous generator through the DC link bus to the inverter is thus controlled by the boost converter. The dc link power equation can be described, neglecting losses as [6]:

$$\frac{1}{2} C \frac{dv^{2}_{dc}}{dt} = P_s - P_g \quad (16)$$

where P_s is the generator stator real power and P_g is the real power delivered by the grid side converter to the grid.

During the aforementioned grid disturbances (16) will not balance, P_g will decrease whereas P_s will continue to supply generated power form the synchronous generator, and thus the dc link voltage will increase.

The boost converter can be controlled to reduce the dc link current by using:

$$\frac{v_{dg+}^{+}}{v_{dg}} \qquad (17)$$

When a single-phase voltage sag occurs the positive sequence voltage $v_{dq+}{}^{+}$ will reduce, however the reference voltage v_{dq} will remain as rated, and therefore the reference signal will be reduced as in (17).

The control block diagram of the generator side converter and the grid side converter is illustrated in Fig. 2.

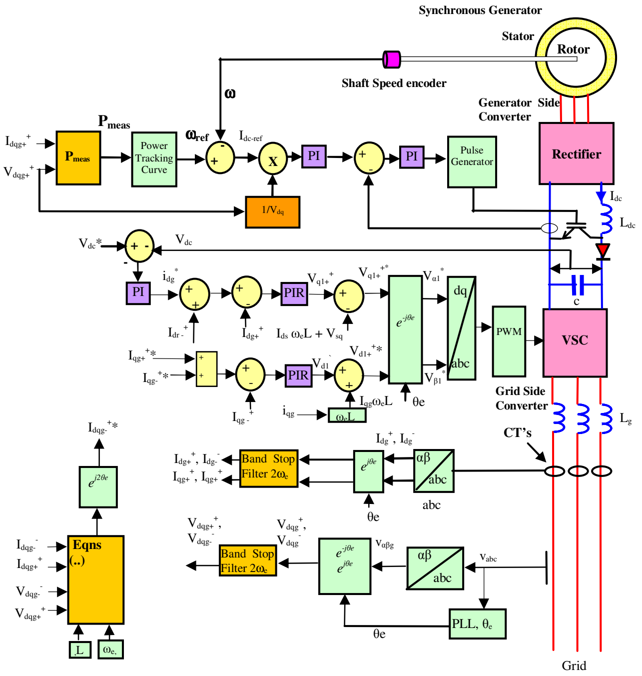


Fig. 2 Synchronous Generator Control

V. Control of Blade Pitch Angle

To reduce the power into the DC link during grid voltage disturbances, the boost converter control scheme can be modified, or the generated power through the generator side rectifier can be reduced. The power reduction through the rectifier can be achieved by altering the flux in the rotor of the synchronous generator, and thus reducing the generated voltage or by adjusting the blade pitch angle (BPA), and therefore reducing the power delivered into the synchronous generator [5].

VI. Control of Synchronous Generator Rotor Flux

The magnetic flux in the rotor of the synchronous generator controls the generated voltage induced in the stator distributed windings. The stator windings feed the three-phase controlled rectifier which in turn feeds the DC link. The rotor flux control loop of the synchronous generator is illustrated in Fig. 3.

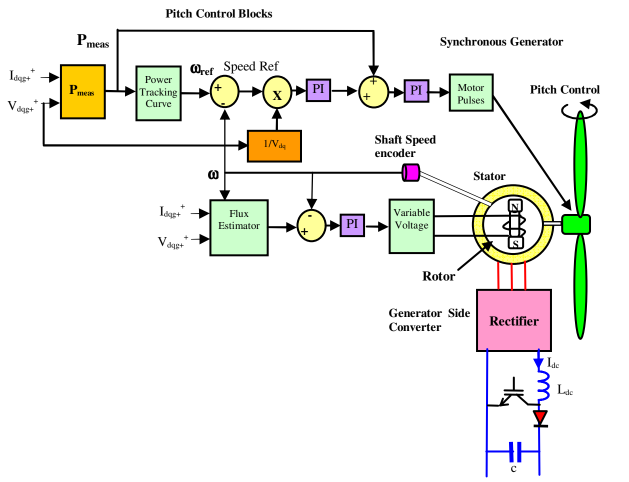


Fig. 3 Blade Pitch Angle Control and Rotor Field Control

VII. Resonant Control of Grid Side Synchronous Generator Converter

The grid-side converter controls the real power delivered to the grid by maintaining adequate DC link voltage, and it can also control reactive power. Resonant controllers have been used to control DFIG's during voltage unbalance conditions [3]. A resonant (*R*) controller can be used in parallel with the *PI* current controller in the grid side convereter of a synchronus generator. The *R* controller requires less positive and negative sequence decomposition and thus less time delay and errors than a parallel control scheme [3].

According to (9) and (10) it is clear that during network voltage unbalance conditions the voltage, current and flux all contain both DC values of the positive sequence components and double frequency ($2\omega_e$) AC values of the negative sequence components in the dq^+ reference frame. The DC components are regulated normally by the *PI* controller however this controller cannot regulate the double frequency components. The negative sequence control currents $I_{dqr}{}^{-}$ have a frequency of $2\omega_e$ (100 Hz) and to control these currents adequately it is thus necessary to use a controller that is tuned to 100 Hz. A proportional, integral plus resonant (*PI+R*) grid-side converter current controller can be implemented for directly controlling both the positive and negative sequence components of real power [3, 8]. The voltage reference output of the *PI&R* controller can be described as:

$$v_{dqg}^{e+`} = \left(i_{dqg}^{e+*} - i_{dqg}^{e+}\right)\left\{k_p + \frac{k_i}{s} + k_{iR}\left(\frac{s}{s^2 + s2\omega_c + (2\omega_e)^2}\right)\right\} \qquad (18)$$

In the scheme described by (18) ω_e is the resonance frequency of the controller, and K_P and K_i are the proportional gain and the integral gains respectively.

The discrete form of (18) is:

$$v_{dqg}^{e+`} = \left(i_{dqg}^{e+*} - i_{dqg}^{e+}\right)\left\{k_p + \frac{k_i T_s}{Z-1} + k_{iR}\left(\frac{a_o + a_1 Z^{-1} + a_2 Z^{-2}}{1 - b_1 Z^{-1} + b_2 Z^{-2}}\right)\right\} \quad (19)$$

And the coefficiants in the Simulink model, for a resonant frequency of 100Hz, obtained using the Tustin approximation are:

$$\frac{s k_{ir}}{s^2 + 2s\omega_c + (2.2.\pi.50)^2} = \frac{z.0.499382.10^{-4} + 0 + 0.499382.10^{-4}}{z^2 - z.1.995557 + 0.9995} \quad (20)$$

This controller has a very high gain around the resonant frequency and it eliminates the steady state error between the reference and the measured signal. The width of the frequency band around the resonance point depends on the integral gain value. A small value produces a very narrow band, whereas a large value produces a wider band. The cut-of frequency ω_c in (18) also increases the band-width.

VIII. Simulation Results of Synchronous Generator

Initially the effect of the voltage unbalance on the terminal connection of the generator converter is considered. Under network voltage unbalance conditions a negative phase sequence component occurs.

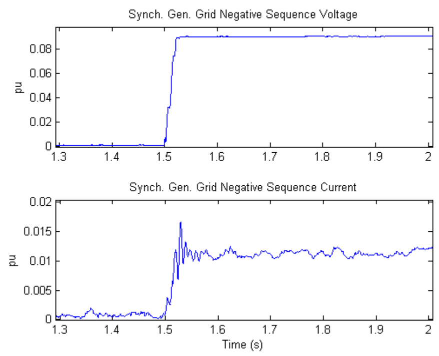


Fig. 4 Grid-Side Voltage and Current unbalance

In the Simulink model a single phase load is connected at the grid-side of the transformer shown in Fig. 1. Fig. 4 shows the negative sequence voltage and current of the synchronous generator system at the grid-side terminals, (a, b, c, (Fig. 1)) predicted by the Matlab/Simulink simulation. The single-phase load is switched-in at 1.5 seconds and introduces a voltage unbalance factor (VUF) of 9%. The current becomes unbalanced with a negative sequence current of approximately 11%.

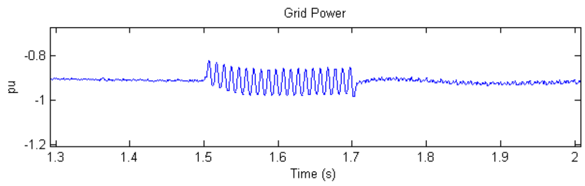


Fig. 5 Grid-Side Real Power

Fig. 5 illustrates the grid-side power oscillations measured at terminals of the inverter (a, b, c in Fig. 1), occurring at 1.5s when the grid voltage unbalance is introduced at the grid-side converter of the synchronous generator. When voltage unbalance compensation to the grid side converter (Fig.2) is incorporated and switched-in at 1.7s the power oscillations are eliminated.

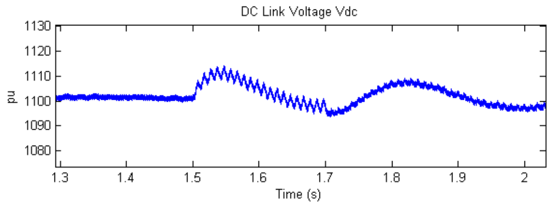


Fig. 6 Synchronous Generator DC Link Voltage

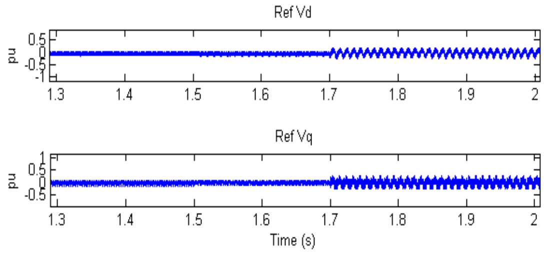


Fig. 7 Reference voltages, V_{dref} and V_{qref}

Fig.6 is a plot of the DC link voltage. Double frequency voltage oscillations occur at 1.5s when the grid voltage becomes unbalanced and quickly improves when the voltage unbalance compensation scheme is introduced at 1.7s. The reference voltages V_{dref} and V_{qref} are plotted in Fig.7. It can be noted that the compensating control is introduced at 1.7s.

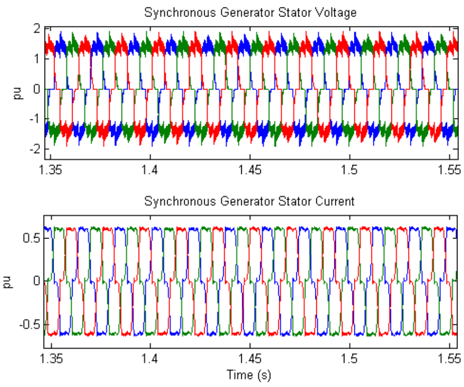


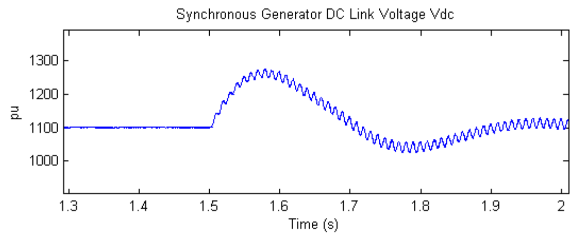
Fig. 8 Synchronous Generator Stator Voltage and Current

Plots of the stator voltage and current at the stator terminals of the synchronous generator are illustrated in Fig. 8. It is clear that during a voltage sag leading to a VUF of 9%, conditions at the synchronous generator terminals are not affected.

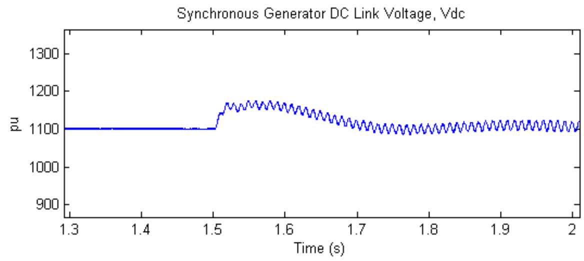
IX. Simulation Results –Single-Phase Fault

During grid voltage sags, the converter on the generator-side continues to control the output of the synchronous generator, however when the grid voltage is reduced, the current to maintain the power at the level before the applied voltage unbalance, needs to increase; but not at a level that will cause damage, so is therefore limited. Thus the power output is reduced from the generator grid side converter, but the power supplied to the synchronous generator remains unchanged, which can cause a power unbalance in the converter [6]. From (16), it can be seen that when the input power is larger than output power on the DC-side capacitance, the DC voltage will rise, which may have serious impact on normal operation of the whole system and may result in component damage.

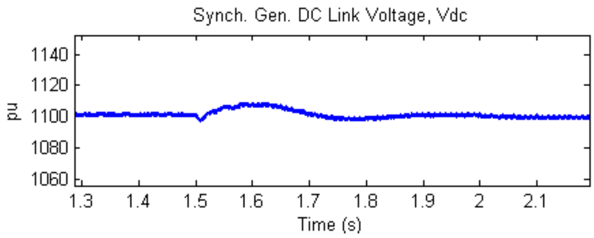
To mitigate against the effects of single-phase faults the control of the grid-side converter, the boost converter and the blade pitch angle control can be modified. The boost converter can be controlled to reduce the DC link power by reducing the DC link current. To reduce the DC link current (17) is introduced into the boost control loop, illustrated in Fig. 2. During single-phase faults the positive sequence voltage will drop, and thus the reference signal for the boost converter will be reduced, and therefore the current in the DC link.



(a)



(b)



(c)

Fig. 8 Synchronous Generator DC Link Voltage

Fig. 8(a) illustrates the effect on the DC link voltage, V_{dc} when a single-phase-to-ground fault occurs on the grid-side of the transformer shown in Fig. 1. The DC link voltage rises to approximately 1300V, probably enough to damage the converter or trip the protection scheme. Fig. 8(b) is a plot of the dc link voltage with a repeat of the single-phase fault. The DC link boost control compensation (17), illustrated in Fig. 3, is introduced into the Simulink model at the onset of the fault at 1.5s, and it is clear that the reduction in the rise of the dc link voltage is significant.

In Fig. 8(a) the DC link voltage rises to nearly 1300V whereas with the dc link boost converter compensation scheme implemented shown in Fig. 8(b), the V_{dc} voltage rise is to approximately 1150V, a significant reduction; however there are still double frequency voltage oscillations.

The Simulink model was then configured to switch-in both the negative sequence compensation scheme in the grid-side inverter (12) and (13), the PIR control (18)), and also the compensation scheme of the dc link boost converter at 1.5s. Fig. 8(c) illustrates the effect of introducing these compensation techniques. The initial amplitude of the rise in the DC link voltage is much reduced and the double frequency voltage oscillations are eliminated.

The model was then investigated for the effects of a single-phase fault on the synchronous generator power oscillations. A single-phase fault was again introduced into the model at 1.5s. Fig. 9 is plot of the power output at the grid side converter, and large double frequency power oscillations are observed as a result of the fault.

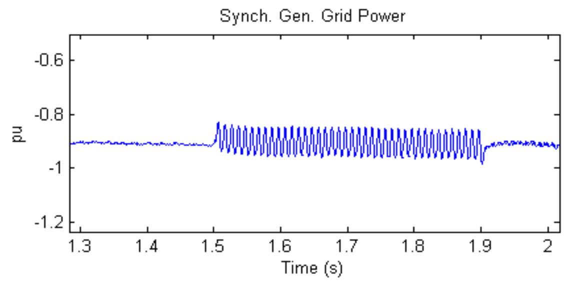


Fig. 9 Grid Power Single-phase Fault

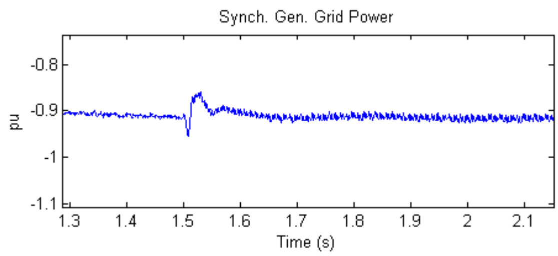


Fig. 10 Grid Power Single-phase Fault

Redo Fig 10 to give -0.6- -1.2

Fig. 10 is a plot of the grid converter power with the compensation scheme (18) switched-in at the onset of the fault. It is clear that the power oscillations as a result of the single-phase fault are eliminated.

X. Conclusion

This paper investigated the control of a synchronous generator WECS connected to the grid during single-phase faults and voltage unbalance conditions. Modifications to the control of the boost converter and the grid side converter were implemented and an improvement in the performance of the synchronous generator to grid disturbances was obtained.

The boost converter controlling the dc link voltage was modified to alleviate the rise in dc link voltage as a result of single-phase faults. The grid side converter control was improved to mitigate against the double frequency oscillation on the DC link and also the power pulsations at the grid side converter during the aforementioned grid disturbances. Improvements to the performance of the synchronous generator WECS during the grid disturbances were illustrated.

XI. APPENDIX

Table 1 Synchronous Generator Parameters

Rated Power	2.0MW	Xd	1.305pu
Frequency	50 Hz	$Xd^{`}$	0.296pu
Rated Voltage	730V	$Xd^{``}$	0.252pu
R_s	0.006 pu	Xq	0.474pu
Inertia Constant	5.04s	$Xq^{`}$	0.243pu
		$Xq^{``}$	0.18pu

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