

## DESIGNING THE EFFICIENT DFIG SYSTEM BACK-TO- BACK CONVERTER TO REPLACE LCL WITH LLCL FILTER

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### ABSTRACT

This report gives the proper understanding of conceptual power control by using direct space vector control technique and its power quality improvement conducted with DFIG. A higher order passive power filter (LLCL-filter) for the back to back converter is becoming attractive for industrial applications due to the possibility to reduce the cost of the copper and the magnetic material. It is concluded that the back to back converter compared with the LCL-filter, the proposed LLCL-filter can not only save the total filter inductance, but also reduce the damping power losses for a stiff grid application. The proposed BTB with LLCL-filter having lesser THD percentage and lesser converter losses compared with LCL-filter. Finally in this report back to back converter with both the filters are compared and all the results are simulated by MATLAB/SIMULINK software with FFT analysis.

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### INTRODUCTION

A Doubly fed induction generator (DFIG) is also called as wound rotor induction generator. Doubly-Fed means, it having both the stator and rotor of an induction machine with a wound rotor is connected to electrical sources. This is popular for the power generation applications to present generations with limited variable speed range. This DFIG can produce or consume power from both stator and rotor of the machine depending upon the speed of the shaft (VijayaRaju Vasipalli, 2015). Depending upon the value of a slip  $s$ , the operation of a DFIG can be classified in three different modes (Phipps, 1997).

- $\omega_r < \omega_s \dots s > 0\dots$ , Sub-synchronous mode
- $\omega_r > \omega_s \dots s < 0\dots$ , Super-synchronous mode
- $\omega_r = \omega_s \dots s = 0\dots$ , Synchronous mode

The operation and control of a Doubly-fed Induction Generator (DFIG) system. This DFIG system is currently the system of choice for multi-MW wind turbines. The aerodynamic system must be capable of operating over a wide range of wind speeds in order to achieve an optimum aerodynamic efficiency by tracking the optimum tip-speed ratio. Therefore, the rotor of the generator must be able to operate at a variable rotational speed. Back to back converter is a two stage of converter, which converts AC-DC-AC. The AC-DC conversion is rectifier stage this converter is called as grid side converter (GSC) and the DC-AC conversion is inverter stage this converter is rotor side converter (RSC). Both converters are connected "back to back" with a DC link capacitor between them. Dc link capacitor puts voltage at constant for efficient inversion. RSC controls the torque or speed of the DFIG and also controls the power factor of the

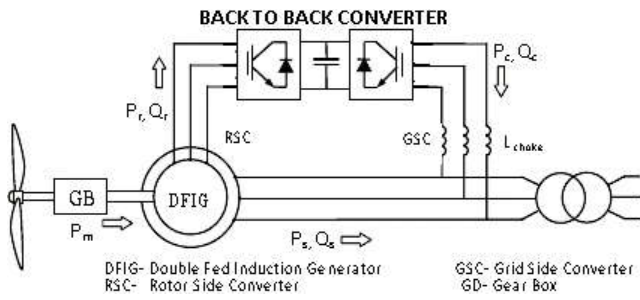


Fig.1. DFIG System with BTB

stator terminals but the GSC only puts DC link voltage at constant GSC works at grid frequency but RSC works at different frequencies according slip speed variations. Back to back converter converts variable voltage; variable frequency into constant voltage, constant frequency or constant voltage, constant frequency into variable voltage, variable frequency in “back to back” directions (John Fletcher and Jin Yang, 2010). This three-phase AC-DC-AC converter is also included in the induction generator rotor circuit through filter topology. The power electronic converters need only be rated to handle a fraction of the total power, and the rotor power is typically about 30% nominal generator power (John Fletcher and Jin Yang, 2010). Therefore the losses in the power electronic converter can be reduced, by using different filter topologies such as LC, LCL and LLCL-filters, compared to a system where the converter has to handle the entire power and the system cost is lower due to the power electronic devices.

## DSVM CONTROL TECHNIQUE

### Rotor Side Converter (RSC) Control

This section will detail the vector-control techniques used for the independent control of torque and rotor excitation current in the DFIG and decouple control of the active and reactive power supplied to the grid. The vector control for the generator can be embedded in an optimal power tracking controller for maximum energy capture in a wind power application. By controlling the active power of the converter it is possible to vary the rotational speed of the generator as well as the speed of the rotor of the wind turbine shaft. This can be used to track the optimum tip-speed ratio as the incident wind speed changes, thereby extracting the maximum power from the incident wind. The grid-side converter control gives potential for optimizing the grid integration with respect to steady-state operation conditions, power quality and voltage stability.

### Voltage Source Inverter Control

The Inverter provides the excitation for the induction machine rotor. With this PWM converter it is possible to control the torque hence the speed of the DFIG and also the power factor at the stator terminals. The Inverter provides a varying excitation frequency depending on the wind speed conditions. The induction machine is controlled in a synchronously rotating dq-axis frame, with the d-axis oriented along the stator-flux vector position in one common implementation. This is called stator-flux orientation (SFO) vector control. In this way, a decoupled control between the electrical torque and the rotor excitation current is obtained. Consequently, the active power and reactive power are controlled independently from each other. To describe the control scheme, the general Park’s model of an induction machine is introduced.

Using the motor convention in a static stator-oriented reference frame, without saturation, the voltage vector equations are

$$\vec{v}_s = R_s \vec{i}_s + \frac{d\vec{\psi}_s}{dt} \quad (5.12)$$

$$\vec{v}_r = R_r \vec{i}_r + \frac{d\vec{\psi}_r}{dt} - j\omega \vec{\psi}_r \quad (5.13)$$

Where  $\vec{v}_s$  is the stator voltage imposed by the grid. The rotor voltage  $\vec{v}_r$  is controlled by the rotor-side converter and used to perform generator control.

The flux vector equations are

$$\vec{\psi}_s = L_s \vec{i}_s + L_m \vec{i}_r \quad (5.14)$$

$$\vec{\psi}_r = L_r \vec{i}_r + L_m \vec{i}_s \quad (5.15)$$

Where  $L_s$  and  $L_r$  are the stator and rotor self-inductances:

$$L_s = L_m + L_{ls}, \quad L_r = L_m + L_{lr}$$

Under stator-flux orientation (SFO), in dq-axis component form, the stator flux equations are:

$$\begin{cases} \psi_{sd} = L_s i_{sd} + L_m i_{rd} = \psi_s = L_m i_{ms} \\ \psi_{sq} = 0 \end{cases} \quad (5.16)$$

Defining leakage factor  $\sigma = 1 - \frac{L_m^2}{L_s L_r}$  and equivalent inductance as

$$L_o = \frac{L_m^2}{L_s}$$

The rotor voltage and flux equations are (scaled to be numerically equal to the ac per-phase values):

$$\begin{cases} v_{rd} = R_r i_{rd} + \sigma L_r \frac{di_{rd}}{dt} - \omega_{slip} \sigma L_r i_{rq} \\ v_{rq} = R_r i_{rq} + \sigma L_r \frac{di_{rq}}{dt} + \omega_{slip} (L_o i_{ms} + \sigma L_r i_{rd}) \end{cases} \quad (5.17)$$

$$\begin{cases} \psi_{rd} = \frac{L_m^2}{L_s} i_{ms} + \sigma L_r i_{rd} \\ \psi_{rq} = \sigma L_r i_{rq} \end{cases} \quad (5.18)$$

Where, the slip angular speed is  $\omega_{slip} = \omega_s - \omega_r$ .

The stator flux angle is calculated from

$$\begin{cases} \psi_{s\alpha} = \int (v_{s\alpha} - R_s i_{s\alpha}) dt \\ \psi_{s\beta} = \int (v_{s\beta} - R_s i_{s\beta}) dt, \theta_s = \tan^{-1} \left( \frac{\psi_{s\beta}}{\psi_{s\alpha}} \right) \end{cases} \quad (5.19)$$

Where,  $\theta_s$  is the stator-flux vector position.

The control scheme of the rotor-side converter is organised in a generic way with two series of two PI-controllers. Fig. 11 shows a schematic block diagram for the rotor-side converter

control. The reference q-axis rotor current  $i_{rq}^*$  can be obtained either from an outer speed control loop or from a reference torque imposed on the machine. These two options may be termed a speed-control mode or torque-control mode for the generator, instead of regulating the active power directly. For speed-control mode, one outer PI controller is to control the speed error signal in terms of maximum power point tracking. Furthermore, another PI controller is added to produce the reference signal of the d-axis rotor current component to control the reactive power required from the generator. Assuming that all reactive power to the machine is supplied by the stator, the reference value  $i_{rd}^*$  may set to zero. The switching dynamics of the IGBT-switches of the rotor converter are neglected and it is assumed that the rotor converter is able to follow demand values at any time.

The control system requires the measurement of the stator and rotor currents, stator voltage and the mechanical rotor position. There is no need to know the rotor-induced EMF, as is the case for the implementation with naturally commutated converters. Since the stator is connected to the grid, and the influence of the stator resistance is small, the stator magnetising current  $i_{ms}$  can be considered constant (Pena et al., 1996). Rotor excitation current control is realised by controlling rotor voltage. The  $i_{rd}$  and  $i_{rq}$  error signals are processed by associated PI controllers to give  $v_{rd}$  and  $v_{rq}$ , respectively, from the rotor voltage equations

$$\begin{cases} v'_{rd} = R_r i_{rd} + \sigma L_r \frac{di_{rd}}{dt} \\ v'_{rq} = R_r i_{rq} + \sigma L_r \frac{di_{rq}}{dt} \end{cases} \quad (5.20)$$

To ensure good tracking of the rotor dq-axis currents, compensation terms are added to  $v'_{rd}$  and  $v'_{rq}$  to obtain the reference voltages  $v_{rd}^*$  and  $v_{rq}^*$  according to

$$\begin{cases} v_{rd}^* = v'_{rd} - \omega_{slip} \sigma L_r i_{rq} \\ v_{rq}^* = v'_{rq} + \omega_{slip} (L_o i_{ms} + \sigma L_r i_{rd}) \end{cases} \quad (5.21)$$

The electromagnetic torque is

$$T_e = -\frac{3}{2} p \operatorname{Im}\{\overrightarrow{\psi}_s \overrightarrow{i}_r^*\} = -\frac{3}{2} p L_o i_{ms} i_{rq} \quad (5.22)$$

For the stator-voltage oriented control the above equation is an approximation. However, for stator-flux orientation, the stator flux current  $i_{ms}$  is almost fixed to the stator voltage. For torque mode control, since it is difficult to measure the torque, it is often realised in an open-loop manner. The torque can be controlled by the q-axis component of the rotor current  $i_{rq}$ . Therefore, the q-axis reference current,  $i_{rq}^{ref}$  can be determined from the reference torque  $T_e^{ref}$  as

$$i_{rq}^{ref} = -\frac{2T_e^{ref}}{3pL_o i_{ms}} = -\frac{2T_e^{ref}}{3p\psi_{ms}}$$

**Grid Side Converter (GSC) Control**

GSC maintains the DC link voltage constant and also controls the power factor.

**FILTER TOPOLOGY**

**Design of LCL Filters**

Fig a. presents the schematic diagram of an LCL filter which is inserted between a PWM converter and the grid. Where,  $U_o$  is terminal voltage of PWM converter,  $U_s$  is grid voltage,  $L_1$  is the converter side inductor,  $R_1$  is the equivalent resistance of  $L_1$ ,  $L_2$  is the grid side inductor,  $R_2$  is the equivalent resistance of  $L_2$ ,  $C_3$  is the capacitor,  $R_3$  is the damping resistor in series with  $C_3$ .

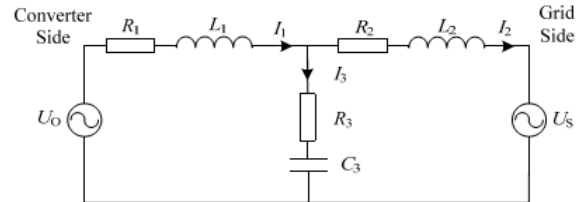


Fig a. LCL filter equivalent circuit diagram (9)

Ignoring  $R_1$  and  $R_2$ , the LCL filter can be viewed as  $L_2$  and  $C_3$  paralleled, then, together they are in series with  $L_1$ .

The transfer function between the input voltage  $U_o$  and the output current  $I_2$  is:

$$H(s) = \frac{R_3 C_3 s + 1}{L_1 L_2 C_3 s^2 + (L_1 + L_2) R_3 C_3 s^2 + (L_1 + L_2) s}$$

**LLCL Parameter Design Procedure**

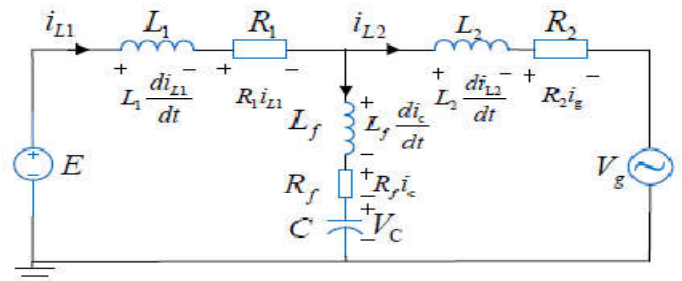


Fig b. LLCL filter equivalent circuit diagram (12)

**Converter-Side Inductance L1**

Being placed at the converter immediate output,  $L_1$  must be sized such that its peak-to-peak current ripple at the converter switching frequency  $f_s$  does not exceed  $\alpha$  times of its peak rated current  $I_{ref}$ . According to (Phipps, 1997)  $\alpha$  can be up to 60% for an LLCL filter with better harmonic attenuation at the converter switching frequency. Based on the derivations presented in (Phipps, 1997),  $L_1$  can then be sized with  $L_1 = U_{dc} / (8f_s \alpha I_{ref})$ , where  $U_{dc}$  is the dc-link voltage marked in Fig. b.

**Capacitance Cf**

$C_f$  can be computed after deciding on  $L_1$ ,  $f_s = 1 / (2\pi \sqrt{L_f C_f})$  and a value for  $f_{rc} \geq f_s / (4\lambda)$  ( $= f_s / 6$  if  $\lambda = 1.5$ ) that satisfies the robust stability criterion. Value for  $C_f$  is therefore not unique, but varies with parameters used for computing it. Where  $C_f$  in p.u. is shown to increase with smaller  $f_s$  and bigger  $\lambda$ . A further constraint should therefore be introduced, which in most cases, is to select  $C_f$  such that the maximum power factor at rated power is less than 5%.

In terms of its base value,  $C_f$  is then constrained according to  $C_f \leq 5\% \times C_b$ , which for the implemented filter.

**Inductance  $L_f$**

After deciding on  $C_f$ , inductance  $L_f$  can be computed immediately since they form a series trap at the converter switching frequency of  $f_s = 10$  kHz. The extent of attenuation introduced by the series trap is however influenced by its quality factor  $Q$  expressed as.

$$Q = \frac{1}{R_f} \sqrt{\frac{L_f}{C_f}} \tag{1}$$

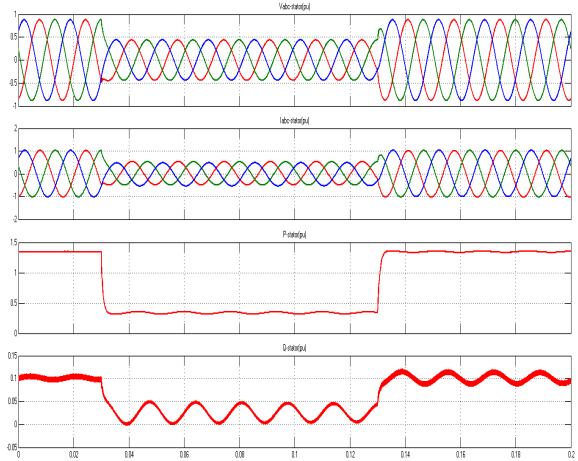
$$n = \sqrt{\frac{L_f}{C_f}} \tag{2}$$

Where  $R_f$  represents the combined equivalent series resistance of  $L_f$  and  $C_f$ . Quality factor  $Q$  therefore depends on both  $R_f$  and  $n$  defined in (eq.2).

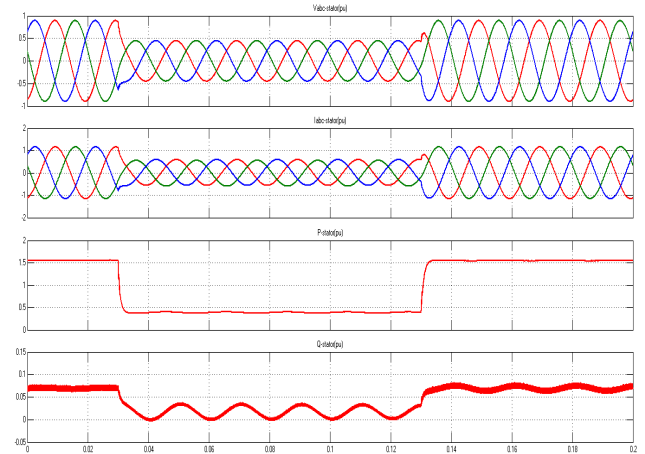
**Grid-Side Inductance  $L_2$**

Inductance  $L_2$  of the  $LLCL$ -filter is the final parameter to design. Its value can be comparably small since it carries no dominant harmonics around the switching frequency, which instead, have been diverted away by the middle  $L_f C_f$  trap. Inductance  $L_2$  therefore needs to attenuate only harmonics around the second integer multiple of the switching frequency to be lesser than 0.3%. The overall range of system resonance frequency  $f_r$  variation can then be computed using (15) by substituting the two probable extreme values of the grid inductance  $L_2$ . The lowest  $f_r$  computed will however still be higher than  $f_{rc}$ . By further placing them ( $f_{rc}$  and  $f_r$ ) above  $f_s / 6$ , (15) will always be met, implying that the designed  $LLCL$ -filtered converter will always be robustly stable regardless of how  $L_2$  varies (13).

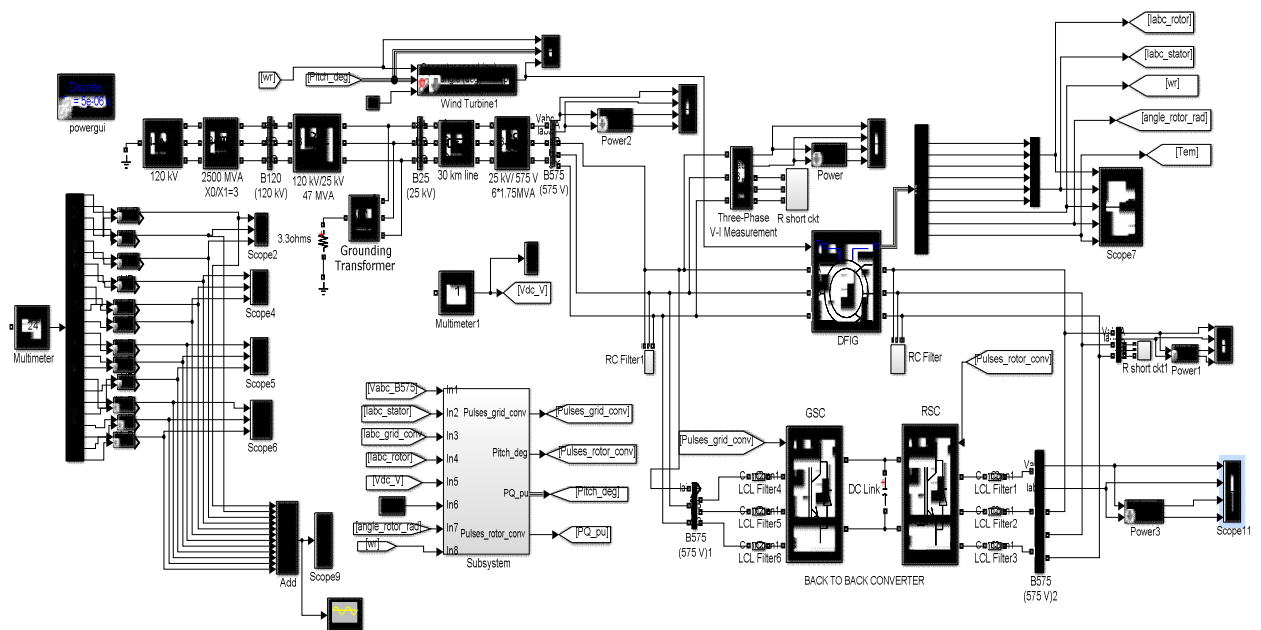
**BTB with LCL-filters in DFIG System**



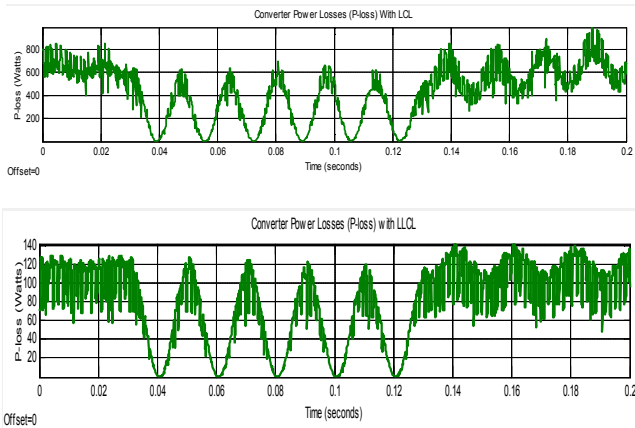
**BTB with LLCL-filters in DFIG System**



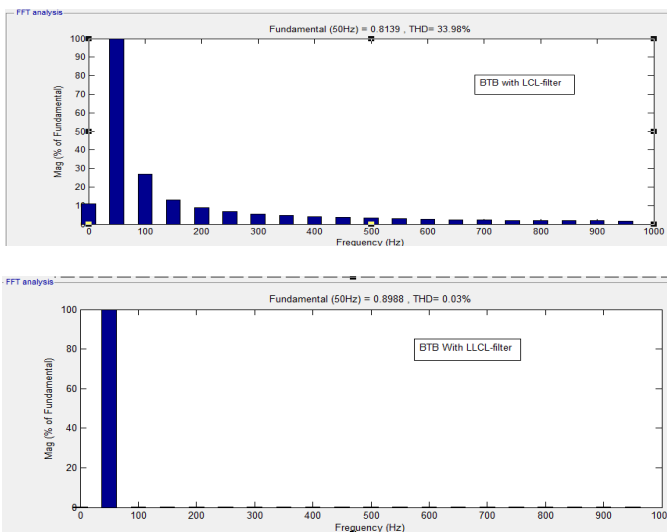
**SIMULATION RESULTS**



**Converter losses in LCL & LLCL**



**FFT analysis for LCL & LLCL**



**Output Results of BTB with filter**

| System Parameters                 | LCL           | LLCL          |
|-----------------------------------|---------------|---------------|
| Losses                            | 600W(Average) | 120W(Average) |
| THD (%)                           | 33.98%        | 0.03%         |
| Voltage Mag. at fundamental freq. | 0.8139 (pu)   | 0.8985(pu)    |
| Current Mag. at fundamental freq. | 0.9967 (pu)   | 1.159(pu)     |
| Base Power                        | 9 (MW)        | 9 (MW)        |
| Total output power                | 12.15 (MW)    | 14.04(MW)     |

**Conclusion**

From both the filters it can be observed that LLCL-filters were efficient one to design the back to back converter with DFIG system for variable wind speeds. In order to track maximum power, back to back converter adjusts the induction generator terminal frequency, and thus the turbine shaft speed. MATLAB simulation and analysis results show that the THD of the current after filtering of BTB with LCL is 33.98% and 0.03% with LLCL-filter respectively, which verified the

effectiveness of the designed filters in attenuating harmonics produced by the back-to-back converter. Compared LLCL with the LCL-filter, an advantage of the A higher order passive power filter (LLCL-filter) for the grid-tied converter is becoming attractive for industrial applications due to the possibility to reduce the cost of the copper and the magnetic material. It is concluded that compared with the LCL-filter, the proposed passive damped LLCL-filter can not only save the total filter inductance but also reduce the total power losses for a stiff grid application.

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