Chapter 4

Power Electronics & Generator Controls

Electronic power converters are an essential part of many wind turbine generators. This chapter will provide an introduction to power electronic converters, with emhasis on the 3-ph H-bridge and its application to wind energy power conversion systems.

I Three phase H-bridge

a) Converter Topology

The 3-ph H-bridge is a useful topology, in that it provides four-quadrant operation. A simplified schematic diagram of the converter topology is shown in Fig. **??**.

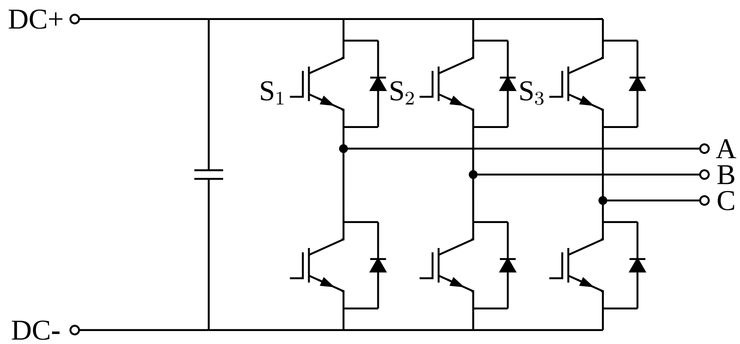

Figure 4.1: The 3-ph H-bridge topology, shown with IGBTs and their internal fly-back diodes.

Additional components are necessary to operate the IGBTs in a safe and controlled manner. Not shown in the schematic are gate-drivers and their respective power supplies, voltage and current sensors, and programmable controller.

b) Converter States

The high- and low-side switches must operate in complementary states. That is, when the high side switch is ON, the low-side switch must be off. Without a proper amount of dead-time between the ON states of the two switches, shoot-through and accidental turn-on can occur which can damage the device.

Each phase of the converter has three states, the output is either dc+, dc-, or Hi-Z. For each converter state, the line-to-neutral, line-to-line, and voltage space-vector is created, as summarized in Table **??**. The top and bottom switches are complimentary pairs. A "0" indicates the top switch is OFF and bottom switch is ON. A "Z" indicates neither switch is turned on. The

Table 4.1: 3-ph H-Bridge Converter States

State (S_1 S_2 S_3)	v_{an}	v_{bn}	v_{cn}	v_{ab}	v_{bc}	v_{ca}	v_{qs}	v_{ds}	$\vert\vec{v}\vert\angle\theta_e$
0 0 0	0	0	0	0	0	0	0	0	0
0 0 1	$\frac{-v_{dc}}{3}$	$\frac{-v_{dc}}{3}$	$\frac{2v_{dc}}{3}$	0	$-v_{dc}$	v_{dc}	$\frac{-v_{dc}}{2}$	$\frac{\sqrt{3}v_{dc}}{2}$	$v_{dc}\angle -120^\circ$
0 1 0	$\frac{-v_{dc}}{3}$	$\frac{2v_{dc}}{3}$	$\frac{-v_{dc}}{3}$	$-v_{dc}$	v_{dc}	0	$\frac{-v_{dc}}{2}$	$\frac{-\sqrt{3}v_{dc}}{2}$	$v_{dc}\angle 120^\circ$
0 1 1	$\frac{-2v_{dc}}{3}$	$\frac{v_{dc}}{3}$	$\frac{v_{dc}}{3}$	$-v_{dc}$	0	v_{dc}	$-v_{dc}$	0	$v_{dc}\angle 180^\circ$
1 0 0	$\frac{2v_{dc}}{3}$	$\frac{-v_{dc}}{3}$	$\frac{-v_{dc}}{3}$	v_{dc}	0	$-v_{dc}$	v_{dc}	0	$v_{dc}\angle 0^\circ$
1 0 1	$\frac{v_{dc}}{3}$	$\frac{-2v_{dc}}{3}$	$\frac{v_{dc}}{3}$	v_{dc}	$-v_{dc}$	0	$\frac{v_{dc}}{2}$	$\frac{\sqrt{3}\ v_{dc}}{2}$	$v_{dc}\angle -60^\circ$
1 1 0	$\frac{v_{dc}}{3}$	$\frac{v_{dc}}{3}$	$\frac{-2v_{dc}}{3}$	0	v_{dc}	$-v_{dc}$	$\frac{v_{dc}}{2}$	$\frac{-\sqrt{3}v_{dc}}{2}$	$v_{dc}\angle 60^\circ$
1 1 1	0	0	0	0	0	0	0	0	0
0 1 Z	$\frac{v_{dc}}{2}$	$\frac{-v_{dc}}{2}$	0	v_{dc}	$\frac{-v_{dc}}{2}$	$\frac{-v_{dc}}{2}$	$\frac{3v_{dc}}{4}$	$\frac{\sqrt{3}v_{dc}}{4}$	$\frac{\sqrt{3}v_{dc}}{2}\angle -30^\circ$
1 0 Z	$\frac{-v_{dc}}{2}$	$\frac{v_{dc}}{2}$	0	$-v_{dc}$	$\frac{v_{dc}}{2}$	$\frac{v_{dc}}{2}$	$\frac{-3v_{dc}}{4}$	$\frac{-\sqrt{3}v_{dc}}{4}$	$\frac{\sqrt{3}v_{dc}}{2}\angle 150^\circ$
1 1 Z	0	0	0	0	0	0	0	0	0
0 Z 1	$\frac{-v_{dc}}{2}$	0	$\frac{v_{dc}}{2}$	$\frac{-v_{dc}}{2}$	$\frac{-v_{dc}}{2}$	v_{dc}	$\frac{-3v_{dc}}{4}$	$\frac{\sqrt{3}v_{dc}}{4}$	$\frac{\sqrt{3}v_{dc}}{2}\angle -150^\circ$
1 Z 0	$\frac{v_{dc}}{2}$	0	$\frac{-v_{dc}}{2}$	$\frac{v_{dc}}{2}$	$\frac{v_{dc}}{2}$	$-v_{dc}$	$\frac{3v_{dc}}{4}$	$\frac{-\sqrt{3}v_{dc}}{4}$	$\frac{\sqrt{3}v_{dc}}{2}\angle 30^\circ$
1 Z 1	0	0	0	0	0	0	0	0	0
Z 0 1	0	$\frac{-v_{dc}}{2}$	$\frac{v_{dc}}{2}$	$\frac{v_{dc}}{2}$	$-v_{dc}$	$\frac{v_{dc}}{2}$	0	$\frac{\sqrt{3}v_{dc}}{2}$	$\frac{\sqrt{3}v_{dc}}{2}\angle -90^\circ$
Z 1 0	0	$\frac{v_{dc}}{2}$	$\frac{-v_{dc}}{2}$	$\frac{-v_{dc}}{2}$	v_{dc}	$\frac{-v_{dc}}{2}$	0	$\frac{-\sqrt{3}v_{dc}}{2}$	$\frac{\sqrt{3}v_{dc}}{2}\angle 90^\circ$
Z 1 1	0	0	0	0	0	0	0	0	0

voltage vector positions are plotted for each state in Fig. **??**. It is important to notice that a continuous constant-magnitude line-to-neutral voltage vector has a maximum amplitude (peak value of the sinusoid) limited by the value of the dc-bus voltage, more specifically

$$V_{LL\text{rms,max}} = \frac{V_{dc}}{\sqrt{2}} \text{ or } V_{LN\text{peak,max}} = \frac{V_{dc}}{\sqrt{3}}.$$

The converter will be operated such that a desired voltage is created at the three phase terminals. The most simple operating method is to use a 6-step operation which results in very rich low frequency harmonic content. A modulation strategy can be used to reduce the low-frequency content. Strategies often used include sine-triangle comparison, hysteresis or delta modulation, and space vector modulation. Space vector modulation (SVM) will be used in the activities included later in this chapter. With this method, the vectors that correspond to states 100, 110, 010, 011, 001, and 101 are generated at very specifc times and for specifc durations, the values of which are determined by the desired amplitude and angle of the resulting fast-averaged vector. For details, see your course textbook.

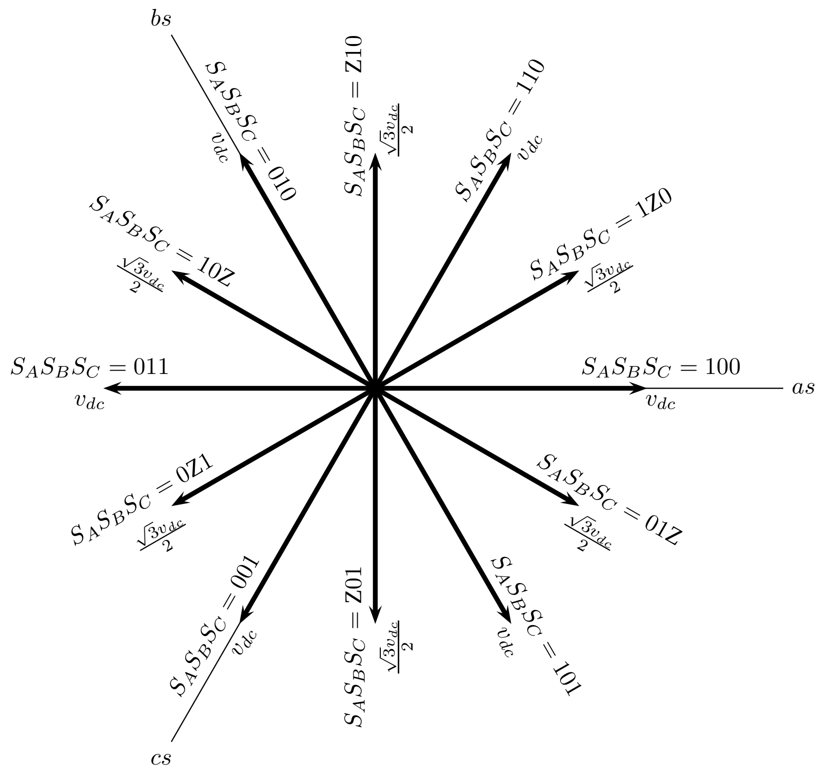

Figure 4.2: Converter states and line-to-line voltage vectors, plotted on stationary *abc* axes.

II Control Systems

The control system relies on sensor measurments to provide feedback to the controller. The three-phase measurements rely on transformation to the synchronously rotating *qd* reference frame. The resulting variables have dc characteristics, which makes it possible to control them using techniques often used for dc systems, such as proportional plug integral compensation.

Three-phase measurements, whether they are voltage or current, are transformed using the *abc*-to-*qd* transformation described in class; it is of the form

$$f_{qd0s} = K_s f_{abcs}$$

where

$$K_s = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

$$\omega = \frac{d\theta}{dt}.$$

Here, ω is the angular velocity of the reference frame. Subscript s denotes arbitrary reference frame. The inverse transformation is

$$f_{abcs} = K_s^{-1} f_{qd0s}$$

where

$$K_s^{-1} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix}.$$

With the measured *qd* quantities, it is relatively simple to compare them to commanded values and implement a PI controller. The PI controller acts on the difference in the measured and commanded quantities; there may be some feed-forward terms included in the output of the controller. The output of a PI controller can be represented as a function in the Laplace-domain, as

$$y(s) = (x^* - x)\left(K_p + \frac{Ki}{s}\right) + FF$$

where x is usually a voltage, current, or torque command. To calculate the proportional and integral gains, the equations that describe the system are set equal to the actual quantities, as

$$f(x^*) = f(x).$$

The equation is the then manipulated to get an output command in terms of the difference of the measured and commanded values. Gains K_p and K_i are computed to place the poles and zeros of the system; natural frequency and settling time can also be used to compute the gains when considering the time-domain response. The control development process will become more clear with an example, provided in an upcoming section.

III DFIG Back-to-Back Converter Application

The back-to-back converter uses two 3-ph H-bridge converters coupled by a dc-link, as shown in Fig. **??**.

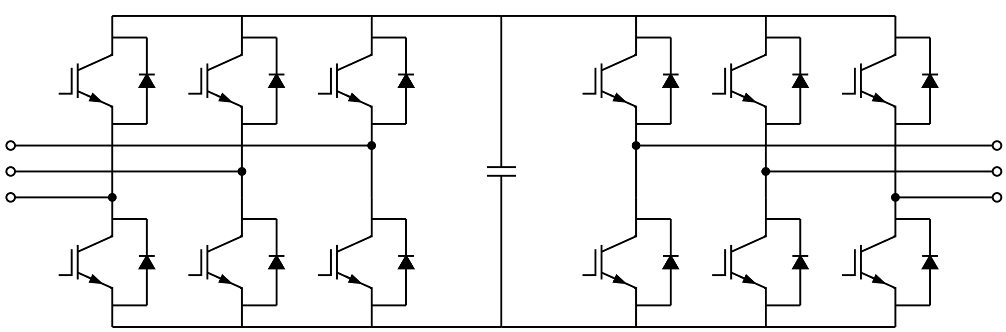

Figure 4.3: The back-to-back converter topology.

Power can flow in either direction of this circuit. When used in a grid-tied DFIG, the torque requirements of the generator specify how much power is delivered to or taken from the three-phase machine-side converter (MSC) terminals. When power is taken from the dc-link and delivered to the generator terminals, the DC-link voltage will tend to drop. In this case, the grid-side converter (GSC) draws power from the grid to maintain the specified DC-link voltage. When power is taken from the MSC generator terminals, the DC-link voltage will tend to rise. In this case, the GSC sends power to the grid. For either case, the GSC usually operates at unity power factor, although it is capable of providing either positive or negative reactive power.

a) Grid-Side Converter

shown in Fig. **??**.

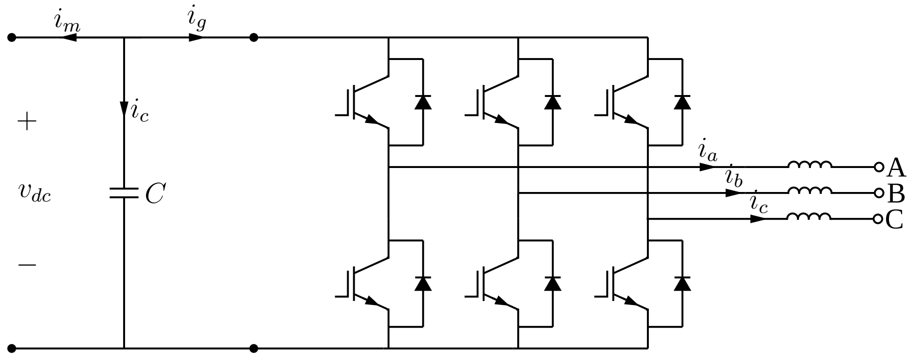

Figure 4.4: Schematic of the GSC coupled with the grid via a three-phase inductor.

The per-phase circuit for the system is shown in Fig. **??**.

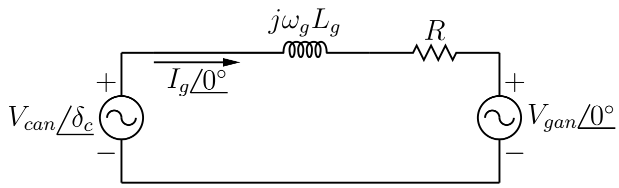

Figure 4.5: The per-phase circuit diagrams of the GSC coupled with the grid.

Transforming this circuit to the arbitrary *qd* reference frameleads to that shown in Fig. **??**. It is valid for both steady-state and transient conditions. The GSC terminal voltage is related to the grid terminal voltage by

$$v_{cqs} = v_{gqs} + Ri_{qds} + L_g p i_{qs} + \omega L_g i_{ds} \tag{4.1}$$
$$v_{cds} = v_{gds} + Ri_{qds} + L_g p i_{ds} - \omega L_g i_{qs} \tag{4.2}$$
$$v_{c0s} = v_{g0s} + Ri_{qds} + L_g p i_{0s}. \tag{4.3}$$

where $L_g i_{ds}$ is the *d*-axis flux linkage, λ_{ds}, and $L_g i_{qs}$ is the *q*-axis flux linkage λ_{qs}, and p is the derivative operator $\frac{d}{dt}$.

PLL for grid voltage sensing

The grid voltage vector is defined here to have magnitude V_m and angular frequency ω_g. At any moment in time, the vector is positioned at θ_g. The rotating reference frame has angular frequency ω_f. At any moment in time, the reference frame is positioned at θ_f. The projection of the grid vector onto the rotating reference frame yields *qd* components

$$v_q = V_m \cos\left(\theta_g - \theta_f\right) \tag{4.4}$$
$$v_d = -V_m \sin\left(\theta_g - \theta_f\right) \tag{4.5}$$

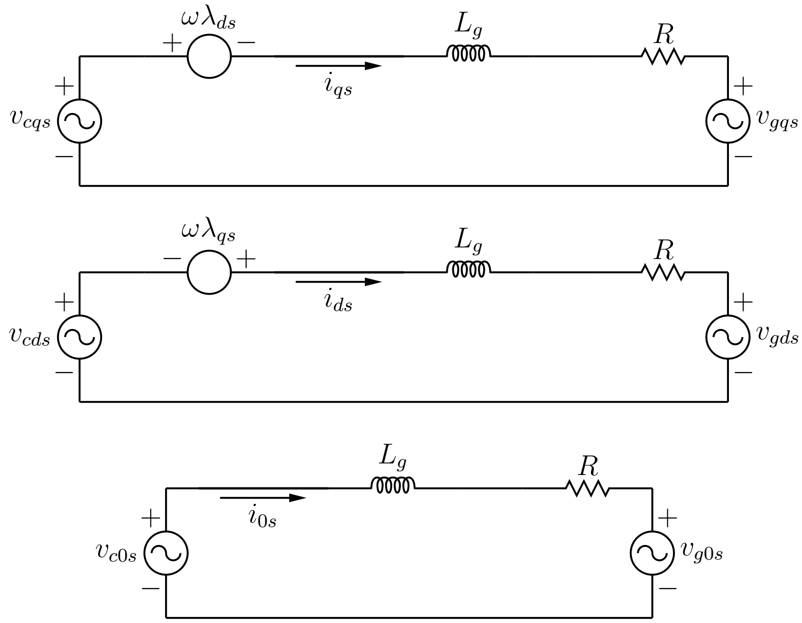

Figure 4.6: The arbitrary *qd* circuit of the GSC coupled with the grid.

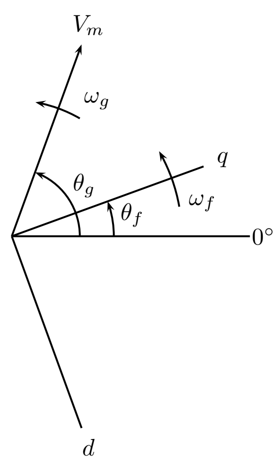

Figure 4.7: Voltage vector relationships for the PLL.

It is clear that when $v_d = 0$, $\theta_f = \theta_g$; the *q*-axis of the rotating reference frame is aligned with the grid voltage vector as illustrated in Fig. **??**.

A PI controller works to keep the angle of the rotating reference frame aligned with the voltage vector. The actual *d*-axis voltage is compared to the desired value of $v_d^* = 0$. When $v_d > v_d^* = 0$, the reference frame needs to slow down. When $v_d < v_d^* = 0$, the reference frame needs to speed up. The difference is used to adjust the frequency of the rotating reference frame, via PI control. For small deviations of the grid speed from nominal, the reference frame angle is

$$\theta_f = \int 2\pi 60 \text{ dt} + \frac{v_d}{V_m}. \tag{4.6}$$

Assuming positive values for parameters K and τ, the commanded angle of the reference frame is defined to be

$$\theta_f^* = \int \left(2\pi 60 + (v_d^* - v_d)\, K \left(1 + \frac{1}{\tau s} \right) \right) \, dt. \tag{4.7}$$

Equating **??** and **??** in the frequency domain, leads to the transfer function

$$H(s) = \frac{v_{ds}}{v_{ds}^*}. \tag{4.8}$$

Parameters K and τ are determined by placing the poles and zeros at locations that result in a satisfactory response. This exercise is left to the experimenter.

Current Control

The *abc* currents are measured and transformed to the rotating reference frame. The *qd* grid currents are controlled by PI controllers. The output of the controllers are the *q*- and *d*-axis voltage commands in the synchronous reference frame.

Voltage equations for the DFIG are addressed earlier in chapter 3.3. The q-axis current and q-axis converter voltage are equated in (3.1); it is restated here in the synchronous reference frame and the Laplace domain.

$$v_{cq}^e = Ri_{gq}^e + L_g i_{gq}^e s + \omega_e L_g i_{gd}^e + v_{gq}^e \tag{4.9}$$

The *q*-axis voltage commanded by the controller is defined here as the voltage present in the circuit which is independent of the controlled *q*-axis current, plus a term which depends on the PI controlled *q*-axis current, as

$$v_{cq}^{e*} = \left(v_{gq}^e + \omega_e L_g i_{gd}^e \right) + K \left(1 + \frac{1}{\tau s} \right) \left(i_{gq}^{e*} - i_{gq}^e \right) \tag{4.10}$$

where i_{gq}^{e*} is the desired *q*-axis current, i_{gq}^e is the actual *q*-axis current, and K and τ are parameters of the PI controller.

The transfer function

$$H(s) = \frac{i_{gq}^e}{i_{gq}^{e*}} \tag{4.11}$$

is then designed to have the poles and zeros of the system located at such positions to have an acceptable dynamic response. By viewing the control variables in real time, it is possible to tune the parameters for increased performance.

The *d*-axis controller is developed in a similar way. This exercise is left to the experimenter.

Reactive Power Control

To regulate the reactive power at the grid terminals, an outer PI control loop is used. The actual reactive power is calculated from the measured grid voltage and line current. For the circuit of Fig. **??**, with the PLL operating so $v_{gd}^e = 0$ V, the *d*-axis current in terms of reactive power is

$$i_{gd}^e = \frac{2}{3} \left(\frac{Q_g}{v_{gq}^e} \right). \tag{4.12}$$

Assuming positive parameters K and τ, the output of the reactive power controller is the d-axis current command, defined as

$$i_{gd}^{e*} = \left(Q_g^* - Q_g\right) K_Q \left(1 + \frac{1}{\tau_Q s}\right). \tag{4.13}$$

Assuming the actual current equals the commanded current, then equating (**??**) and (**??**) in the Laplace domain leads to the transfer function

$$H(s) = \frac{Q_g}{Q_g^*}. \tag{4.14}$$

The poles are zeros are placed to form a stable system with acceptable transient response.

DC-Link Voltage Control

The dc-link circuit diagram is in Fig. **??**. The dc-link is initially charged via the grid voltage through the six-switch converter flyback diodes. A PI controller regulates the dc-link voltage to a value sufficiently high enough to allow normal operation of the converter.

The machine-side current, i_m, varies with wind power, and does so much more slowly than i_g. Therefore, the capacitor current is essentially

$$i_c = C\frac{dv_{dc}}{dt} = -i_g. \tag{4.15}$$

Positive power is defined as out of the converter three-phase terminals, and positive capacitor power is defined as into the capacitor. When power is extracted from the grid, it is injected into the capacitor, so in the synchronous *qd* reference frame,

$$-\frac{3}{2}v_{gq}^e i_{gq}^e = v_{dc}C\frac{dv_{dc}}{dt}. \tag{4.16}$$

Rearranging leads to the grid *q*-axis current in terms of the dc-link voltage, as

$$i_{gq}^e = -\frac{v_{dc}C\frac{dv_{dc}}{dt}}{\frac{3}{2}v_{gq}^e}. \tag{4.17}$$

The dc-link voltage is regulated by adjusting the power at the grid terminals. This is accomplished via the *q*-axis grid current command, defined as

$$i_{gq}^{e*} = -\left(v_{dc}^* - v_{dc}\right) K \left(1 + \frac{1}{\tau s}\right). \tag{4.18}$$

Again, parameters K and τ are assumed positive. When the actual dc-link voltage is larger than the commanded voltage, the current command will be increased, extracting more power from the dc-link and thereby reducing the voltage.

Assuming the actual current equals the commanded current, equating (**??**) and (**??**) in the frequency domain yields the transfer function

$$\frac{v_{dc}}{v_{dc}^{*}} = \frac{\frac{K3v_{gq}^{e}}{2Cv_{dc}}\left(s+\frac{1}{\tau}\right)}{s^2+\frac{K3v_{gq}^{e}}{2Cv_{dc}}s+\frac{K3v_{gq}^{e}}{2Cv_{dc}\tau}}. \tag{4.19}$$

The poles and zeros are placed to form a stable system with acceptable transient response.

b) Machine-Side Converter

The dynamic *qd* circuit model of the DFIG is shown in Fig. **??** . This circuit has all quantities referred to the stator.

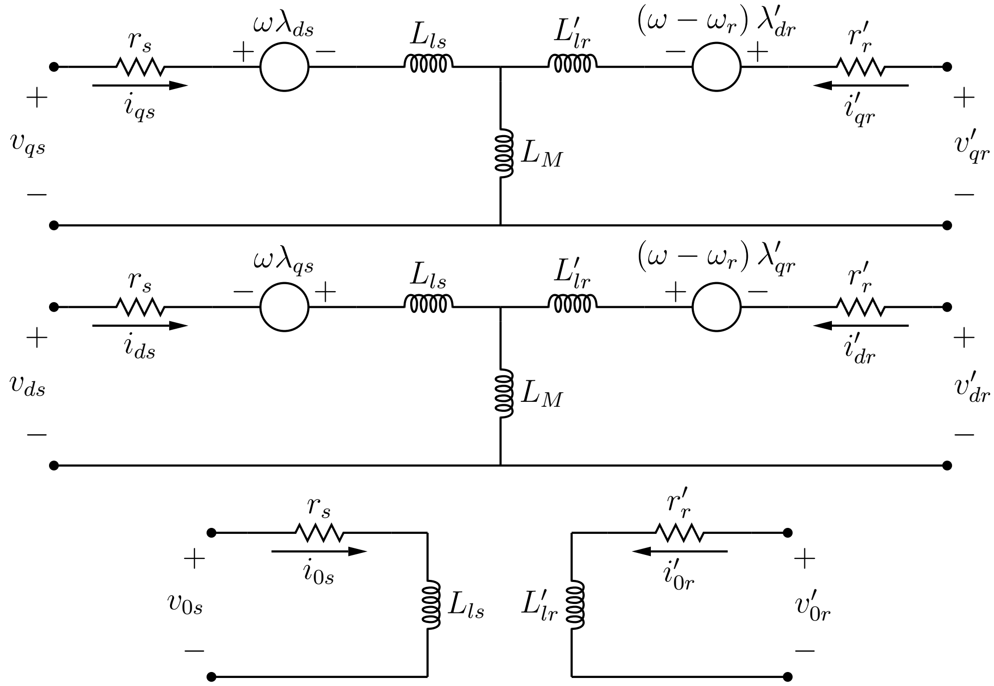

Figure 4.8: Dynamic DFIG circuit model in the arbitrary *qd0* reference frame.

In this model, ω is the angular frequency of the stator currents, and $\omega - \omega_r$ is the angular frequency of the rotor currents. In the rotor-tied configuration, the power electronics are connected to the stator. In this configuration, the reference frame for which the stator *qd* voltages have dc values is called the synchronous reference frame; ω is labeled ω_e. The speed of the reference frame for which the rotor *qd* voltages have dc values is $\omega_e - \omega_r$. In the rotor-tied configuration, $\omega_e - \omega_r = 2\pi 60$ rad/s.

In the stator-tied configuration, the power electronics are connected to the rotor. In this configuration, $\omega = \omega_e = 2\pi 60$ rad/s, and the reference frame for which the rotor *qd* voltages have dc values is still $\omega_e - \omega_r$.

All control operations are performed in the synchronous reference frame, which is specific to the DFIG configuration. For sake of controlling the machine, it is convenient to express the *qd* terminal voltages in terms of current, which will be a measured quantity. In the rotor-tied configuration, the synchronous *qd* stator terminal voltage in terms of rotor flux and stator current is

$$v_{qs}^{e} = \left(r_s i_{qs}^{e} + \sigma L_s p i_{qs}^{e}\right) + \left(\omega_e \sigma L_s i_{ds}^{e} + \omega_e \frac{L_M}{L_r'} \lambda_{dr}'^{e} + \frac{L_M}{L_r'} p \lambda_{qr}'^{e}\right) \tag{4.20}$$

$$v_{ds}^{e} = \left(r_s i_{ds}^{e} + \sigma L_s p i_{ds}^{e}\right) + \left(-\omega_e \sigma L_s i_{qs}^{e} - \omega_e \frac{L_M}{L_r'} \lambda_{qr}'^{e} + \frac{L_M}{L_r'} p \lambda_{dr}'^{e}\right). \tag{4.21}$$

where $\sigma = \left(1 - \frac{L_M^2}{L_s L_r'}\right)$. In the stator-tied configuration, the synchronous *qd* rotor terminal voltage in terms of stator flux and current is

$$v_{qr}'^{e} = \left(r_r' i_{qr}'^{e} + \sigma L_r' p i_{qr}'^{e}\right) + \left(\left(\omega_e - \omega_r\right) \sigma L_r' i_{dr}'^{e} + \left(\omega_e - \omega_r\right) \frac{L_M}{L_s} \lambda_{ds}^{e} + \frac{L_M}{L_s} p \lambda_{qs}^{e}\right) \tag{4.22}$$

$$v_{dr}'^{e} = \left(r_r' i_{dr}'^{e} + \sigma L_r' p i_{dr}'^{e}\right) + \left(-\left(\omega_e - \omega_r\right) \sigma L_r' i_{qr}'^{e} - \left(\omega_e - \omega_r\right) \frac{L_M}{L_s} \lambda_{qs}^{e} + \frac{L_M}{L_s} p \lambda_{ds}^{e}\right) \tag{4.23}$$

where $\sigma = \left(1 - \frac{L_M^2}{L_s L_r'}\right)$.

It is also useful to quantify the electromagnetic torque in terms of current. For the rotor-tied configuration, the torque in terms of stator current and rotor flux is

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\frac{L_M}{L_r'}\right)\left(-\lambda_{qr}'^{e} i_{ds}^{e} + \lambda_{dr}'^{e} i_{qs}^{e}\right), \tag{4.24}$$

and for the stator-tied configuration, the torque in terms of rotor current and stator flux is

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\frac{L_M}{L_s}\right)\left(-\lambda_{ds}^{e} i_{qr}'^{e} + \lambda_{qs}^{e} i_{dr}'^{e}\right). \tag{4.25}$$

Mechanical torque is applied to the shaft via the wind, and in terms of electrical rotor speed is

$$T_L = \frac{1}{2} \rho C_p A \left(\frac{r}{g\lambda}\right)^3 \left(\frac{2}{P}\omega_r\right)^2 \tag{4.26}$$

where P is the number of poles, r is the radius of swept area, A is the swept area, λ is the tip-speed ratio, g is the gear-ratio, ρ is the air density, and C_p is the performance coefficient.

Reactive power at the machine-to-grid terminals can also be controlled in the DFIG. The reactive power at the grid-tied terminals for each configuration is

$$Q_r = \frac{3}{2}\left(v_{qr}'^{e} i_{dr}'^{e} - v_{dr}'^{e} i_{qr}'^{e}\right) \tag{4.27}$$

$$Q_s = \frac{3}{2}\left(v_{qs}^{e} i_{ds}^{e} - v_{ds}^{e} i_{qs}^{e}\right). \tag{4.28}$$

In terms of the converter-side *d*-axis current, it is

$$Q_r = \frac{3}{2}\left(\frac{v_{qr}'^{e} \lambda_{dr}'^{e}}{L_r'} - \frac{v_{qr}'^{e} L_M i_{ds}^{e}}{L_r'}\right) \tag{4.29}$$

$$Q_s = \frac{3}{2}\left(\frac{v_{qs}^{e} \lambda_{ds}^{e}}{L_s} - \frac{v_{qs}^{e} L_M i_{dr}'^{e}}{L_s}\right). \tag{4.30}$$

Development of current, reactive power, and torque controlare left to the reader.

IV Homework

1. Sketch the components of a back-to-back power electronic converter. Be sure to include power switches, gate drivers, sensors, and anything else you feel is important. Also, briefly describe its operations.

2. Create the d-axis current controller transfer function. Calculate the values of K and τ to place the center of the real part of the poles at -790. Select a value of τ to make the system critically damped.

3. Calculate the line current rms value through the grid filter reactor of the GSC, and the fundamental component of the voltage at the GSC terminals. The grid voltage is three-phase 195 V, 60 Hz. The reactor has parameters $r = 0.09\ \Omega$ and $L = 5$ mH. The real power should be 2.5 kW into the grid, and the reactive power should be 0 VAR. If the maximum inductor current is 8 A, how much reactive power could the converter supply to the grid when the real power is 2.5 kW? How about if the real power is 0 W? And -2.5 kW?

4. The DFIG in the lab has parameters $r_s = 15.9$ mΩ, $r_r' = 8.7$ mΩ, $L_{ls} = 1.9$ mH, $L_{lr}' = 1.9$ mH, $L_M = 17.1$ mH, and $\frac{N_s}{N_r} = 1.067$. It is rated for $f = 60$ Hz. $V_r = 195$ V, $V_s = 208$ V, $I_s = 31$ A, $I_r = 26$ A, and $P_{\text{shaft}} = 7.5$ kW. This machine is not configured like the normal DFIG. Instead, the grid is connected to the rotor at the machine's rated values (195 V grid connection at the rotor terminals). The three-phase terminals of the back-to-back converter are connected to the stator terminals. Calculate the steady-state torque vs speed curve for a constant stator resistance of 4.9 ohm.

   (a) Calculate the steady-state stator line current and frequency, and shaft torque when operating at 1000 rpm.

   (b) What is the equivalent stator resistance if operating at 1000 rpm and 15 Nm with zero reactive power at the stator terminals?

   (c) Calculate the amount of power lost in the stator and rotor windings due to resistive elements. What is the efficiency at this condition?

Experiment 4.1: Back-to-back converter Inspection & Operation

Goals: Understand the topology of the back-to-back converter. Identify major components of the system. Understand theory of operation and limitations that may apply. Operate the converter and observe its behavior

Procedure:

1. Obtain the Semikron three-phase H-bridge power converter. Remove the cover to observe the interior of the system. As a group, discuss the components of the system and how they work to manage the power conversion process. Also consider and discuss this converter in the application of the back-to-back converter.

2. Using the Texas Instruments three-phase converter and the MATLAB code supplied with this laboratory, generate individual space vector states. With a dc-bus voltage of 5 V, and a permanent magnet machine connected to the three phase output, command a sequence of discrete switch states according to the table and vectors described earlier in this chapter, and observe the motor behavior. If time permits, reconfigure the model to command *qd* voltages with a reference frame angle equal to the machine shaft angle. Use a DC-bus voltage of 30 V. Observe the motor behavior.

3. Here, you will operate the GSC using the equipment configured to operate with the 7.5 kW DFIG. Connect a programmable constant power load to the DC-link, and keep it disabled; the power will be changed during operation. Enable the PLL to measure the grid voltage, and ensure that the controller is measuring it properly. Turn on the GSC breaker to establish a DC-link voltage via rectification of the grid voltage, through the fly-back diodes. Set the desired GSC dc-link voltage to 350 V, and enable the converter. Observe the associated currents, voltages, and control variables. Change the DC-link voltage command and the reactive power commands, and explore the converter response. Observe the power quality at $P_g = -2.5$ kW and $Q_g = 0$ VAR using a 3-ph power analyzer. What is the current harmonic distortion, and the actual reactive power?

Deliverables:

1. Sketch a block diagram of the back-to-back converter as you see it. Identify the major components, including the power switches, gate drivers, sensors, dc-link capacitors, and anything else you feel is important. Also, describe how each of the components contributes to the overall system.

2. Upon operating the GSC, answer the following: What is the rectified grid voltage value? Sketch the DC-link voltage during a step of reactive power from 0 VAR to 500 VAR. Sketch the DC-link voltage during step change from 294 V to 350 V. Use an oscilloscope to capture the waveform, but sketch it with pencil and paper. Use an oscilloscope to measure the line current when operaing at 2.5 kW, and sketch the waveform. What is the total current harmonic distortion measured via the power analyzer? Does this seem reasonable?

Experiment 4.2: Steady-State Operation of a DFIG

Goals: Operate a DFIG that is controlled with a back-to-back power electronic converter. Observe physical and control variables in real time. Measure performance characteristics under loaded conditions.

Procedure:

1. Connect the DFIG and back-to-back converter, and verify the variac is set to the appropriate terminal voltage. Set the dynamometer to control the rotor speed to 800 rpm. Energize the GSC to control the dc-link voltage to 350 V. Use the MSC to adjust the generator torque and grid-terminal reactive power.

2. Operate the machine at a variety of speed, torque, and reactive power combinations; try to stay within nameplate current ratings.

3. Adjust the proportional and integral gains on the torque and reactive power controllers, and observe the system response to changes in torque, speed, and reactive power command.

Deliverables:

1. Select a specifc torque and speed to operate at. For this condition, measure the shaft torque as well as the stator and rotor current magnitude and frequency? Knowing the machine parameters are $r_s = 15.9$ mΩ, $r'_r = 8.7$ mΩ, $L_{ls} = 1.9$ mH, $L'_{lr} = 1.9$ mH, $L_M = 17.1$ mH, and $\frac{N_s}{N_r} = 1.067$, calculate the stator and rotor current magnitude and frquency for the test condition. Are the measured values close to those calculated?

2. Measure the power at the shaft as well as at the generator rotor and filter inductor grid-side terminals. What is the efficiency of the system at the measured condition? Estimat the thermal loss due to winding resistance.

3. Control the rotor speed to 1200 rpm using the dynamometer, and use the MSC to increase the generator torque to 20 Nm. What do you observe at this condition? What happens to current harmonic distortion near syncronous speed? What, if any, difficulties arise with controlling the machine near syncronous speed?

4. Sketch the dc-link voltage in response to a 5 Nm step change in generator torque, at 1000 rpm. Also sketch it for a reactive power step change of 2000 VAR.