DYNAMIC INTEGRATION OF A GRID CONNECTED DFIG 
WIND TURBINE WITH A FUEL CELL

by
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ABSTRACT

For the past decade, the deregulation of the electric power industry has created an environment where traditional generation is being reexamined and new forms of generation are being created. Most likely wind turbines and fuel cells will be the dominant grid connected distributed generators.

This project proposes a novel integration of a doubly-fed induction generator (DFIG) and a fuel cell. With the proposed scheme, it is possible to inject power from a dc power source like a fuel cell into the ac grid without using an additional inverter. The fuel cell is connected across the dc link of the back-back converters of the DFIG. It operates as a power source integrated in the rotor circuit injecting power into the ac grid or the rotor circuit depending on the availability of wind energy and power requirements at the site. This is achieved by a low voltage dc link which also results in considerable savings in electronic devices used for the back-back converters.

As DFIGs and fuel cells are dynamic devices, accurate dynamic models are required to study the interaction between these two systems and the power system to which they are connected. As more power is injected into the system, they may begin to influence the overall system dynamics. Therefore, it is necessary to carry out simulation and laboratory studies to understand the influence of these devices in the overall power system.

Dynamic models of DFIG and PEM fuel cell have been derived which are used to simulate the proposed integrated system. Through vector control it is possible to control the active and reactive power generated by DFIG as well as operate the machine as an active filter. In addition, power factor correction can also be achieved. The complete system was simulated in Matlab/Simulink and an experimental setup was built to validate the proposed scheme. It is shown that the experimental results agree very well with simulation results.
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LIST OF ABBREVIATIONS

DFIG  Doubly-fed induction generator
WRIM(G)  Wound-rotor induction machine (generator)
SGIM(G)  Squirrel cage induction machine/motor (generator)
PEM  Polymer electrolyte membrane
PV  Photovoltaic
REC  Rotor-end converter
FEC  Front-end converter
IGBT  Insulated gate bipolar transistor
SPWM  Sinusoidal pulse width modulation
SVM  Space vector modulation
THD  Total harmonic distortion
SCR  Silicon controlled rectifier
DAQ  Data acquisition
DOS  Disk operating system
GUI  Graphical user interface
I/O  Input/output
pc  Personal computer
PCI  Peripheral component interconnect
PCB  Printed circuit board
Y  Star connection
dc  Direct current
ac  Alternating current
wb  Weber
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CHAPTER 1
INTRODUCTION

1.1 Background

During the last few decades, there has been a huge increase in energy demand that has accelerated the depletion of fossil fuel supplies. This combined with environmental concerns have created an opportunity for renewable energy sources to grab a larger share of the global energy market. In the long run, they will dominate for the simple reason that there is no other alternative.

Research has made renewable energy more affordable today than it was few decades ago. Currently, of all the renewable energy sources, wind energy and hydrogen energy can compete with conventional energy sources. One of the challenges with these two renewable energy sources is the integration with existing electric systems. The voltage generated by variable-speed wind power generators and fuel cells cannot be directly connected to the grid. Power electronics is the enabling technology that allows injection of power from renewable energy sources into grid.

Variable speed wind turbines equipped with doubly-fed induction generators (DFIGs) are becoming increasingly popular for high power applications. The stator of a wound rotor induction generator is directly connected to the ac grid and rotor currents are controlled to enable variable speed constant frequency operation. One major advantage of a DFIG system is that the converters are rated to handle only the rotor power which is typically 25% of the total generator power. This is also results in reduced losses in the converter compared to stator connected converters.

A DFIG with bi-directional converters in the rotor circuit can be used to generate optimized clean wind energy as well as to improve the power quality of the system [1], which has become a major issue due to proliferation of non-linear loads. DFIGs, when
operating below synchronous speed, absorb slip power from the ac grid through the rotor circuit in order to continue generating power from the stator side.

After initial use in aerospace applications, new research has significantly reduced the cost of fuels for terrestrial applications. Fuel cells provide clean energy conversion from hydrogen and other hydrocarbons. They are compact, silent, need only a few moving parts and are of modular technology. These are the reasons why fuel cells are being touted as the most promising innovation in the market of alternative energies for stationary, portable and automotive applications. Fuel cells are low voltage dc power sources. So, a dc-ac inverter is needed to inject the fuel cell power into the ac grid.

Most of the current research on DFIGs is primarily focused on developing accurate dynamic models of the grid connected system [2]. Various cases of grid connected generators are being analyzed. The same is the case with fuel cells. Researchers from various disciplines have come up with multiple dynamic models that can be used to study the transient nature of the fuel cell response [3]. Considerable research is also being conducted in developing suitable converters for grid connected fuel cells [4]. However, none have addressed the possibility of integrating a grid connected DFIG system with a fuel cell. This project proposes a novel integration of a DFIG system with a fuel cell system.

1.2 Proposed System

The schematic of the proposed integrated system in shown in fig.1.1. The fuel cell operates as a power source integrated in the rotor circuit of the DFIG injecting power into the grid or the rotor circuit. This scheme, while providing a renewable energy power source for the DFIG system, also eliminates the need of an inverter for fuel cell to inject power into the ac grid. The integration is achieved by a low voltage dc link which while allows the integration of low voltage fuel cells is also cost effective. The power electronic devices need only be rated for the dc link voltage.
1.3 Goals and Outline of Thesis

Based on the previous two sections, the following are the goals of this project:

1) To develop transient models of DFIG and fuel cell.
2) Derive vector control methods to control active and reactive power generated by the induction generator and operated the generator as an active filter.
3) Simulate the complete integrated system in Matlab/Simulink.
4) Build an experimental setup to verify simulation results.

This thesis is organized as follows:

- **Chapter 2** This chapter gives a detailed introduction on DFIGs and its common configuration. Steady-state characteristics are discussed. Various control methods currently in use are discussed.

- **Chapter 3** A d-q axis model for a DFIG is derived. Vector control methods to control the back-back converters are derived. It is shown that in a DFIG, active and reactive power can be controlled and harmonic compensation can be achieved.

- **Chapter 4** This chapter starts with a brief introduction of PEM fuel cells. An electrochemical model of the PEM fuel cell is derived. Brief description of the fuel cell simulator is also presented.

- **Chapter 5** The models of DFIG and fuel cell presented in chapters 3 and 4 are implemented in Matlab/Simulink. Simulink results showing active/reactive power control, harmonic compensation and the integrated operation are presented.

- **Chapter 6** Experimental setup to validate the simulation results was built. Main components and circuits are described in this chapter.

- **Chapter 7** Experimental results showing the integrated operation of DFIG and fuel cell are presented. Some of the problems faced are discussed. Simulation results are compared with experimental results.

- **Chapter 8** Conclusion and future work are discussed.
CHAPTER 2
DOUBLY-FED INDUCTION GENERATOR

The induction machine is the most common of all ac machines. They have advantages over conventional synchronous generators such as reduced installation cost, lower maintenance requirements, absence of power supply for excitation and natural protection against system overcurrents. Although, they are mostly used in motor applications, their use as a generator has regained importance particularly with respect to renewable energy applications.

There are two main types of induction machines: squirrel cage machines, with rotor windings short circuited and wound rotor induction machines with accessible slip rings that can be either short circuited or connected to an external circuit. Wound rotor machines are used in applications where it is desirable to influence the rotor circuit keeping the stator supply constant. Before the advent of semiconductors, external resistors were used to control the slip and consequently torque was lost in those resistors. By using power electronic converters it is possible recover this slip power lost in resistances. Thus, a wound rotor induction generator (WRIG) with converters in the rotor circuit i.e. fed from both stator and rotor is called a doubly-fed induction generator (DFIG). This chapter describes the advantages of such a system and its characteristics.

2.1 DFIG Configuration and Advantages

There are few variations of a doubly-fed machine [5]. Fig.2.1 shows the typical DFIG configuration with two back-back PWM converters in the rotor side. This configuration is currently being used by all major wind turbine manufacturers and is the only configuration studied in this thesis. The stator side of the induction machine is directly connected to grid and the rotor side is connected to grid through two back-back
converters. These converters are known by various names. In this thesis, the converter connected directly to the rotor terminals will be referred to as rotor end converter (REC) and the converter connect to the grid will be called as front end converter (FEC).

Doubly-fed machines were not very popular due to the maintenance required for the slip rings. More recently, with the development of new materials, powerful digital controllers and power electronics, the doubly-fed induction generator became a solution in power generation for up to several hundreds of kW ratings. Power converters, (whose cost for large units becomes irrelevant compared to the whole system) usually make up the need for a variable frequency source for the rotor. The following are the advantages of a DFIG compared to a squirrel cage induction generator (SGIG) [6]:

- In order to control a SCIG, a power converter with full power-processing capability is required. Whereas a DFIG requires a smaller power converter to process the slip power. Therefore, smaller the range of operating slip, smaller is the rating of the power converter required. The size of the power converter may strongly affect the cost of energy ($/kWh).
• A DFIG has a simpler control because the magnetizing current is practically constant regardless of the rotor frequency. The purpose of the control is to synchronize the rotor current with respect to stator reference.

• The utility connection to the DFIG can be controlled from both sides of machine; the power factor can be controlled from the stator or the rotor side of the WRIG.

• The DFIG can be commanded by either of the two techniques: (1) active and reactive power on the stator side can be controlled from the rotor side, or (2) the stator voltage can be set up from the rotor side. A DFIG can also be controlled to operate as an active filter compensating for the harmonics generated by power electronic devices.

• If a wound rotor generator system can operate in four-quadrants around the synchronous speed it can then operate in motor mode, for example for pumped hydro applications.

• A DFIG system increases the power system dynamic stability by quickly exchanging energy from the power system during fluctuations to machine inertia without loss of synchronism as happens with synchronous machines.

### 2.2 Steady State Characteristics of a DFIG

Figure 2.2 shows the per-phase equivalent circuit of a wound rotor induction machine with unity turns ratio. Standard conventions were followed in naming the machine

![Per-phase equivalent circuit of a wound rotor induction machine](image)

Figure 2.2 Per-phase equivalent circuit of a wound rotor induction machine.
parameters. For high power machines where \(|(r_s + j\omega_e L_{ls})| \ll \omega_e L_m\), the equivalent circuit can be simplified by moving the magnetizing inductance branch to left \([4]\). \(I_r\) is the current imposed by the converter on the rotor side; therefore, the impressed voltage \(V_{rs}/s\) on the rotor side has some phase shift \(\angle \phi\) with respect to the stator side. Using this simplified circuit, current \(I_r\) can be related to stator voltage by equation 2.1. From rotor current, electrical torque can be calculated as shown in equation 2.2, which is a function of slip \(s\) for constant stator voltage and frequency.

\[
\bar{I}_r = \frac{V_s \angle 0^\circ - \frac{V_r}{s} \angle \phi}{\sqrt{\left(\frac{r_s + r_r}{s}\right)^2 + \omega_e^2 \left(\frac{L_{ls} + L_{lr}}{s}\right)^2}} \tan^{-1} \left( \frac{\omega_e \left(\frac{L_{ls} + L_{lr}}{s}\right)}{r_s + \frac{r_r}{s}} \right)
\]

\[
T_e = 3 \left(\frac{p}{2}\right) I_r^2 \frac{r_r}{s\omega_e} = 3 \left(\frac{p}{2}\right) r_r \frac{V_s - 2 \frac{V_r}{s} \cos \phi + \left(\frac{V_r}{s}\right)^2}{s\omega_e \left(\frac{r_s + \frac{r_r}{s}}{s}\right)^2 + \omega_e^2 \left(\frac{L_{ls} + L_{lr}}{s}\right)^2}
\]

Figure 2.3 shows a family of curves where the phase shift between stator voltage and current will define the position and shape of the torque-slip curve. The rotor side voltage is assumed to be nearly constant and the phase shift would be varied to match the required constant air-gap flux. Figure 2.3 shows the torque-slip characteristic for short-circuited rotor windings (passive rotor power flowing in a squirrel cage type machine). As negative rotor power is extracted from the rotor the machine increases speed to the super-synchronous region in the curve operating at point a. The machine can have positive rotor power injected making a decrease in speed to the sub-synchronous region and operates at point b. It is clear that although super-synchronous operation is preferable to have generation by both stator and rotor, a stable operation for same torque levels
requires higher slip (s) and more losses incur at the rotor side. Therefore, it is advisable to implement a management of the optimum operating point that minimizes the losses in the super-synchronous mode.

![Figure 2.3 Effect of injected slip rotor power on the torque-slip characteristics of a DFIG.](image)

The operating characteristics of the induction generator from a current source are quite different from a voltage source. High power machines have small stator resistance drop and when controlled from an impressed voltage source, the air-gap voltage is closer to the stator voltage, but under impressed current the air-gap voltage and stator voltage vary with shaft loading. Rotor voltage control leads to motoring-only stable operation in sub-synchronous mode and to generating-only stable operation in super-synchronous mode. For rotor current control both motoring and generating forms are stable in sub- and super-synchronous modes. Fig. 2.4 shows the power distribution of an induction generator when operating in sub and super-synchronous modes. The power distribution for the generator is indicated in the operating region from $0.7\omega_s$ to $1.3\omega_s$. For operation at sub-synchronous region the slip is positive and therefore the rotor circuits receives
power from the line whereas for super-synchronous region the slip is negative and the rotor power supplements extra generating power at the grid.

Figure 2.4 Torque-slip curve of DFIG in sub- and super synchronous modes.

Figure 2.5 shows the power balance in a DFIG at sub-synchronous generation where \( s > 0 \) and the power flows into the rotor by a current-controlled inverter. Figure 2.6 shows the super-synchronous generating mode where the mechanical speed is greater than the electrical synchronous speed. Since the slip is negative \( (s < 0) \), the rotor voltages will have their phase sequence reversed. In this mode, \( P_g < 0 \) and \( P_r < 0 \). The rotor circuit contributes in generating power to the line with improved efficiency. It is important to note that the shaft incoming power indicates \( P_m = (1+s)P_g \) to show the extra capability of power conversion. Thus, higher conversion efficiency can be achieved using the super-synchronous mode.
2.3 DFIG Control Methods

Several converter topologies can be used to control a DFIG and many control approaches have been studied and implemented. Nonetheless it is possible to classify them into two broad approaches: (i) a complete controller where the prime mover active power and the line-side reactive power are the set-points for a rotor frame controller, for a grid-connected system and (ii) a simplified current controller with a line voltage control for stand-alone applications that not require full active/reactive power management. Both approaches are currently implemented using vector control theory. The REC will receive the set-points from the vector controlled based system. For back-back converter topology,
an inner control loop for dc-link voltage control will be required, which will be sent to FEC.

In this project, approach (i) is used. The induction machine is always connected to grid on the stator side. Active and reactive power generated by the induction generator is controlled by the rotor end converter. Dc link voltage and power factor in the rotor circuit are controlled by the front end converter. In addition, the REC also works as an active filter by controlling the harmonics generated on the stator side. These controlled techniques are derived in chapter 3.

2.4 Back-Back PWM Converters

Fig. 2.7 shows the arrangement of switches in a back-back converter system. A large electrolytic capacitor is used to keep the dc link voltage constant and provide a path for rapidly changing inverter currents. A 3300 \( \mu \)F electrolytic capacitor is used in this project. Each converter is a set of six switches where the three upper switches are connected to the positive side of the dc link, and the lower three switches are connected to the negative side of the dc link. IGBTs are a preferred choice in small-medium power applications. In this project, IGBT converter modules manufactured by Powerex are used. The module contains an in-built driver circuit which simplifies the overall circuit. Six gate voltage signals have to be input to the module for the six switches. These gate signals determine whether the switches are ON or OFF. Each IGBT switch has an inverse parallel connected diode called a free wheeling or feedback diode to provide a path for current to flow when the IGBTs are turned off.

2.4.1 Sinusoidal Pulse Width Modulation

For the IGBT converters to generate the desired three phase voltages, a carrier based modulation method needs to be used to generate gate voltages from the reference
voltages. The choice of the modulator has a significant effect on the performance of the PWM converter. Different modulators produce different responses from the converters such as different THD (total harmonic distortion) levels, current ripple, peak inverter output voltage, switching losses etc and the modulators by themselves can be of varying levels of complexity.

Several methods have been proposed in literature e.g., sinusoidal PWM, sinusoidal PWM with third harmonic injection and space vector modulation (SVM). All these methods have constant carrier frequency which is usually much higher than the fundamental frequency of the inverter voltage. Of these three methods, SVM is the most complex and sinusoidal PWM is the simplest. After studying these modulation methods, it was found that SVM has the lowest THD and the highest peak inverter fundamental voltage. Sinusoidal PWM performed only slightly weaker compared to SVM but, it is a lot simpler method to implement both in software and hardware. So, sinusoidal pulse width modulation (SPWM) was chosen as the modulation method for this project.

Fig. 2.8 shows how SPWM is implemented. The reference waveform for each phase is compared to a triangular waveform of a much higher frequency. When the magnitude of the reference waveform is higher than the triangular waveform, upper IGBT in that leg is turned ON and when the magnitude of reference waveform is lower than the triangular
waveform, lower IGBT in that leg is turned ON. This method is explained in detail in chapter 5.

![Carrier and reference waveforms](image)

Figure 2.8 Sinusoidal pulse width modulation technique.
CHAPTER 3
DYNAMIC MODELING AND VECTOR CONTROL OF THE DFIG

In this chapter, a dynamic model of a DIFG is derived and vector control methods to control the same are developed. Per-phase equivalent circuit shown in fig.2.2 is inadequate for dynamic analysis of an induction machine and it also results in mutual inductances between stator and rotor varying with rotor position. This coupling can be eliminated by using a two-axes space vector model of the machine. In this system, all the three phase variables in the induction machine are represented in a two-phase system. A brief description of this three-phase to two-phase transformation, also known as d-q or Park’s transformation is presented. After developing equations to model an induction machine, vector control of a DFIG in explained in detail.

3.1 D-Q Transformation

D-Q transformation is a transformation of coordinates from the three-phase stationary system to the rotating two-phase system. This is made in two steps. First, the stationary three phase-variables (a-b-c) are transformed to stationary two-phase (d^e-q^e) variables. These are then transformed to rotating two-phase (d^e-q^e) variables.

Fig.3.1 shows the vector representation of stationary three-phase variables a, b, c and stationary two phase variables d^e, q^e. For the sake of simplicity, vector d^e is assumed to be aligned with vector a. Equation 3.1 shows the transformation matrix. For a three phase balanced system, the zero axis component is zero. Therefore, the transformation can be simplified as shown in equations 3.2. Inverse transformation can also be calculated as shown in equation 3.3.
The second transformation is to rotate the axes of the two-phase system at a certain frequency. Therefore, any vector rotating at this frequency will appear as a dc value in that frame. Vector representation of these two frames is shown in fig. 3.2. The $d^c$-$q^c$ frame
is also referred to as reference frame or synchronous frame when it is rotating at synchronous frequency.

Equation 3.4 shows the transformation matrix. These equations can again be simplified to equation 3.5. Inverse transformation back to stationary frame is shown in equation 3.6. The superscript ‘e’ for reference frame quantities will be omitted in future references for convenience. Equation 3.1 to 3.6 can now be used to transform any three-phase quantities to rotating two-phase quantities. In this project, two rotating frames are used. One rotating at the stator electrical frequency for transforming stator quantities and other rotating at the rotor slip frequency for transforming rotor variables.

\[
\begin{bmatrix}
    x_d^e \\
    x_q^e \\
    x_0^e
\end{bmatrix} =
\begin{bmatrix}
    x_d^s \\
    x_q^s \\
    x_0^s
\end{bmatrix}
\begin{bmatrix}
    \cos \omega t & -\sin \omega t & 0 \\
    \sin \omega t & \cos \omega t & 0 \\
    0 & 0 & 1
\end{bmatrix}
\]

\[
x_d^e = x_d^s \cos (\omega t) + x_q^s \sin (\omega t)
\]

\[
x_q^e = -x_d^s \sin (\omega t) + x_q^s \cos (\omega t)
\]

\[
x_d^e = x_d^s \cos (\omega t) - x_q^s \sin (\omega t)
\]

\[
x_q^e = x_d^s \sin (\omega t) + x_q^s \cos (\omega t)
\]
3.2 Park’s Model of the Induction Machine

The following equations of the induction machine, well known in literature, obtained from fig.3.3 are used to model a wound rotor induction generator. Motor model convention was used. So, the currents are the inputs and real and reactive powers have a negative sign when they are fed into the grid. The subscripts ‘s’ and ‘r’ indicate stator and rotor quantities respectively.

![d-q axes equivalent circuit of an induction machine](image)

Figure 3.3 d-q axes equivalent circuit of an induction machine.

Stator and rotor voltage equations obtained from fig.3.3 are shown in equation 3.7. \( \omega_e \) and \( \omega_r \) are stator electrical frequency and rotor electrical angular speed respectively.

\[
\begin{align*}
\nu_{ds} &= R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_e \psi_{qs} \\
\nu_{qs} &= R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_e \psi_{ds} \\
\nu_{dr} &= R_r i_{dr} + \frac{d\psi_{qr}}{dt} - (\omega_e - \omega_r) \psi_{qr} \\
\nu_{qr} &= R_r i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega_e - \omega_r) \psi_{dr}
\end{align*}
\] (3.7)

Flux linkages developed in the machine are calculated using the equations shown in equation 3.8.
\[ \psi_{ds} = L_d i_{ds} + L_m (i_{ds} + i_{dr}) \]  
\[ \psi_{qs} = L_d i_{qs} + L_m (i_{qs} + i_{qr}) \]  
\[ \psi_{dr} = L_d i_{dr} + L_m (i_{ds} + i_{dr}) \]  
\[ \psi_{qr} = L_d i_{qr} + L_m (i_{qs} + i_{qr}) \]  
\[ (3.8) \]

From equations 3.8, flux linkages in the induction machine can be calculated. From these calculated fluxes, by a simple matrix inversion, the currents generated are obtained as shown in equation 3.9

\[
\begin{bmatrix}
  i_{ds} \\
  i_{qs} \\
  i_{dr} \\
  i_{qr}
\end{bmatrix} =
\begin{bmatrix}
  L_{ls} + L_m & 0 & L_m & 0 \\
  0 & L_{ls} + L_m & 0 & L_m \\
  L_m & 0 & L_{lr} + L_m & 0 \\
  0 & L_m & 0 & L_{lr} + L_m
\end{bmatrix}^{-1}
\begin{bmatrix}
  \psi_{ds} \\
  \psi_{qs} \\
  \psi_{dr} \\
  \psi_{qr}
\end{bmatrix}
\](3.9)

The electrical torque in the machine generated is calculated using equation 3.10 where, \( P \) is the number of poles.

\[ T_e = \frac{3}{2} P (\psi_{dr} i_{qr} - \psi_{qr} i_{dr}) \]  
\[ (3.10) \]

The mechanical angular velocity of the generator is calculated by:

\[ \frac{d \omega_m}{dt} = \frac{(T_m - T_e)}{J} \]  
\[ (3.11) \]

\( \omega_m \) is the mechanical angular speed, \( J \) is the system inertia and the mechanical torque input or the wind turbine torque input, \( T_m \), to the induction generator is calculated by
equation 3.12. \( p \) is the air density, \( v \) is the wind speed, \( r \) is the propeller radius, \( CT \) is the wind turbine power coefficient and \( N_{gear} \) is the gearbox ratio.

\[
T_m = \frac{Dv^2 \pi r^3 CT}{2N_{gear}} \tag{3.12}
\]

Equations for active and reactive powers generated/consumed by the induction generator can be written in terms stator current components as shown in 3.13. With these equations, modeling of the induction generator is complete.

\[
Q_s = \frac{3}{2} \text{Im}(v_{qds} \cdot i_{qds}) = \frac{3}{2} (v_{qs} i_{ds} - v_{ds} i_{qs}) 
\]

\[
P_s = \frac{3}{2} \text{Re}(v_{qds} \cdot i_{qds}) = \frac{3}{2} (v_{qs} i_{qs} + v_{ds} i_{ds}) \tag{3.13}
\]

### 3.3 Vector Control of a Doubly-fed Induction Generator

Induction machines have several advantages such as size, weight, efficiency, cost etc. However, being polyphase electromagnetic machines they have a highly interactive multivariable control structure and thus are difficult to control. The technique of field-oriented or vector control permits an algebraic transformation that converts the dynamic structure of the ac machine into that of a separately-excited decoupled control structure with independent control of flux and torque.

Several vector control methods have been proposed in literature to control a DFIG [7]. Stator flux oriented rotor current control is the most common way of controlling a DFIG [7, 8, 9, 10]. References [11, 12] use air-gap flux oriented control method. For high-power machines, if the stator resistance can be considered small, stator flux orientation gives orientation with the stator voltage [13, 14]. According to ref. [13], pure
In this project, stator flux-oriented control is used to control the rotor end converter and grid voltage oriented control is used to control the front end converter [9]. Stator flux orientation is achieved by on-line estimation of the stator flux vector position. This type of control, also known as direct vector control (DVC), is less sensitive to machine parameters. It is dependent only on stator resistance, which is easy to correct. It is very robust due to real-time tracking of machine parameter variation with temperature and core saturation, but typically does not work at zero shaft speed. This approach is suitable for induction generator control because zero speed operation is not required.

3.3.1 Rotor End Converter Control

The REC is used to control the active and reactive power generated by the DFIG as well to achieve harmonic compensation. A stator flux oriented vector control scheme is used to achieve decoupled control of active and reactive power [1, 9]. The same control procedure can also be used to achieve harmonic compensation. The stator flux vector orientation along the rotating reference frame as shown in fig.3.4. Since $d^e$ axis is aligned along the stator flux vector, the $q$-axis component of stator flux is zero.

![Figure 3.4 Stator flux orientation](image-url)
Assuming small stator resistance voltage drop and since stator is connected to grid, stator flux vector will remain constant and lags the stator voltage vector by $90^\circ$. Therefore, due to stator flux orientation, $v_{ds} = 0$. Stator active and reactive power equations shown in 3.13 can be rewritten as:

$$Q_s = \frac{3}{2} v_{qs} i_{ds}$$

(3.14)

$$P_s = \frac{3}{2} v_{qs} i_{qr}$$

Since the control of the induction generator is through the rotor currents, stator quantities must be written in terms to rotor quantities. Substituting $\psi_{qs}=0$ in stator flux linkage equations of 3.8, the d-axis rotor current component is obtained as:

$$i_{dr} = -\frac{L_s}{L_m} i_{ds} + \frac{1}{L_m} \psi_{ds}$$

(3.15)

where, $L_s = L_{ls} + L_m$. From 3.15, a positive injection of $i_{dr}$ will result in lesser value of $i_{ds}$ being drawn from the stator side. That is, amount of reactive power drawn from grid can be controlled using $i_{dr}$. Similarly, q-axis rotor current component is obtained as:

$$i_{qr} = -\frac{L_s}{L_m} i_{qs}$$

(3.16)

From equation 3.16, the magnitude of $i_{qs}$ is directly proportional to $i_{qr}$. That is, active power generated by the machine can be controlled using $i_{qr}$ and the induction generator behaves like a current transformer for active power flow. Injection of positive $i_{qr}$ will
result in negative $i_{qs}$ being drawn from grid terminals or active power is being injected into the grid. Substituting equations 3.15 and 3.16 in rotor flux linkage equations in 3.8:

$$
\psi_{dr} = \sigma L_r i_{dr} + \frac{L_m}{L_s} \psi_{ds}
$$

$$
\psi_{qr} = \sigma L_r i_{qr}
$$

where, $L_r = L_{tr} + L_m$ and $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ Using equations 3.15 - 3.17, the rotor voltage equations shown in 3.7 can be rewritten as:

$$
v_{dr} = R_{dr} i_{dr} - (\omega_e - \omega_r) \sigma L_r i_{qr} + \sigma L_r \frac{di_{dr}}{dt} + \frac{L_m}{L_s} \frac{d\psi_{ds}}{dt}
$$

$$
v_{qr} = R_{qr} i_{qr} + (\omega_e - \omega_r) \sigma L_r i_{dr} + (\omega_e - \omega_r) \frac{L_m}{L_s} \psi_{ds} + \sigma L_r \frac{di_{qr}}{dt}
$$

From equations 3.19, it is observed that there is cross coupling between d and q axes due to the presence of rotational emf terms. The current loop dynamics along d and q axes can be made independent by compensating for these terms. However, as the operating slip range of a DFIG is limited the contributions of these terms are rather small. Also, since the stator flux is practically constant, the transformer emf term depending on derivative of flux can be neglected. Therefore, the governing rotor voltages equations for active and reactive power control can be written as:

$$
v_{dr}^* = (k_{qp} + k_{qi}) (i_{dr}^* - i_{dr}) - (\omega_e - \omega_r) \sigma L_r i_{qr}
$$

$$
v_{qr}^* = (k_{pp} + k_{pq}) (i_{qr}^* - i_{qr}) + (\omega_e - \omega_r) \sigma L_r i_{dr} + (\omega_e - \omega_r) \frac{L_m}{L_s} \psi_{ds}
$$

Where $k_{qp}$, $k_{qi}$ are proportional and integral gains for d-axis current (reactive power) respectively, $k_{pp}$, $k_{pq}$ are proportional and integral gains for q-axis current (active power)
respectively and $i_{dr}^*,$ $i_{qr}^*$ are references for reactive and active power. These d-q axis reference voltages are converted to a-b-c frame to generate commands for the rotor end PWM converter.

### 3.3.1.1 Harmonic Compensation

If a non-linear load is connected at the stator terminals of the induction generator, it is possible to compensate for the harmonics generated by the load by adding the harmonic current reference to the rotor currents. If $i_{dlh}^*$ and $i_{qllh}^*$ are the d-q axes load currents obtained after filtering out the fundamental from the non-linear load current, the harmonic reference that needs to be added to the rotor current reference is given by equation 3.21. These currents are obtained using a band pass filter that filters out everything except the 5th, 7th, and 11th harmonics. In a three phase star-connected system, odd harmonic currents that are multiples of three do not exist.

\[
\begin{align*}
    i_{drh}^* &= -\frac{L_s}{L_m} i_{dlh}^* + \frac{1}{L_m} \psi_{ds} \\
    i_{qrh}^* &= -\frac{L_s}{L_m} i_{qllh}^*
\end{align*}
\]

Therefore, the total rotor current reference is the sum of power reference and harmonic compensation reference given by:

\[
\begin{align*}
    i_{dr}^* &= i_{dr-r}^* + i_{drh}^* \\
    i_{qr}^* &= i_{qr-a}^* + i_{qrh}^*
\end{align*}
\]

where $i_{dr-r}^*, i_{qr-a}^*$ are references for active and reactive power respectively. Equation 3.23 shows the relation between rotor currents and power demand. Therefore, without making
any major changes to the existing DFIG control system, it can be made to operate as an active filter.

\[
Q_s = \frac{3}{2} V_s \left( \frac{\psi_{ds} - L_m i_{dr-r}}{L_s} \right)
\]

\[
P_s = -\frac{3}{2} V_s \frac{L_m}{L_s} i_{qr-a}
\]

### 3.3.1.2 Stator Flux Calculation

Stator flux calculation, also known in literature as stator flux observer is calculating the magnitude and phase of the stator flux vector without directly measuring the flux. Various methods have been proposed to calculate the stator flux [15-17]. The most common way of calculating stator flux is shown in equation 3.24 obtained from stator voltage and current measurements.

\[
\psi_{ds}^s = \int (\psi_{ds}^s - R_s i_{ds}) \, dt
\]

\[
\psi_{qs}^s = \int (\psi_{qs}^s - R_s i_{qs}) \, dt
\]

\[
|\psi_{ds}| = |\psi_{qs}| = \sqrt{\left(\psi_{ds}^s\right)^2 + \left(\psi_{qs}^s\right)^2}
\]

Equations 3.25 and 3.26 show the calculations for stator flux vector position and angular speed.

\[
\theta_e = \tan^{-1} \frac{\psi_{qs}^s}{\psi_{ds}^s}, \quad \omega_e = \frac{\psi_{ds}^s \frac{\partial}{\partial t} (\psi_{qs}^s) - \psi_{qs}^s \frac{\partial}{\partial t} (\psi_{ds}^s)}{\left(\psi_{qs}^s\right)^2 + \left(\psi_{ds}^s\right)^2}
\]

\[
\cos \theta_e = \frac{\psi_{ds}^s}{|\psi_{ds}|}, \quad \sin \theta_e = \frac{\psi_{qs}^s}{|\psi_{ds}|}
\]
This direct integration method to calculate stator flux works very well in simulation. However, it poses problems in an experimental setup. Few disadvantages of using this method are sensitivity to stator resistance, drift due to offset in the signals and incorrect initial value for integration. For generator applications, stator resistance sensitivity can be neglected as the generator usually operates at high speeds. Even if the stator resistance calculation is slightly off, the voltage drop across the resistance is small and variation can be ignored. The other two problems can be compensated by using a low-pass filter instead of direct integration.

\[
\psi_{ds}^s[s] = \frac{1}{s + \omega_c} \left( v_{ds}^s[s] - R_s i_{ds}^s[s] \right)
\]

\[
\psi_{qs}^s[s] = \frac{1}{s + \omega_c} \left( v_{qs}^s[s] - R_s i_{qs}^s[s] \right)
\]

where \( \omega_c \) is the corner frequency of the filter. This frequency has to at least ten times the frequency of the machine. Equation 3.28 shows the recursive filter equation used in the experimental setup.

\[
\psi_{ds}^s[n] = \frac{1}{2T + \omega_c} \left[ \left( v_{ds}^s[n] - R_s i_{ds}^s[n] \right) + \left( v_{ds}^s[n-1] - R_s i_{ds}^s[n-1] \right) \right]
\]

where \( T \) is the sampling time. \( \omega_c \) is chosen to be 20 rad/sec. Figure 3.5 shows the block diagram for the rotor end converter. As shown in figure, stator flux oriented vector control requires measurement of stator and rotor currents, stator voltages and rotor angular position. The harmonic references for active filter operation are obtained from the non-linear connected to grid.
3.3.2 Front End Converter Control

Ideally, when the generator is operating in sub-synchronous mode FEC is not required. Power control and harmonic compensation can be accomplished using just the REC driven by a dc power source. But, DFIG generates from both the stator and rotor when operating above synchronous speed. Therefore, FEC is used to provide a path for power flow from REC into grid in super-synchronous mode as well as power into REC during sub-synchronous mode. It allows bidirectional power flow in the rotor circuit. Other important function of FEC is to keep the dc link capacitor voltage constant regardless of direction and magnitude of power flow. The FEC can also be used to
control the reactive power flow into the grid. A grid (stator) voltage vector oriented vector control scheme is used. This allows decoupled control of dc link voltage power and reactive power while allowing bidirectional power flow [9]. The voltage vector is oriented along d-axis as shown in fig. 3.6.

![Figure 3.6 Voltage vector orientation.](image)

Control structure of FEC is very similar to REC except that due to d-axis orientation of voltage, active power is related to d-axis current and reactive power is related to q-axis current. Fig. 3.7 shows the arrangement of the converter. L and R are the line inductance and resistance respectively. The converter is connected to grid through transformers as the dc link is operated at a lower voltage level. The voltage balance equations across the inductors shown in fig.3.7 are shown in equation 3.29. Transforming equation 3.29 into d-q reference frame, following equations are obtained:

\[
\begin{bmatrix}
    v_a \\
    v_b \\
    v_c
\end{bmatrix}
= R
\begin{bmatrix}
    i_a \\
    i_b \\
    i_c
\end{bmatrix}
+ L \frac{d}{dt}
\begin{bmatrix}
    i_a \\
    i_b \\
    i_c
\end{bmatrix}
+ \begin{bmatrix}
    v_{at} \\
    v_{bt} \\
    v_{ct}
\end{bmatrix}
\]

\[v_d = Ri_d + L \frac{di_d}{dt} - \omega_L i_q + v_{dl}\]  \(3.30\)

\[v_q = Ri_q + L \frac{di_q}{dt} + \omega_L i_d + v_{ql}\]
Figure 3.7 Front end converter arrangement.

where $\omega_g$ is the angular speed of the grid voltage vector calculated from the stationary d-q axis grid voltages using equation 3.31.

$$\theta_g = \int \omega_g \, dt = \tan^{-1} \frac{v_q^{\ast}}{v_d^{\ast}}$$  \hspace{1cm} (3.31)

and $\cos \theta_g = \frac{v_d^{\ast}}{\sqrt{(v_d^{\ast})^2 + (v_q^{\ast})^2}}$, $\sin \theta_g = \frac{v_q^{\ast}}{\sqrt{(v_d^{\ast})^2 + (v_q^{\ast})^2}}$

Since the d-axis of the reference frame is oriented along the grid voltage vector, q-axis component of grid voltage is zero. From the active and reactive power equations shown in 3.32, active power is proportional to d-axis component of current and reactive power is proportional to q-axis component of current.

$$P_g = \frac{3}{2} v_d i_d$$ \hspace{1cm} (3.32)

$$Q_g = -\frac{3}{2} v_d i_q$$
The energy stored in the electrolytic dc link capacitor is given by \( CE^2 / 2 \). The time derivative of this energy must be equal to the sum of instantaneous grid power and the rotor power. Neglecting harmonics due to transistor switching and losses in the system, the following equations are obtained at the dc link shown in fig.3.7.

\[
\frac{1}{2} C \frac{dE^2}{dt} = P_g - P_r \quad \Rightarrow \quad CE \frac{dE}{dt} = P_g - P_r
\]  

(3.33)

where \( P_g = \frac{3}{2} v_d i_d \) and \( P_r = \frac{3}{2} (v_{dr} i_{dr} + v_{qr} i_{qr}) \)

From fig. 3.7 \( i_{or} = \frac{P_r}{E} \) and \( i_{og} = \frac{P_g}{E} \)

\[
\therefore \quad C \frac{dE}{dt} = i_{og} - i_{or}
\]

From equation 3.33 it can be observed that the dc link voltage can be controlled using the active power reference current (d-axis component of current). Thus, d-axis current is controls the dc link voltage and reactive power is controlled using the q-axis current. Equation 3.30 can be rewritten as shown below:

\[
v_{d1} = \left( Ri_d + L \frac{di_d}{dt} \right) + \omega_q L i_q + v_d
\]  

(3.34)

\[
v_{q1} = \left( Ri_q + L \frac{di_q}{dt} \right) - \omega_q L i_d
\]

Therefore, the governing voltages equations for FEC are given by:

\[
v_{d1}^* = -(k_{eq} + k_{el}) (i_d^* - i_d) + \omega_q L i_q + v_d
\]  

(3.35)

\[
v_{q1}^* = (k_{qeq} + k_{qel}) (i_q^* - i_q) - \omega_q L i_d
\]
where \( v_{d1}^* \) and \( v_{q1}^* \) are the reference values for the front end converter and \( i_{d}^* \) is derived from the dc link voltage error. \( k_{ep} \), \( k_{ei} \) are proportional and integral gains for d-axis current (dc link voltage) respectively, \( k_{qp}, k_{qi} \) are proportional and integral gains for q-axis current (reactive power) respectively. These d-q axis reference voltages are converted to a-b-c frame to generate commands for the front end PWM converter. Feed forward terms shown in the right hand side of equation 3.35 are the rotational emf terms that appear as cross coupling terms due to the d-q transformation. These are included as compensation terms to provide proper decoupling between the axes and improve the transient response of the converter. Figure 3.8 shows the block diagram for the front end converter.

![Figure 3.8 Vector control scheme for the front end converter.](image)
CHAPTER 4
DYNAMIC MODELING OF THE PEM FUEL CELL

One of the main goals of this project is to integrate a dc power source such as a fuel cell with the DFIG. In this project, a polymer electrolyte membrane (PEM) fuel cell is connected across the dc link of the DFIG system. However, as mentioned previously, a real fuel cell cannot be used in the laboratory due to safety concerns. Therefore, a fuel cell simulator is built using an SCR phase controlled rectifier controlled using an electrochemical model of a PEM fuel cell in Labview [18, 19]. The simulator is shown to closely reproduce the response of a real fuel cell. It responds to changes in load and operating parameters such as pressure, temperature, humidity etc in a similar way to the real fuel cell. Parameters of a 500W Avista PEM fuel cell are used for this project. This chapter describes the electrochemical model of the PEM fuel cell, equivalent electrical circuit model as well as the basic hardware setup for the fuel cell simulator. Basic operation of a PEM fuel cell is also explained. Simulation of the electrochemical model in Matlab/Simulink and Labview is explained in chapter 5. Chapter 6 explains in detail the hardware used for the fuel cell simulator.

4.1 PEM Fuel Cell System

Fuel cells convert chemical energy in gases such as hydrogen, methane and oxygen into electrical energy through electrochemical reactions. There are different types of fuel cells classified according to its operation at low or high temperatures. PEM fuel cells are low temperature fuel cells (about 120 °C). In a PEM fuel cell, the conversion of chemical energy to electrical energy is facilitated by an electrode-electrolyte structure that operates on principles similar to chemical batteries. However, while a battery’s fuel and oxidant supplies are stored within the cell, PEM fuel cells permit fuel and oxidants to
continuously flow through the cell. The direct conversion of fuel and air to electricity is much more efficient than internal combustion engines and other methods of generating electricity. Therefore, fuel cells can generate more electricity from the same amount of fuel. Furthermore, by skipping the combustion process that occurs in traditional power-generating methods, the generation of pollutants during the combustion process is avoided. PEM fuel cells are currently used as commercial and residential power sources as well as in electric vehicles. They are being considered to be the best type of fuel cell to substitute the internal combustion engines in automobiles and eventually replace the gasoline and diesel.

Operation of a PEM fuel cell is shown in fig.4.1. The fuel cell uses a solid polymer membrane (a thin plastic film) as the electrolyte. This polymer is permeable to protons when it is saturated with water, but it does not conduct electrons. The fuel for the cell is hydrogen and the charge carrier is the hydrogen ion (proton). At the anode, the hydrogen molecule is split into hydrogen ions (protons) and electrons. The hydrogen ions permeate across the electrolyte to the cathode while the electrons flow through an external circuit and produce electric power. Oxygen, usually in the form of air, is supplied to the cathode and combines with the electrons and the hydrogen ions to produce water. The reactions at the electrodes are as follows:

Anode reaction: \( H_2 \rightarrow 2H^+ + 2e^- \) \hspace{1cm} (4.1)
Cathode reaction: \( O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \)
Overall reaction: \( 2H_2 + O_2 \rightarrow 2H_2O + \text{heat} + \text{electrical energy} \)

Compared to other types of fuel cells, PEM fuel cells generate more power for a given volume or weight of fuel cell. This high-power density characteristic makes them compact and lightweight. In addition, the operating temperature is less than 100° C, which allows rapid start-up. These traits and the ability to rapidly change power output are some of the characteristics that make the PEM the top candidate for automotive
power applications. Other advantages result from the electrolyte being a solid material. The sealing of the anode and cathode gases is simpler with a solid electrolyte, and therefore, less expensive to manufacture. The solid electrolyte is also more immune to difficulties with orientation and has fewer problems with corrosion, compared to many of the other electrolytes, thus leading to a longer cell and stack life. One of the disadvantages of the PEM for some applications is that the operating temperature is low. Temperatures near 100°C are not high enough to perform useful cogeneration. Also, since the electrolyte is required to be saturated with water to operate optimally, careful control of the moisture of the anode and cathode streams is important.

An electrical energy generation system using a stack of PEM fuel cells can be represented according to Fig. 4.2. The figures shows a fuel cell stack supplied with hydrogen, oxygen (air) and water for refrigeration and the output products are hot water and electricity. Under normal operation, a single fuel cell typically produces 0.5 V to 0.9 V. For use in generation systems, where relatively high power is needed, several cells are connected in series, arranged in a stack that can supply hundreds of kW of power. \( V_s \) represents the total stack output voltage, which is obtained by multiplying the cell voltage with the number of cells. The reformer is also represented, for obtaining hydrogen from a
hydrocarbon. The electrical output of the cell is connected to a generic load. There is no restriction with respect on the type of load as long the power supplied by the stack is capable of feeding it or if they do not represent starting motors and fast transient response loads. When the fuel cell is injecting power into the grid, the load could represent a boost dc/dc converter, followed by a dc/ac converter, linked to the grid through a transformer. In isolated systems it can represent a pure resistive load (heating) or a resistive-inductive load (motor), for example.

In this project, the fuel cell is connected across the dc link of the DFIG system through a boost dc/dc converter. The fuel cell utilizes the back-back converters to inject power into the grid or into the machine. This is explained in detail in later sections.

Figure 4.2 Typical PEM fuel cell generating system.

4.2 Electrochemical Model of a PEM Fuel Cell System

Currently a lot of research is being done to derive reliable mathematical models of fuel cells suitable for transient analysis. Such models could be used to evaluate the dynamic performance of fuel cells, reducing cost and time in designing management and
control systems. Models presented in [20, 21] are more suitable for electrochemical analysis than for transient electrical analysis. Others [26–26] have presented simplified electrical models. This section presents a dynamic electrochemical model of the PEM fuel cell based on ref. [18]. The model predicts the output voltage of the cell as a function of load current and other operational parameters. Performance of the fuel cell can be analyzed during commonly encountered situations in electrical power generation systems, like insertion and rejection of loads, efficiency and power characteristics.

The output voltage of a single cell can be defined as the result of the following expression [20, 27, 28]:

\[ V_{FC} = E_{Nernst} - V_{act} - V_{ohmic} - V_{con} \] (4.2)

In equation 4.2, \( E_{Nernst} \) is the thermodynamic potential of the cell and it represents its reversible voltage; \( V_{act} \) is the voltage drop due to the activation of anode and cathode (also known as activation overpotential), a measure of the voltage drop associated with the electrodes; \( V_{ohmic} \) is the ohmic voltage drop (also known as ohmic overpotential), a measure of the voltage drop resulting from the resistances to the conduction of protons through the solid electrolyte and the electrons through their path; and \( V_{con} \) represents the voltage drop resulting from the reduction in concentration of the reactant gases or, alternatively, from the transport of mass of oxygen and hydrogen (also known as concentration overpotential). There is another voltage drop associated to the internal currents and/or the fuel crossover [28]. This voltage drop is considered in the model, using a fixed current density even at no-load operation (represented by \( J_n \)). The first term of equation 4.2 represents the fuel cell open circuit voltage, while the three last terms represent reductions in this voltage to supply the useful voltage across the cell electrodes, \( V_{FC} \), for a certain load current. Each one of the terms of 4.2 is discussed and modeled separately in the subsections that follow. Also, the following sections show the dynamic behavior of fuel cells and the equations for electrical power generation.
4.2.1 Cell Reversible Voltage

From the chemical reaction shown in equation 4.1, it is possible to obtain the electrical voltage generated during the process. Two electrons pass through the external circuit for each water molecule produced and each molecule of hydrogen spent. So, the electrical work done to move these charges is expressed by:

\[ G = \int 2qde = -2FE \]  \hspace{1cm} (4.3)

Where, F is the Faraday constant (96,487 C) and E is the fuel cell voltage. If the system is reversible (no losses) then the electrical work is equal to the Gibbs free energy released, which is the "energy available to do external work, neglecting any work done by changes in pressure and/or volume". The Gibbs energy is listed in the literature [20] for the reaction of water formation from \( 2H_2 \) and \( O_2 \) as -220 kJ when the cell is operating at 200° C. From equation 4.3, fuel cell voltage may be obtained as \( E=1.14 \text{ V} \).

The activity of the reactants and products changes the Gibbs free energy of a reaction. Balmer [29] has shown that temperature and pressure affect the reaction activity resulting in an emf equation given in terms of the product, and/or reactant activity, called Nernst reversible voltage, \( E_{\text{Nernst}} \). Therefore, reversible voltage of the cell is the cell potential obtained in an open circuit thermodynamic balance (no load). In this model, \( E_{\text{Nernst}} \) is calculated starting from a modified version of the Nernst equation, with an extra term to take into account changes in the temperature with respect to the standard reference temperature, 25° C and 100 kPa or 1.00 atmosphere pressure [20]. This is given by equation 4.4 as follows:

\[ E_{\text{Nernst}} = \frac{\Delta G}{2F} + \frac{\Delta S}{2F} (T - T_{\text{ref}}) + \frac{RT}{2F} \left[ \ln(p_{H_2}^*) + \frac{1}{2} \ln(p_{O_2}^*) \right] \]  \hspace{1cm} (4.4)

where:
ΔG is the change in the free Gibbs energy (J/mol)
ΔS is the change of entropy (J/mol)
R is the universal constant of gases (8,314 J/K.mol)
$p_{H_2}^*$ and $p_{O_2}^*$ are the partial pressures (atm) of the hydrogen and oxygen, respectively
T is the absolute temperature of the operating cell (K)
$T_{ref}$ is the reference absolute temperature (K).

Using the above standard temperature and pressure values for ΔG, ΔS and $T_{ref}$, equation 4.4 can be simplified to equation 4.5 as shown below:

$$E_{Nernst} = 1.229 - 0.85 \times 10^{-3} (T - 298.15) + 4.31 \times 10^{-5} T \left[ \ln(p_{H_2}^*) + \frac{1}{2} \ln(p_{O_2}^*) \right]$$  \hspace{1cm} (4.5)

It has to be noted that membrane temperature and partial pressures of reactant gases change with cell current: with increasing current, partial pressure of hydrogen or oxygen decreases, whereas temperature increases.

### 4.2.2 Activation Voltage Drop

As shown in [20], the activation overpotential, including anode and cathode, can be calculated by:

$$V_{act} = - \left[ \xi_1 + \xi_2 T + \xi_3 T \ln(c_{O_2}) + \xi_4 T \ln(i_{FC}) \right]$$  \hspace{1cm} (4.6)

where $i_{FC}$ is the cell operating current (A), the $\xi$'s represent parametric coefficients for each cell model, whose values are defined based on theoretical equations with kinetic, thermodynamic and electrochemical foundations [20]. $c_{O_2}$ is the concentration of oxygen in the catalytic interface of the cathode (mol/cm³), determined by:
4.2.3 Ohmic Voltage Drop

The ohmic voltage drop results from the resistance to the transfer of electrons through the collecting plates and carbon electrodes, and the resistance to the transfer of protons through the solid membrane. In this model, a general expression for resistance is defined to include all the important parameters of the membrane. The equivalent resistance of the membrane is calculated by:

\[ R_M = \frac{\rho_M l}{A} \]  

(4.8)

where \( \rho_M \) is the specific resistivity of the membrane for the electron flow (\( \Omega \cdot \text{cm} \)), \( A \) is the cell active area (\( \text{cm}^2 \)) and \( l \) is the thickness of the membrane (cm), which serves as the electrolyte of the cell. The Nafion membrane type considered in this work, is a registered trademark of Dupont and broadly used in PEM fuel cell technology. Numerical expression shown in equation 4.9 is used to calculate resistivity of the Nafion membranes. Dupont uses the product designations shown below to denote the Nafion membrane thickness.

- Nafion 117: 7 mil (\( l = 178 \mu \text{m} \))
- Nafion 115: 5 mil (\( l = 127 \mu \text{m} \))
- Nafion 112: 2 mil (\( l = 51 \mu \text{m} \))
\[
\rho_M = \frac{181.6 \left[ 1 + 0.03 \left( \frac{i_{FC}}{A} \right) + 0.062 \left( \frac{T}{303} \right)^2 \left( \frac{i_{FC}}{A} \right)^{2.5} \right]}{\psi - 0.634 - 3 \left( \frac{i_{FC}}{A} \right) \exp \left[ 4.18 \left( \frac{T - 303}{T} \right) \right]}
\] (4.9)

In equation 4.9, the term \(181.6/(\psi-0.634)\) is the specific resistivity (\(\Omega\cdot\text{cm}\)) at no load current and at 30\(^\circ\)C; the exponential term in the denominator is the temperature factor correction of the cell when it is not operating at 30\(^\circ\)C. The parameter \(\psi\) is an adjustable parameter with a possible maximum value of 23. This parameter is influenced by the preparation procedure of the membrane and it is a function of relative humidity and stoichiometry relation of the anode gas. It may have a value order of 14 under the ideal condition of 100% of relative humidity. There are also reported values in the order of 22 and 23 under oversaturated conditions.

Using the equation 4.8 for the membrane resistance, the following expression determines the ohmic voltage drop:

\[
V_{ohmic} = i_{FC} \cdot (R_M + R_C)
\] (4.10)

where \(R_C\) represents the resistance to the transfer of protons through the membrane, usually considered constant.

4.2.4 Concentration or Mass Transport Voltage Drop

The concentration or mass transport affects the hydrogen and oxygen concentrations. This in turn, causes a decrease of the partial pressures of these gases. Reduction in the pressure of oxygen and hydrogen depends on the electrical current and the physical characteristics of the system. To determine an equation for this voltage drop, maximum current density parameter, \(J_{\text{max}}\) is defined. \(J_{\text{max}}\) is the current density when the fuel
supplied is completely utilized. The current density cannot surpass this limit because the fuel cannot be supplied at a larger rate. Typical values for $J_{\text{max}}$ are in the range of 500 to 1500 mA/cm$^2$. The voltage drop due to the mass transport can be determined by:

$$V_{\text{con}} = -B \ln \left( 1 - \frac{J}{J_{\text{max}}} \right)$$

(4.11)

where $B$ (V) is a parametric coefficient, that depends on the cell and its operation state and $J$ represents the actual current density of the cell (A/cm$^2$).

### 4.2.5 Dynamics of the Cell

Before setting up the final equivalent model or circuit to represent the fuel cell dynamics, it is important to take into consideration the phenomenon known as "charge double layer". This phenomenon is of extreme importance for the understanding of the cell dynamics: whenever two differently charged materials are in contact there is a charge accumulation on their surfaces or a load transfer from one to other. The charge layer on the interface electrode/electrolyte acts as storage of electrical charge and energy and, in this way, it behaves as an electrical capacitor. If the current changes, there will be some elapsed time for the load (and its associated voltage) to decay (if the current decreases) or to increase (if the current increases). Such delay affects the activation and concentration potentials. It is important to point out that the ohmic over potential is not affected, since this has a linear relationship with the cell current through the Ohm’s Law. Thus, a change in the current causes an immediate change in the ohmic voltage drop. So, it can be considered that a first order delay exists due to the activation and concentration voltages only. The associated time delay $\tau(s)$ is the product:

$$\tau = C.R_a$$

(4.12)
where $C$ represents the equivalent capacitance (F) of the system and $R_a$ the equivalent resistance ($\Omega$). The value of the capacitance is of the order of few Farads. The resistance $R_a$ is determined from the cell output current and of the calculated activation and concentration voltages. In this way, these voltages will change dynamically with the current, until they reach their new steady-stated values. Taking capacitive effect into account assures good dynamic performance of the cell, since the voltage moves smoothly to a new value in response to a change in the load current demand. $R_a$ is obtained as shown in equation 4.13. With these equations, derivation of electrochemical model of a PEM fuel cell is complete.

$$R_a = \frac{V_{act} + V_{con}}{i_{FC}}$$  \hspace{1cm} (4.13)

4.3 Modeling of the SR-12 Avista Fuel Cell

Colorado School of Mines received an SR-12 Modular PEM fuel cell stack, rated at 500 W. The SR-12 PEM fuel cell, manufactured by the Avista Laboratories, is a modular FC stack, which has some characteristics adequate for use in electrical generation systems [10]. Since the IGBT back-back converters are rated at 1.5 kW, they can easily handle the SR-12 output power. The data provided by Avista Laboratories for the SR-12 stack was used to match the model derived in the previous section. The procedure to obtain the parameters for this specific stack is outlined below:

1) Initially, it is necessary to obtain the basic information from the manufacturer’s data sheet. In this case, the information provided was: (i) number of cells, $n$, equals 48; (ii) hydrogen pressure: 1.47628 atm; (iii) oxygen pressure: 0.2095 atm (air at atmospheric pressure); and (iv) normal operation temperature: 50°C.
2) The Avista Laboratories allowed access to the polarization curve for this generator. From this data, it was possible to obtain: (i) maximum current: 42 A; and (ii) open circuit voltage: 41.7 V. Avista Laboratories also provided information about the membrane thickness, \( l = 25 \mu m \) and the membrane active area \( A = 62.5 \, \text{cm}^2 \).

3) Initially, the values for the electrochemical parameters \( \xi_i \) and \( \psi \) are considered to be the same as the ones used for the Ballard Mark V fuel cell in ref. [19].

4) The maximum current density can be calculated using \( J = \frac{i_{FC}}{A} \), for maximum current and membrane active area, resulting in a maximum current density, \( J_{\text{max}} \), of 0.672 A/cm\(^2\).

5) Now it is necessary to obtain the equivalent current density for the internal currents/fuel crossover (\( J_n \)) and the B-parameter, used in the calculation of the concentration overpotential, equation 4.11. In order to obtain \( J_n \) it is necessary just to run the program, and verify the open circuit stack voltage. The value chosen for \( J_n \) is the one that makes the resulting simulated open circuit voltage approximately equal to the manufacturer’s data. For the SR-12 module, \( J_n = 22 \, \text{mA/cm}^2 \). It can be noted that this value is relatively high, when compared to other fuel cells [28].

6) The next step is to obtain the value of B. First, one has to choose a first guess for B (for example, 0.016 V, Ballard Mark V). This value must be played in a way that the voltage characteristic has approximately the same behavior as the manufacturer’s one. For the SR-12 stack, this value is again high, \( B = 0.15 \, \text{V} \).

7) As a last step, the parameters \( \xi_i \) needed to be adjusted for this model. Using the same parameters as the Mark V fuel cell, the activation voltage drop is too large, equation 4.6. For the SR-12 stack, the parametric coefficients \( \xi_3 \) and \( \xi_4 \) were decreased to their new values: \( \xi_3 = 7.22 \times 10^{-5} \) and \( \xi_4 = -1.0615 \times 10^{-4} \).

Using the procedure and data presented above, Table 4.1 shows the parameters set for the Avista SR-12 Modular PEM fuel cell.
Table 4.1 – Parameters of the SR-12 fuel cell stack.

<table>
<thead>
<tr>
<th>Param.</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>48</td>
<td>$\xi_1$</td>
</tr>
<tr>
<td>$T$</td>
<td>323 K</td>
<td>$\xi_2$</td>
</tr>
<tr>
<td>$A$</td>
<td>62.5 cm$^2$</td>
<td>$\xi_3$</td>
</tr>
<tr>
<td>$l$</td>
<td>25 $\mu$m</td>
<td>$\xi_4$</td>
</tr>
<tr>
<td>$P_{H2}$</td>
<td>1.47628 atm</td>
<td>$\psi$</td>
</tr>
<tr>
<td>$P_{O2}$</td>
<td>0.2095 atm</td>
<td>$J_{max}$</td>
</tr>
<tr>
<td>$B$</td>
<td>0.15 V</td>
<td>$J_n$</td>
</tr>
<tr>
<td>$R_C$</td>
<td>0.0003 $\Omega$</td>
<td>$I_{max}$</td>
</tr>
</tbody>
</table>

Using the data presented in Table 4.1, fig. 4.3 shows the results for the polarization curve. The simulated curve is in good agreement with the manufacturer’s data. An important point to notice is that at the beginning of the curve, there is no noticeable voltage decrease. This is because the stack has a low activation voltage drop. So, the parametric coefficients, $\xi_3$ and $\xi_4$ were decreased to represent this characteristic. More simulation results in Matlab/Simulink and Labview are presented in chapter 5.

Figure 4.3 Avista SR-12 PEM polarization curve.
4.4 Fuel Cell Simulator

The subject of simulating fuel cells and fuel cell stacks can be found in the literature [2]-[6] and [9]-[10]. These publications deal with computer simulations and screen animations. Ref. [9] presents a fuel cell plant simulator. But, the authors address more of the overall system and do not intend to reproduce the fuel cell characteristics (such as voltage, power and efficiency) to supply real electrical loads. In ref. [30], the authors present a fuel cell dynamical modeling for distributed generation. The work deals only with computational modeling and it does not present any hardware to actually supply the real emulated power. In addition, these papers do not deal with evaluation of reaction/cooling humidity and temperature.

The hardware simulator presented in ref. [19] allows real load to be connected at the output terminals. The electrochemical model presented earlier is used to predict the dynamic operation of a fuel cell stack. The steady state and dynamic characteristics of a fuel cell are closely reproduced in such a way that actual loads respond as if they are being driven by a real fuel cell. The simulator characteristics include the membrane temperature and humidity, efficiency, flow of the reactants, cooling air fan and water pumps, the actual air temperature and humidity, and the electrical load. Using this, any type of fuel cell of ordinary size can be simulated without having to use hydrogen with improved safety and flexibility. Complete analysis of the fuel cell generation system including all on-site electrochemical variables can be made using the simulator. Parameters for the Avista SR-12 fuel cell stack shown in table 4.1 are used for the hardware simulator in this project.

4.4.1 Basic Setup

Fig. 4.4 shows the basic schematic of the simulator. The main components of the setup are: three phase SCR phase controlled rectifier (Enerpro PCM-3 power control module), LC filter, personal computer running Labview and sensors for measuring fuel
cell current and voltage. This hardware can be operated in isolated mode supplying a dc load or can be connected to grid through a dc/ac inverter. Here though, the output terminals of the simulator are connected to dc link of the DFIG system. Inductor $L_2$ is additionally used to inject power into the dc link. The various other hardware used are explained in more detail in chapter 6.
CHAPTER 5
SIMULATION STUDIES

The models of DFIG and fuel cell derived in previous chapters are simulated to observe how close the models approximate the real system and to evaluate the performance of the proposed control methods. Matlab/Simulink was chosen to simulate the entire system. Parameters of the DFIG and the fuel cell that will eventually be used in the experimental setup are used in the simulation setup to predict the operation of the system. This chapter begins with description of various steps involved in simulating the system in Matlab/Simulink. Simulation results showing the operation of DFIG and fuel cell in isolation and in integrated mode are presented. Power flow between the DFIG, fuel cell and the grid is analyzed in detail.

5.1 Simulation Setup

Transient models of induction machine and fuel cell developed in previous chapters are in the form of differential equations. Simulink tool box in Matlab is very well suited for dynamic simulation and analysis of these types of systems. There are many advantages of using Simulink over other similar circuit-based software packages. Simulink has an extensive library of computational blocks which can be dragged and dropped into the system. Custom made blocks can also be built in Simulink using simple equations. A basic block element in Simulink is composed of an input vector, system of equations and an output vector. This graphical user interface (GUI) allows the user to build the system in the form of a block diagram consisting of blocks each solving a set of model equations. With this structure, it is easy to debug the system and monitor inputs/outputs of each block.
Simulink version 5.0 on a Pentium 4, 2 GHz, 512 MB RAM personal computer is used for simulation. The computation time of the entire system for 2.5 s of simulation time was about 8 minutes. The step time used is twenty times lower than the operating frequency of the PWM converters. Figure 5.1 shows the block diagram of the complete system in Simulink. Due to the complexity of the system, the block diagram was implemented step by step. First, the WRIM was implemented and tested in open loop mode. REC was then implemented and attached to the rotor circuit. After obtaining good results with REC, FEC is attached to the dc link to complete the DFIG model. The fuel cell model developed was initially tested in isolated mode and later integrated with the DFIG system. Each of these steps is explained in later sections.

Figure 5.1 Simulink block diagram of the integrated system.
5.2 DFIG Open-Loop Operation

Equations developed in section 3.2 for a wound rotor induction machine are implemented in Simulink. Fig. 5.2 shows implementation of equation 3.7 in Simulink. Equations 3.8 – 3.13 are similarly implemented in a block diagram form. To test the DFIG model, the model was initially run in open loop mode. Fig. 5.3 shows the DFIG model connected to a variable frequency voltage source in the rotor circuit. The stator of the machine is tied to a three-phase balanced grid. PWM converter operation is omitted here for simplicity. The three-phase voltages in the rotor circuit are generated through stationary dq-abc transformation of cos and sine signals. The response of the induction machine model to variations in frequency and magnitude of the rotor voltage source was observed. The model was tested for both positive and negative slip frequencies.

Figure 5.2 Implementation of equation 3.7 in Simulink.
Parameters and ratings for the induction machine used are shown in table 5.1. The induction machine is simulated to be driven by a wind turbine. The mechanical torque input to the model is based on equation 3.12. The turbine torque input is dependent on:

Table 5.1 Induction machine parameters.

<table>
<thead>
<tr>
<th>Ratings</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>2 H.P.</td>
<td>Rs</td>
<td>0.73 Ω</td>
</tr>
<tr>
<td>Speed</td>
<td>1750 RPM</td>
<td>Rr</td>
<td>0.80 Ω</td>
</tr>
<tr>
<td>Voltage</td>
<td>220/440 V</td>
<td>Ls</td>
<td>2.73 mH</td>
</tr>
<tr>
<td>Current</td>
<td>11/5.5 A</td>
<td>Lr</td>
<td>2.73 mH</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hz</td>
<td>Lm</td>
<td>55.5 mH</td>
</tr>
<tr>
<td># of Poles</td>
<td>4.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
wind speed and turbine parameters. The wind speed profile used is shown in fig. 5.4. All the DFIG simulations shown in this chapter are for a simulation time of 2.5 s.

![Wind speed profile](image)

**Figure 5.4 Wind speed profile**

The DFIG model was first run with a positive slip frequency of 1 Hz. The dc link voltage was kept constant at 50 V and modulation factor of 0.5 was used. Fig. 5.5 shows the response the induction machine to positive slip input. As expected the rotor speed of the machine is 59 Hz (~371 rad/sec). The machine was initially started with rotor terminals short circuited (squirrel cage operation) and at 0.7 s the rotor terminals are connected to the voltages sources in the rotor circuit. Fig. 5.6 shows the three-phase stator and rotor currents generated in the machine.

![Rotor speed](image)

**Figure 5.5 Rotor speed for positive slip input.**
The stator current magnitude during squirrel cage motor operation is slightly higher than the rated current shown in table 5.1. This is to be expected as losses and saturation effects in the machine are neglected in the modeling process. Otherwise, the DFIG model approximated the real machine quite well. The model was also tested with a negative slip frequency input of 1 Hz. As shown in fig. 5.7, the rotor speed of the machine is 61 Hz (~383 rad/sec). The phase sequence of the rotor is reversed as the slip is negative. Similar open loop tests were also performed on the real machine. The simulation results shown compare well with the experimental results presented in chapter 7.
5.3 DFIG Closed-Loop Operation

This section presents the operation of DFIG without the fuel cell. For DFIG closed-loop control, REC and FEC simulation models are developed. REC is directly connected to the rotor terminals and FEC connects the rotor circuit to grid to allow bidirectional power flow in rotor circuit. The DFIG model was initially tested with REC programmed to control just the active and reactive power and not perform harmonic compensation. FEC maintains the dc link voltage constant and also controls the power factor in the rotor circuit. Simulation results without active filter operation are analyzed. Next, REC control is modified to compensate the harmonics generated by a non-linear load attached to grid.

As explained in chapter 2, PWM converters are used to generate the variable magnitude and frequency voltage inputs required for controlling the induction machine.

5.3.1 Three Phase PWM Converter Simulation

This section explains how PWM converter switching operation is implemented in Simulink. Fig. 2.7 is redrawn here to explain the modeling of a three phase PWM converter connected to a star-connected load in Simulink. As shown in fig. 5.8, the three upper switches labeled ‘H’ connected to the positive terminal of the dc bus and the three
lower switches labeled ‘L’ are connected to the negative terminal of the dc bus. When upper IGBTs are turned ON, E is impressed on the output terminals and when lower IGBTs are turned ON, zero voltage is impressed. These voltages, however, are in reference to the ground terminal ‘O’ on the dc bus. The desired voltages are \( V_{aN}, V_{bN} \) and \( V_{cN} \) across the load terminals. These voltages can be calculated from the voltages at the converter as shown in equations 5.1 and 5.2. For a balanced load, \( V_{aN} + V_{bN} + V_{cN} = 0 \).

\[
\begin{align*}
\begin{bmatrix} V_{aN} \\ V_{bN} \\ V_{cN} \end{bmatrix} &= \frac{1}{3} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} &= \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \\
\Rightarrow \begin{bmatrix} V_{aN} \\ V_{bN} \\ V_{cN} \end{bmatrix} &= \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}
\end{align*}
\]

where \( V_{ab}, V_{bc} \) and \( V_{ca} \) are the load line voltages.

Sinusoidal pulse width modulation (SPWM) explained briefly in section 2.4.1 is used in the simulation. Fig. 5.9 shows the implementation of an SPWM converter in Simulink.
The inputs to the block are $V_a^*, V_b^*$ and $V_c^*$, the reference voltages generated from the control blocks and the converter output voltages are $V_a, V_b$ and $V_c$. The reference voltages are compared to a triangular waveform at a much higher frequency to generate the gate signals for the IGBTs.

Fig. 5.9 Three-phase IGBT converter in Simulink.

Fig. 5.10 shows an example SPWM converter raw output and filtered output for a dc link voltage of 70 V. The converter is operated at 2 kHz. It can be seen from the figure that the output voltage can take five distinct levels: $2E/3$, $E/3$, $0$, $-E/3$, $-2E/3$, depending upon the switching (E is the dc bus voltage). The magnitude and frequency of the fundamental voltage (filtered waveform) are similar to the reference waveform. The magnitude of the fundamental is given by $m*E/2$, where $m$ is the modulation factor given by $V_{p-p, ref} / V_{p-p, tri}$. A modulation factor of 1 is used in the example. So, the peak value of the fundamental waveform shown in figure is 35 V.
5.3.2 Active and Reactive Power Control

Next step is to simulate the induction machine operation with the back-back converters. Harmonic compensation was not implemented initially. It is simpler to understand and explain the operation of DFIG without the harmonic compensation. The induction machine was first tested connected to just the REC. Active and reactive power control can be achieved through REC. With no FEC, the power is unidirectional in the rotor circuit. The stator active power has to be controlled so that the rotor active power is positive (injected into the rotor). Simulation results for REC are not shown. FEC is connected to dc link when the results from REC were found be satisfactory. This section presents the simulation results with both the converters operating in the rotor circuit controlling the active and reactive power generated by DFIG.
5.3.2.1 REC

Stator flux oriented vector control method described in section 3.3.1 is implemented for REC. Control equations 3.20 are implemented in Simulink as shown in figures 5.11 and 5.12. Fig. 5.11 shows the flux controller or the reactive power controller. The command $i_{dr}^*$ is generated for the reactive power equation in 3.23. Stator flux magnitude is approximated at 0.43 Wb and since $V_{ds} = 0$, $V_{qs} = 169.7$ V. The stator injects reactive power into the grid when the d-axis rotor current exceeds 8.1 A. The $i_{dr}$ error signal is passed through a PI controller to obtain the d-axis voltage reference for the converter. Feed-forward terms are added as shown.

![Figure 5.11 Flux controller.](image)

Fig. 5.12 shows the torque controller or the active power controller. The command $i_{qr}^*$ is generated from the active power equation in 3.23. Stator active power is directly proportional to rotor q-axis current as approximately -242.5 W/A. Negative sign indicates that power is being injected into the grid. As in the previous case, the $i_{qr}$ error signal is passed through a PI controller to obtain the q-axis voltage reference for the converter. Feed-forward terms are added as shown. The d-q reference voltages are transformed back to a-b-c to generate gate signals for the IGBT converter.
S.3.2.2 FEC

A grid voltage oriented vector control method described in section 3.3.2 is implemented for FEC. Control equations shown in 3.35 are implemented as shown in figures 5.13 and 5.14. The d-axis reference current or the active power reference is derived from the dc link voltage error as shown in fig. 5.13. The dc link voltage is maintained at 75 V in this simulation. The d-axis current error is passed through a PI controller to generate the d-axis reference voltage for the FEC. Cross-coupling terms are added as shown. Fig. 5.14 shows the reactive power or the power factor controller. The q-
axis reference current is derived from the reactive power equation in 3.32. The power factor, however, is usually maintained at unity. So, q-axis reference current is set to zero for unity power factor.

### 5.3.2.3 Simulation Results

As the dc link voltage is regulated at 75 V, a transformer is required to inject power from the rotor circuit to grid. In simulation, the transformer is implemented as a simple gain block with a turns ratio of 6. The line inductance and resistance in fig. 3.7 are 5 mH and 1 Ω respectively. The wind speed profile shown in fig. 5.4 allows the machine to run in both sub and super-synchronous modes of operation. The simulation was run for 2.5 s during which various conditions are imposed on the system. Fig. 5.15 shows the angular speed variation of the rotor in response to the active and reactive power commands.

![Figure 5.15 Rotor speed of the induction machine.](image)
Fig. 5.16 shows the response of REC to active and reactive power references. The references are varied as shown. The induction machine is initially commanded to absorb about 500 W of active power \((i_q = -2 \text{ A, motoring mode})\) and about 1400 VAR \((i_d = 2\text{A})\) of reactive power. At 0.6 s, a step change in id is made. The reference is changed to 2 A \((-500 \text{ W})\) at which instant the generator begins to generate active power. Reactive power reference is changed to 4 A at 1 s and active power reference is changed to 5 A at 1.4 s. At 1.8 s, the reactive reference is changed to 10 A. At this point, the DFIG is generating both active and reactive power. Variation in rotor speed can be observed when active power reference is changed.

![Figure 5.16 Response of DFIG to step changes in rotor currents (- reference, - actual)](image)

It can be seen from the fig. 5.16 that the REC controller works very well in tracking the reference currents. The rise time for both the flux and torque controllers is less than 1
ms and there is no steady state error. Active and reactive power waveforms are shown in fig. 5.17. The decoupled nature of active and reactive power control can be observed from the figure. From fig. 5.17 (a), in steady state the stator generates about 1250 W of active power. From fig. 5.17 (b) it can be seen that after 1.8 s, the rotor supplies the entire reactive power required by the stator and injects about 500 VAR of reactive into the grid. From a practical point of view, it is desirable to supply the reactive power to stator from the grid to reduce losses on the rotor back-back converters. Fig. 5.18 shows the stator current and voltage waveforms during the step change in reactive power command. From the phase relationship between the current and voltage, it can be seen that before 1.8 s, part of the magnetizing current is supplied by the rotor and the remaining is absorbed from the grid. After 1.8 s, the rotor supplies the entire magnetizing current.

![Figure 5.17 Active power and reactive power generated by DFIG.](image-url)
Rotor voltage and current waveforms are shown in fig. 5.19 showing the smooth operation of the DFIG through synchronous speed. The machine passes through synchronous speed at around 1.2 s. The rotor currents are dc at that point and a phase reversal can be observed above synchronous speed.

Figure 5.19 Operation of DFIG through synchronous speed (- a, - b, - c).
Fig. 5.20 shows the response of FEC. As mentioned earlier, the dc link voltage is regulated at 75 V and power factor is maintained at unity. It can be seen from the figure that the controller works very well in maintaining the dc link voltage and reactive power. Transients in both waveforms can be observed during step changes in rotor currents but they recover quickly. The largest transient is at 1.8 s when there is a step change in reactive power demand on the stator side. The generator begins to inject reactive power into grid from absorbing reactive power. The controller recovers in about 0.4 s. The reactive power command ($i_q$) can be modified so that reactive power is injected into grid from the rotor side. In fig. 5.17 (b), until 1.8 s, the rotor does not supply the entire reactive power required by the stator. Part of it is absorbed from the grid. In that case, FEC can be programmed to compensate for the reactive power absorbed and improve the overall power factor. Active power flow in the rotor circuit is shown in fig. 5.21. When
the active power command in the stator is -2 A (DFIG is absorbing active power, motoring mode), the excess power is injected into the grid through the rotor circuit. When the active power command is increased to 5 A, about 120 W of power is injected from the rotor into the stator. With bidirectional power flow in the rotor circuit, it is thus possible to operate the DFIG either as generator or motor above or below synchronous speed.

5.4 PEM Fuel Cell Model

Fuel cell model based on the electrochemical model derived in section 4.2 is implemented in Simulink. Equation 4.2 is implemented in as shown in fig. 5.22. Each of the equations from 4.3 – 4.13 are implemented in the blocks shown. The output voltage of the fuel cell primarily depends on the load current but is also affected by other operational parameters such as hydrogen and oxygen (air) pressure, membrane temperature and humidity in the system. Sensitivity of the fuel cell output voltage to variation in these parameters was studied. Parameters of the 500 W Avista SR-12 PEM fuel cell shown in table 4.1 are used in the simulation.

Fig. 5.23 shows the response of the fuel cell model to step changes in load current. The model is initially run with no-load current and step change to 20 A is made at 1 s. The open circuit voltage of the fuel cell model is 40.55 V, which is very close the
Figure 5.22 Block diagram of the fuel cell model in Simulink.

Figure 5.23 Response of the SR-12 fuel cell model to load current variation.
manufacturer’s data for SR-12 as shown in fig. 4.3. When the current is increased to 20 A, the output voltages decreases to 31.5 V and increases back to 35.8 when the current is decreased to 10A. Fig. 5.24 shows the polarization curve for the SR-12 fuel cell model. The effects of pressure, temperature, humidity and other modeling parameters on the performance of the fuel cell are discussed in next section.

![Polarization curve for the Avista SR-12 fuel cell model.](image)

**5.4.1 Parameter Sensitivity**

Increased pressure results in voltage gain. In fig. 5.23, the operating hydrogen pressure was 1.47 atm. When the pressure is increased to 3 atm, the open circuit voltage increased to 41.5 V from 40.5 V. As the efficiency of the fuel cell is directly proportional to the output voltage, it is advantageous to operate the fuel cell at higher pressures. The increase can be attributed to an increase in exchange current density and reduction in cathode activation overvoltage. Equation 5.3 shows that the boost in voltage is directly proportional to the logarithm of the pressure rise [31].

\[
\Delta V = \frac{RT}{4F} \ln \left( \frac{P_2}{P_1} \right)
\]

(5.3)

where \( P_1, P_2 \) are the pressures of the hydrogen gas.
Increase in temperature has a similar affect on the fuel cell output voltage. When the operating temperature was increased to 100 °C from 50 °C as in fig. 5.23, the open circuit output voltage increased to 42.5 V from 40.5 V. Higher temperatures result in lower values of Tafel slope and conductive resistance, and higher values of exchange current density. Activation overvoltage, shown in equation 4.6, is the most important irreversibility and cause of voltage drop in the fuel cell. Increase in exchange current density reduces the activation overvoltage. In real applications, however, high temperature and low humidity has a negative effect on the performance of the fuel cell due to loss of ionic conductivity in both the membrane and cathode catalyst layer. So, air should be sufficiently humidified when the fuel cell is operating high temperatures.

Humidity of air in a PEM fuel cell must be carefully controlled. The air must be dry enough to evaporate the product water, but not so dry that it dries the electrolyte membrane too much. There must be sufficient amount of water content in the polymer electrolyte as proton conductivity is directly proportional to the water content. However, the humidity must be below 100%, or liquid water would collect at the electrodes blocking the pores in the gas diffusion layer. In the simulation, the parameter $\psi$ is a function of relative humidity. This parameter has only a marginal effect on the open circuit voltage but has a significant effect on the output voltage at higher currents.

Sensitivity of the fuel cell model to other modeling parameters is explained in detail in ref. [34]. Following conclusions are made for the parameters shown in table 4.1:

- **Insensitive**: $A$, $l$, $R_C$.
- **Sensitive**: $J_m$, $B$, $\xi_4$.
- **Highly sensitive**: $J_{\text{max}}$, $\xi_1$, $\xi_3$.

The insensitive parameters are basically the ones related to the cell construction: their influence on the model accuracy is not critical and it is not necessary to know their exact
values to have a good response. Parameter \( J_n \) only affects the simulation results at low current values, because its value will define the resulting open-circuit voltage, considering the internal current and crossover effect. Parameters \( B \) and \( \xi_4 \) have more influence on the stack voltage for high current values. However, their effects are not as prominent as \( J_{\text{max}} \). The parameter \( B \) defines the form of the polarization curve, especially in its final portion (near the maximum stack current). The final portion of the polarization curve is characterized by a fast decrease in the voltage, as shown in fig. 5.23.

For the parameter \( J_{\text{max}} \), the model results are more affected for high current values. This can be explained by the logarithm term in equation 4.11. When the current density is close to the maximum value, the logarithm term tend to be close to zero. This results in concentration voltage drop. However, for parameters \( \xi_1 \) and \( \xi_3 \) the model results are affected for the entire current range. The two parameters are defined as:

\[
\xi_1 = -\frac{\Delta G_a}{2F} \frac{\Delta G_c}{\alpha_c n F} \quad \text{and} \quad \xi_3 = \frac{R(I - \alpha_c)}{\alpha_c F}
\]  

(5.4)

where:
\( \Delta G_a \): free activation energy for the standard state (J/mol), referred to the anode;
\( \Delta G_c \): free activation energy for the standard state (J/mol), referred to the cathode;
\( \alpha_c \): parameter for the anode chemical activity;
\( A \): cell active area (cm\(^2\));
\( c_{\text{H}_2} \): hydrogen concentration (mol/cm\(^3\)); and
\( c_{\text{H}_2O} \): water concentration (mol/cm\(^3\)).

There is a first order delay the fuel cell voltage in response to change in load current as shown in fig. 5.23. As explained in section 4.2.4, the charge double layer effect is responsible for a delay. The parameter used to describe this behavior is the equivalent capacitance \( C \). This capacitance does not influence the stack polarization curve; because
each point of this curve is obtained after the voltage has reached its steady-state value. As shown in fig. 5.23, for a step change in load current, the stack voltage presents an instantaneous change (caused by the ohmic overpotential), followed by a first order delay until it reaches its new final steady-state value. The capacitance used is only a representative of the fuel cell dynamical behavior and does not represent a real capacitor. The time needed for the stack voltage to reach its new steady-state value is strongly dependent on the value chosen for the equivalent capacitance.

5.5 DFIG – FC Integration and Harmonic Compensation

This section presents the simulation results of integrated operation of the DFIG and the PEM fuel cell. The integration process is explained in detail. Also, the vector control scheme for the REC is modified so that the DFIG operates as an active filter cleaning up the harmonics generated from a non-linear load attached to grid.

5.5.1 Integration of DFIG with PEM Fuel Cell

As the dc link voltage is regulated at 75 V, the fuel cell is connected to the dc link through a dc-dc boost converter. Fig. 5.25 shows the schematic of the fuel cell connected across the dc link of the back-back converters through a boost converter. The main function of the boost converter is to step up the fuel cell voltage to the desired level and to control the power supplied by the fuel cell by controlling the inductor current. A PI controller was used to control the inductor current, \(i_{FC}\) by controlling the duty ratio, \(D\). The following equations are used to model the boost converter:

\[
i_{FC} = \int \frac{1}{L} [V_{FC} - (1-D)E]
\]

\[
i_b = (1-D)i_{FC}
\]
where, \( V_{FC} \) is the output voltage of the fuel cell derived from the electrochemical model for a source current \( i_{FC} \), \( L \) is the inductance of the boost converter, \( E \) is the DC link voltage and \( i_b \) is the load current injected into the dc link. The dc link voltage equation 3.33 is now modified to take into account the power being injected from the fuel cell into the dc link as shown below:

\[
C \frac{dE}{dt} = i_{eg} - i_{or} + i_b
\]  

(5.7)

FEC controls the dc link voltage by controlling the active power flow in the rotor circuit. As more power is injected into the dc link through the fuel cell, the FEC has to redirect the power either into the rotor through REC or into the grid. Thus when the mechanical power input to the machine is low, the fuel cell can be used to inject power into the rotor circuit so that the stator could still generate from the stator side. This can be very useful for islanded applications where grid is not available.

\subsection{5.5.2 Harmonic Compensation}

As shown in fig. 3.5, a non-linear load is connected to the grid. With a slight modification in REC control, it can be made to operate as an active filter supplying the harmonic currents required for the non-linear load. The rotor reference currents are
modified according to equation 3.21. In simulation, the harmonic currents are derived using a high-pass filter to fundamental from a three-phase sine source containing 20% 5th, 10% 7th and 5% 11th harmonic currents. Fifth, seventh and eleventh harmonic currents are the most significant harmonics consumed by non-linear loads. These harmonic reference currents are added to the active and reactive power reference currents as in equation 3.22. Fig. 26 (a) shows the a-b-c load harmonic reference currents. These currents have to be transformed to rotor quantities as the control is on the rotor side. Fig. 26 (b) shows the transformed harmonic reference currents in reference frame.

Figure 5.26 Harmonic reference currents
(a) Actual load harmonic currents (- a, - b, - c) (b) Transformed rotor currents (- d, - q).
5.5.3 Simulation Results

Simulation results shown here use the same parameters used in sections 5.3 and 5.4 for isolated operation of fuel cell. The simulation is started with the fuel cell initially not connected to the dc link. The switch is turned on at 0.6 s and the fuel cell is programmed to inject a constant load current of 10 A which is about 350 W. The boost converter boosts the fuel cell voltage from 35.8 V to 75 V. So, approximately 4.8 A of current is injected into the dc link through the boost converter. Active and reactive power reference currents are the same as in section 5.3.2.3 except the reactive power reference $i_{dr}$ is 8.1 A after 1.8 s. The d-axis harmonic reference shown in fig. 5.25 (b) that is added to $i_{dr}$ is of a higher magnitude and has a dc component. The stator generates about the same amount of reactive power.

Fig. 5.27 shows DFIG working both as a power source and as an active filter i.e. the

![Figure 5.27](image-url)

Figure 5.27 Response of REC to harmonic current reference (- reference, - actual).
induction machine is now not only supplying the active/reactive power but also compensating for the harmonics generated by the non-linear load current. The REC once again works very well in tracking the reference currents. The zoomed rotor currents waveforms show how well the actual currents follow the reference currents. The stator currents now contain 5\textsuperscript{th}, 7\textsuperscript{th} and 11\textsuperscript{th} harmonic currents. Instantaneous active and reactive waveforms are not as clean as compared to fig. 5.17 but, the average value is agreement with equations derived in chapter 3. The DFIG, in this case again, generates about 1250 W of active power and 500 VAR of reactive power. The electrical torque generated by the machine is relatively noisy but the speed profile is same as in fig. 5.15.

Fig. 5.28 shows the response of FEC to harmonic compensation and integration of fuel cell across the dc link. The dc link and $i_q$ current waveforms are apparently noisier compared to fig. 5.20 due the high frequency harmonics in rotor currents. Once again
the FEC vector controller does well keeping the dc link voltage and reactive power reference constant. A large transient can be observed in the dc link voltage waveform at $t = 0.6$ s when the fuel cell is connected across the dc link. Fig. 5.29 (a) shows the power flow in the rotor circuit and fig. 5.29(b) shows the power injected by the fuel cell. In fig. 5.21, the rotor absorbs power from the grid when the machine is running in generating mode. When the fuel cell integrated in the DFIG system, the machine no longer absorbs power from the grid. The fuel cell injects the required power into the rotor and the remaining power is injected to the grid. As shown in fig. 5.29(b), the fuel cell injects about 60 W of power into the rotor and 290 W of power is injected into the grid. The fuel cell is able to inject power into grid without a dc-ac inverter. If a fuel cell of larger size is connected, the rating of the FEC converter might have to be increased. The rating of the REC is only dependent on the speed range. So, one of the converters might have to

![Graph](image)

Figure 5.29 (a) Active power flow in the rotor circuit (b) Fuel cell output power.
be rated higher which is still advantageous than purchasing a separate inverter for the fuel cell. Other dc power sources like PV cells can also be connected across the dc link. In the experimental setup, a SCR phase controlled rectifier simulating a PEM fuel is used.
CHAPTER 6
LABORATORY SETUP

This chapter describes various hardware and equipment that were used in this experiment. The experimental setup followed the simulation as closely as possible to provide a fair comparison of simulation and experimental results. Fig. 6.1 shows the schematic of the complete experimental setup. The components include an induction machine driven by a dc motor, two back-back IGBT converter modules, SCR phase controlled rectifier emulating a fuel cell, current and voltage sensors to measure
quantities for vector control, two personal computers: one running the vector control schemes and the other running the Labview model of the fuel cell, analog and digital circuits to convert the stationary d-q voltages from the DAQ card to gate voltages for the IGBT modules, an incremental optical encoder to measure the rotor speed and other miscellaneous components such as transformers, circuit breakers and fuses. Fig. 6.2 shows the picture of the experimental setup excluding the two computers. A brief description of all the components in this setup is explained in the following sections.

Figure 6.2 Picture of experimental setup.
6.1 Induction machine and DC motor

The ac machine is a laboratory 2HP, three-phase, 115V, 1780 rpm, Y connected wound rotor induction machine. The induction machine is driven by a 1 HP dc motor acting as a prime mover. The dc motor is fed by a constant 160V dc cage supply. One of the difficulties that were faced during this project was the lack of a speed control loop on the dc motor. This is explained in later sections.

6.1.1 Induction machine parameters

The induction machine parameters needed ($R_s$, $R_r$, $L_{ls}$, $L_{lr}$, $L_m$) for vector control are obtained by performing a series of standard tests [1]. Each test was performed several times and average values of machine parameters are calculated. Equivalent circuit of an induction machine is shown in fig. 6.3.

![Per-phase equivalent circuit of an induction machine.](image)

The first test performed was the dc test. In this test, a small dc voltage is applied to the stator terminals. Since the current is dc, no voltage is induced in the rotor circuit and there is no reactance. Therefore, stator resistance can be calculated using this test. Rotor resistance is usually determined from another standard test called the locked-rotor. However, there is a problem with locked-rotor test if the machine is energized with rated frequency as it does not represent the normal operating conditions of the rotor. So, a dc test was also performed on the rotor terminals. Table 6.1 shows the dc test results.
Table 6.1 DC test results.

<table>
<thead>
<tr>
<th>Vdc (V)</th>
<th>Idc (A)</th>
<th>Rs (Ω)</th>
<th>Vdc (V)</th>
<th>Idc (A)</th>
<th>Rr (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.63</td>
<td>3.15</td>
<td>0.73</td>
<td>1.65</td>
<td>1.10</td>
<td>0.75</td>
</tr>
<tr>
<td>5.32</td>
<td>3.60</td>
<td>0.74</td>
<td>2.22</td>
<td>1.49</td>
<td>0.74</td>
</tr>
<tr>
<td>6.25</td>
<td>4.36</td>
<td>0.72</td>
<td>4.77</td>
<td>3.14</td>
<td>0.76</td>
</tr>
<tr>
<td>6.97</td>
<td>4.77</td>
<td>0.73</td>
<td>5.16</td>
<td>3.47</td>
<td>0.74</td>
</tr>
<tr>
<td>7.53</td>
<td>5.15</td>
<td>0.73</td>
<td>5.37</td>
<td>3.54</td>
<td>0.76</td>
</tr>
<tr>
<td>7.59</td>
<td>5.20</td>
<td>0.73</td>
<td>5.70</td>
<td>3.76</td>
<td>0.76</td>
</tr>
<tr>
<td>7.81</td>
<td>5.34</td>
<td>0.73</td>
<td>6.02</td>
<td>3.99</td>
<td>0.75</td>
</tr>
<tr>
<td>7.99</td>
<td>5.49</td>
<td>0.73</td>
<td>6.31</td>
<td>4.21</td>
<td>0.75</td>
</tr>
<tr>
<td>Average</td>
<td>0.73</td>
<td></td>
<td>Average</td>
<td>0.75</td>
<td></td>
</tr>
</tbody>
</table>

Second test performed was the no-load test. During this test, slip is very small. So, the equivalent circuit reduces to fig. 6.4. Input power, stator currents and stator voltage are measured. Most of the voltage drop will be across the inductive components in the equivalent circuit. Table 6.2 shows the results for this test.

![Per-phase equivalent circuit during no-load test.](image)

Table 6.2 No-load test results.

<table>
<thead>
<tr>
<th>Vph (V)</th>
<th>Iph (A)</th>
<th>Pin (W)</th>
<th>Xs + Xm (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>113.74</td>
<td>5.00</td>
<td>190</td>
<td>22.75</td>
</tr>
<tr>
<td>116.05</td>
<td>5.21</td>
<td>230</td>
<td>22.29</td>
</tr>
<tr>
<td>121.82</td>
<td>5.84</td>
<td>190</td>
<td>20.85</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>21.96</td>
</tr>
</tbody>
</table>
Final test performed is the locked-rotor test or the short-circuit test. In this test, the rotor is blocked so that it cannot move and a small voltage is applied to the motor. Since the rotor does not move, slip is unity. Input power, stator currents and stator voltage are measured similar to the no-load test. Under these conditions, the equivalent circuit looks like a series combination of $X_s$, $R_s$, $X_r$ and $R_r$. Results from this test are shown in table 6.3. Rotor resistance obtained from locked-rotor test was close to the value obtained from the dc test and this value is used in both simulation and experimental parts. Table 6.4 has the complete set of induction machine parameters used in this project.

Table 6.3 Locked-rotor test results.

<table>
<thead>
<tr>
<th>$V_{ph}$ (V)</th>
<th>$I_{ph}$ (A)</th>
<th>$P_{in}$ (W)</th>
<th>$\Theta$</th>
<th>$X_s+X_r$ (Ω)</th>
<th>$R_s+R_r$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.96</td>
<td>5.06</td>
<td>119.00</td>
<td>0.92</td>
<td>2.56</td>
<td>1.55</td>
</tr>
<tr>
<td>15.91</td>
<td>6.31</td>
<td>183.00</td>
<td>0.92</td>
<td>2.52</td>
<td>1.53</td>
</tr>
<tr>
<td>18.88</td>
<td>7.34</td>
<td>254.00</td>
<td>0.91</td>
<td>2.57</td>
<td>1.57</td>
</tr>
<tr>
<td>21.19</td>
<td>8.05</td>
<td>292.00</td>
<td>0.96</td>
<td>2.63</td>
<td>1.50</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>2.57</strong></td>
<td><strong>1.54</strong></td>
</tr>
</tbody>
</table>

Table 6.4 Induction machine parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_s$</td>
<td>0.73 Ω</td>
</tr>
<tr>
<td>$R_r$</td>
<td>0.80 Ω</td>
</tr>
<tr>
<td>$L_s$</td>
<td>2.73 mH</td>
</tr>
<tr>
<td>$L_r$</td>
<td>2.73 mH</td>
</tr>
<tr>
<td>$L_m$</td>
<td>55.5 mH</td>
</tr>
</tbody>
</table>

6.2 IGBT Converters

The back-back PWM converters used in this experiment are the Powerex PS21865 IGBT modules rated at 600 V, 20 A and 1.5 kW. This package contains both the bridge and gate driver circuits which makes the interface circuit quite simple. All the six gate voltage signals have to be provided unlike some of the other modules. The module
requires that there is a dead time between the upper gate signal and the lower gate signal and vide-versa. This dead time is provided by an external circuit. Circuit topology and interface circuit of this module are discussed in detail in later sections of this chapter. The PS21865 module is shown fig. 6.5 along with the heat sink and the cooling fan used.

![Powerex PS21865 IGBT module](image)

**Figure 6.5 Powerex PS21865 IGBT module.**

### 6.3 SCR Phase Controlled Rectifier

As explained in chapter 4, a fuel cell emulator is used instead of a real fuel cell. The emulator is an SCR phase controlled rectifier that is controlled using the labview model (derived in chapter 4) in such a way that the response of the rectifier corresponds to that of a 500W PEM fuel cell stack. The SCR bridge used in this project is the PCM-3 power control module manufactured by Enerpro rated at 600 Vac and 25 Aac. Fig. 6.6 shows the picture of the PCM-3 module.

This ready to use module has three dual-SCR modules mounted on an 8" heat sink with a cooling fan, an Enerpro FCOG6100 SCR firing board and Enerpro RC-MOV snubber circuits. All of the connections between these components are factory made. A 0 - 5 V dc gate delay control voltage has to be supplied externally to the firing board. The gate delay angle varies in negative proportion to the command voltage. That is 5 V corresponds to 0° (or 6° for this module) and 0 V corresponds to maximum firing angle (84°). The firing circuit’s phase-locked loop circuit forms a set of phase-balanced, 60°-spaced, thyristor gate pulses in response to control input. The control power supply for
the board can be obtained from the three-phase ac inputs voltages or can be supplied externally. The firing board has a phase loss inhibit circuit which removes the thyristor gate drive if there is a loss of phase voltage due to a blown fuse or other cause is detected. Gating is enabled when the proper phase balance is restored. The board also has an instantaneous inhibit circuit that can be used to turn off the gate voltages externally during fault conditions.

![Figure 6.6 PCM-3 SCR rectifier module.](image)

### 6.4 Circuits

This section describes in detail the various circuits designed to control both the induction generator and the fuel cell emulator. The circuits are broken down into different sections and the signals are traced from their starting point to the inverter or rectifier gate terminals. This project utilizes several current and voltage sensors to gather data for the vector control schemes and the Labview model. Data from these sensors in collected by
two data acquisition (DAQ) cards installed in two personal computers (pc). As shown in fig. 6.1, pc-1 with the PCI-12AIO card performs all calculations to control the DFIG and pc-2 with the Labview card runs the fuel cell model. The fuel cell model requires one voltage \( v_{kF} \) and one current sensor \( i_{kF} \). The Labview card outputs a voltage signal proportional to the gate delay angle and it is connected to the gate delay terminals of the FCOG6100 firing board through an analog isolation amplifier. This circuit is quite simple to implement as it involves using just two sensors.

The circuits required for the DFIG, however, are rather complex. The PCI-12AIO card has only four analog outputs. So, stationary d-q voltages are used as outputs instead of a-b-c voltages. Therefore, these signals have to be transformed to three-phase quantities. Before this circuit, the expensive DAQ card is isolated from the rest of the circuit using analog isolation amplifiers. The reference a-b-c signals from d\( q^2 \)-abc circuit are then compared with a triangular wave to generate gate signals for the inverter. Again, these control signals are isolated from the power circuit through optocouplers. An interface circuit is required for the IGBT module and is built based on the powerex manual. The vector control schemes require rotor speed. An incremental optical encoder is used to sense the rotor speed. The data from the encoder is read through the 16-bit digital port on the DAQ card. All of these circuits are designed on printed circuit boards (PCB) due to noise concerns. PCB design / layout using Ivex is explained in appendix A.

Since the signals are isolated in two places, three isolated dc power supplies are required to power the circuits. Other circuits designed are a charging circuit for the dc link and a dynamic brake circuit for dumping excess power off the dc link.

### 6.4.1 Current and Voltage sensors

Nine current sensors and eight voltage sensors are used in this project. The quantities that are required for implementing the DFIG vector control methods are \( V_{as}, V_{bs}, V_{cs}, I_{as}, I_{bs}, I_{ar}, I_{br}, V_{dc}, V_{ag}, V_{bg}, V_{cg}, I_{ag}, I_{bg}, I_{ah} \) and \( I_{bh} \). Only two measurements are required for
the currents as the star point of the Y connection is ungrounded or isolated and so the currents must be balanced \((I_a + I_b + I_c = 0)\). In a Y connection, voltages need not be balanced. So, all the three phase voltages are measured. For the Labview model, \(I_{fe}\) and \(V_{fe}\) are measured. LEM hall-effect transducers are used to measure these quantities. The transducers provide an output voltage signal proportional to quantity that is being measured. LV-25NP is used for voltage measurements and LAH-25NP is used for current measurements. The sensors are placed at various locations as shown in fig.6.1. Fig. 6.7 shows the circuit diagram of these two transducers. External resistors can be adjusted to vary the gains of the sensors.

Figure 6.7 LEM current and voltage sensor circuits.

Both the current and voltage signals are filtered using a first order op-amp low-pass filters, and gained to obtain a range of approximately \(\pm 5V\). Equations 6.1 and 6.2 shows
gain calculations for current and voltage measurements. Due to tolerances in resistances and other irregularities, average gain of each transducer is calculated by taking multiple measurements. These measurements are then sent through the DAQ card to the computer. The sensors circuits are soldered onto a PCB shown in fig.6.8. The transducers also provide isolation between the DAQ and power circuit.

\[ V_{in} = V_{out} \cdot \frac{1000}{2500} \cdot \frac{16000}{150} \Rightarrow V_{in} = 42.667 \cdot V_{out} \]  

\[ I_{in} = V_{out} \cdot \frac{1000}{100} \cdot \frac{1500}{4700} \Rightarrow I_{in} = 3.191 \cdot V_{out} \]  

Figure 6.8 Picture of PCB with sensor circuits.
6.4.2 Incremental Optical Encoder

The angular speed required for the vector control of the induction machine is sensed using an incremental optical encoder. The encoder is attached to the machine shaft and it outputs a 16-bit word corresponding to the shaft speed which is then sent to the DAQ. The main components of the encoder are the code wheel; the optical encoder module and the quadrature decoder/counter chip. Fig. 6.9 shows the circuit for the encoder.

The plastic optical code wheel (HP-HEDM) approximately 2” in diameter and 0.01” thick is attached to the induction machine shaft via an aluminum coupler. The rotational motion of the code wheel is detected using the incremental optical encoder module HP HEDS-9000, which consists of an LED and two closely-spaced photosensors. The code wheel is carefully mounted in between the LED and the two photosensors without touching them. The code wheel used has 1024 black stripes, which means that each of these photosensors will output 1024 counts per revolution. Also, the photosensors are arranged in such a way that the two signals lead or lag each other by 90° depending on the direction of shaft rotation.

![Incremental optical encoder circuit](image)

Figure 6.9 Incremental optical encoder circuit.
The two quadrature signals (CHA and CHB) from HEDS-9000 are sent to HP HCTL-2016, a 16-bit quadrature decoder/counter chip. HCTL-2016 has been specifically designed for use with optical code wheels. Internal circuitry of this chip is quite complex. The signals from the encoder are first cleaned up and then the resolution is increased by four times (4x decoded). The 16-bit count information from these signals is sent to the eight output pins of the chip. This data is read using the 16 bit digital I/O port in the DAQ card. The first eight bits of this port are set as input and next two as outputs. The two outputs are connected to SEL and !OE pins on the HCTL chip. These pins have to be used to read the high byte first and then read the low byte. C language code to read data from the HCTL-2016 chip and then calculate the rotor speed is attached in appendix B. Because of the 4x quadrature decoding the resolution of the encoder has now been increased to 4096 counts per revolution. Fig. 6.10 shows the picture of code wheel attached to the machine shaft and the optical encoder module. The counter chip and the 5 MHz clock are soldered separately on a protoboard.

![Image of optical encoder](image)

Figure 6.10 Picture of the optical encoder.

### 6.4.3 Analog Isolation

Signals from the sensors and the encoder are sent to the DAQ card. The pc then performs the vector control calculations and outputs stationary d-q reference voltages.
These analog signals are transformed by external circuits into gate signals for the two back-back PWM converters. The DAQ card used (PCI 12AIO) is expensive. So, it was decided to have analog isolation amplifiers between the DAQ analog outputs pins and the external circuit. An isolation amplifier helps in noise rejection and breaks ground loops since the input and output are floating relative to each other. Isolation devices are not required at the DAQ analog input pins because the current and voltage transducers are by themselves isolation devices.

TI ISO124 is used to provide analog isolation between the DAQ and the dq^s^-abc circuit. It provides galvanic isolation between the input and output. The ISO124 isolation amplifier transmits the analog input signal intact digitally across a differential capacitive barrier. The amplifier requires two ±12 V dc isolated power supplies each connected at the input and output sections. It does not need any other external components except decoupling capacitors for the dc power supplies. Four isolation amplifiers are used for the four analog output signals V^s_r, V^s_q, and V^s_d, V^s_q for the rotor-side converter and front-side converter respectively.

### 6.4.4 dq^s^-abc Transformation

The reference stationary d-q voltages from the analog isolation amplifiers have to be transformed to a-b-c quantities for spwm. This transformation is made using equations 6.3. Fig. 6.11 shows the op-amp circuit that implements the transformation. This circuit is built twice for the two converters. It can be seen from the figure that the d-q voltages from the DAQ card are gained by 0.25. The maximum values of the d-q voltages were set to ±1.2 inside the computer. To achieve better resolution on the analog outputs on the DAQ card, the d-q voltages are multiplied by 4 so that the output range from the computer is about ±4.8V. Since the analog output range of the DAQ was set to ±5V, this makes the outputs utilize the full range of the card.
$$V_a = V_d^s$$

$$V_b = -\frac{1}{2}V_d^s + \frac{\sqrt{3}}{2}V_q^s$$

$$V_c = -\frac{1}{2}V_d^s - \frac{\sqrt{3}}{2}V_q^s$$

(6.3)

Figure 6.11 Op-amp circuit to implement dq$^s$-abc transformation.

6.4.5 SPWM

Sinusoidal pulse width modulation (spwm) is used to generate gate voltages for the IGBT converters from the a-b-c reference voltages. In spwm, the desired output voltage at the converter terminals is achieved by comparing the reference waveform with a high-frequency triangular waveform. Depending on whether the reference voltage is larger or smaller than the triangular waveform, either the positive or negative dc bus voltage is applied at the output. The resulting square waveform has the fundamental whose magnitude and frequency a similar to the reference waveform.

To do this, triangular waveform of desired frequency and has to be generated and then compared with the reference voltages. Fig. 6.12 shows the circuit that implements spwm. The circuit of the left hand side generates a triangular waveform with a peak value of approximately 1.2 V and its frequency can be adjusted by a potentiometer. Sometimes
there might be a small offset the triangular voltage waveform. Another potentiometer is used to adjust the offset of the triangular waveform.

The frequency is set to 15 kHz for this experiment. The amount of power that the IGBT module can provide is inversely proportional to the switching frequency. At higher frequencies the module provides less power to the machine. However, at lower frequencies, it becomes difficult the filter the voltage and current waveforms acquired through the sensors and this there is more overall noise in the system. Also, at lower frequencies the module might generate an audible noise. The switching frequency of 15 kHz provides the required power to the machine while eliminating audible noise and reducing the size of filtering components. The current and voltage waveforms are filtered at 1 kHz to eliminate the PWM switching noise.
The three comparators shown compare the triangular waveform with the a-b-c reference voltages and output +12 V if the reference voltage is higher than the triangular waveform and -12 V if the reference voltage is less than the triangular waveform.

6.4.6 Optical Isolation

Before transferring the SPWM signals to the IGBT modules, they must be isolated from the power side. Optocouplers can be used to provide the isolation between the signal side and the power side. Optocouplers are very cheap compared to analog isolation amplifiers used in section 6.4.3. TPL2631 optocoupler modules are used in this project. Each optocoupler module consists of couple of LEDs and signals are transmitted via light to a phototransistor on the other side. There is no electrical connection between the two sides. The output is of open collector type and the signal is inverted compared to the input. Fig. 6.13 shows the picture of PCB with dq^8-abc, SPWM and optocoupler circuits.
It was observed that the output signals generated from the optocouplers are not tight squares waves (rise time) and are noisy. To solve this problem, the output signals from the optocouplers were passed through digital buffers that make distinct square waves from the noisy optocoupler signals. SN7407 hex buffers are used.

The signals generated from the optocoupler circuit are the only the high signals for the IGBT bridge i.e. for the top switches. The IGBT module requires both high and low signals. So, the high signals are inverted to generate signals for the bottom switches. This assures that any instant the IGBTs in the same leg are not simultaneously on. Fig. 6.14 shows the optocoupler, buffer and inverter circuits for phase A. SN74LS05 hex inverters are used. Two different ground symbols can be noticed in fig. 6.13. This means the two grounds on either side of the optocoupler are floating with respect to each other.

![Figure 6.14 Optocoupler, buffer and inverter circuit.](image)

**6.4.7 IGBT Module Interface Circuit**

The signals obtained from the previous circuit are inverted and there is no dead time between the high and low signals. As mentioned earlier in section 6.2, the PS21865 IGBT modules require all six gate pulses with a finite dead time between the switching of top and bottom IGBTs. Fig. 6.15 shows the circuit that implements dead time for the module. Buffers are used again to make sure that the signals are clean. The output signal from the
buffer is passed through a simple delay generating circuit. When the input from the buffer is high, the diode conducts and there is no delay in input as shown in the timing diagram in fig. 6.15. The inverter then inverts the signal to low with no delay. When the input is low, the capacitor takes a finite amount of time to discharge before the inverter switches the signal from low to high. Dead time was created for all the six gate signals.

Next step is to build the interface circuit for the IGBT module. Fig. 6.16 shows the interface circuit as per the Powerex manual. As shown, the module has both the driver and bridge circuit with free-wheeling diodes. The module operates from a single +15 V control power supply. Various integrated circuits within the module provide signal conditioning and protection functions for the IGBTs. There are two main protective functions. When the +15 V control power supply voltage falls below a trip value of 10.5 V, an under voltage (UV) lockout is activated and the IGBTs are turned off and fault signal $f_{G}$ is asserted. The fault signal may be used to trigger external protection circuits. No external protection circuits are implemented in this project for the IGBT module. The other protection function is the short circuit (SC) trip. The value of trip current can be set by an external current sensing resistor. This value of trip current is set to 16 A in this experiment. Again, the IGBTs are turned off and a fault signal is asserted during SC trip. Both these lockouts are automatically released when normal conditions resume.
6.4.8 DC Link and Other Miscellaneous Circuits

Fig. 6.17 shows the dc link circuit implemented. As shown in the main schematic in fig. 6.1, the dc link capacitor is connected to the back-back IGBT converters and the SCR bridge simulating a fuel cell. The SCR rectifier (with the LC filter) is connected to the dc
Dynamic brake

Battery: Enerpro PCM-3 DC link

Figure 6.17 DC link circuit.

link through an inductor \(L_2\) and a diode so as not to inject current back into the bridge. The vector control methods for DFIG require an initial voltage on the dc link. So, the dc link capacitor has to be charged to required voltage level before starting the controller. This is done through a battery (as shown) and the charging resistor \(R_1\).

Couple of safety measures are also implemented. The maximum dc bus voltage that the IGBT modules can handle is 450 V. A 300 V zener diode is connected across the dc link to limit the maximum voltage. Another safety measure implemented was the dynamic brake. It is a simple circuit connected across the dc link comprising of a power resistor \(R_2\) and a transistor. When the voltage on the dc link exceeds a specific value, the transistor is turned on and the excess power on the dc link is dumped into the power resistor.

As explained in previous sections, the circuits implemented are isolated in two places. Therefore, three isolated dc power supplies are required to power the circuits. Three switching power supplies are used as shown in fig. 6.18. A 24 V power supply is also used for the cooling fans used.
Data Acquisition and Control

As shown in fig. 6.1, two personal computers are used for controlling the DFIG and the fuel cell. A PC is preferred over a DSP for induction machine control as it offers increased flexibility in handling data and customizing and is easier to work with. The program environment is chosen to be DOS based because Microsoft Windows based systems are not designed for real-time applications. In Windows, other programs may conflict the controller and cause gaps in control calculations.

SCR bridge, simulating Avista SR-12 fuel cell is controlled using Windows based Labview. The fuel cell simulator does not require a hard real-time environment. The response of the real fuel cell is quite slow. So, Labview is quite sufficient. Data acquisition and control for DFIG and fuel is explained in detail in the following sections.

6.5.1 DFIG

Step time is an important parameter in choosing the DAQ card and the operating system. For vector control of induction machines, step time needs to be less than 200 μs.
The smaller the step time, the smoother the output waveforms will be. There are two main factors that influence this parameter. The first is the acquisition or A/D conversion rate of the DAQ card. This acquisition time has to be few orders smaller than the final step time. Other factor is the computational complexity of the program itself. The program has to be kept simple so that the time required to run each iteration is small.

For DFIG control, PCI12AIO, a PCI analog I/O card manufactured by General Standards is used. The vector control methods for back-back converters were written in C++ language and are run in a DOS environment. The step time used in 150 μs i.e. data is acquired and output voltages are updated every 150 μs. A simple interactive GUI also is implemented.

6.5.1.1 DAQ Card

PCI12AIO is a 12-bit analog input/output PCI card. It handles all communication between the circuits and computer. The card has a maximum of 32 single-ended or 16 differential analog input channels that can be sampled at a maximum frequency of 1.5 Msps (mega samples per second). All the analog input signals in this experiment (current and voltage sensors) have a common ground. So, single-ended acquisition is chosen. Since 15 single-ended channels are used for vector control, the effective sampling rate on each channel is 100 ksp. It has 4 single-ended analog output channels that can be sampled at a maximum rate of 300 ksp per channel. The card also has a 16-bit bidirectional digital I/O port that is used to interact with the rotor optical encoder. Digital port is also used to measure the time required to execute a particular portion of the program. This is very important to determine the real time capability of the system. The analog input/output range used was ±5 V. The sensors are gained so that the output voltage does not exceed ±5 V. As explained in section 6.4.4, the output signals from the controller, which have a range of ±1 V, are multiplied by 4 to utilize the complete analog output voltage range. Fig. 6.19 shows the picture of the DAQ card.
6.5.1.2 Interrupts

Unlike many other analog I/O DAQ cards, this card does not utilize an internal clock for triggering interrupts. PCI interrupts are edge-sensitive and have to be triggered from an auxiliary signal. One of the problems with external triggering is the noise and variation in frequency of the clocks. If the interrupts are not triggered at a constant rate, it can cause serious timing problems especially for time sensitive calculations such as rotor speed, integrators and PI controllers. After trying few oscillators with average results, LTC6900 oscillator manufactured by Linear Technology was used. This chip provided a nearly constant frequency auxiliary signal for interrupts. The frequency is set based on the time required to run the entire DOS program. The total time needed to acquire the required analog and digital data and compute vector control calculations was measured to be around 90 μs. So, the interrupts were triggered at 150 μs to allow enough time to run each iteration, display the GUI and record data if required.

C++ code implemented to initialize the board, enable and trigger interrupts and to acquire and output data is attached in appendix B.1 (pcil2aio.cpp). Code for vector control calculations for both the converters is attached in appendix B.2 (cdfig.h) and B.3 (cdfig.cpp). The function ‘NewISR’ is set up as the interrupt service routine. It is run every time an interrupt request is generated no matter what the computer is doing.
including writing data onto the hard drive. The processor returns to its previous operation only after completing the interrupt service routine. The NewISR function acquires the required data, performs vector control calculations and outputs the computed voltages for every interrupt.

6.5.1.3 Analog and Digital I/O Setup

For analog I/O, before data is acquired or sent, the DAQ card must be configured in terms of number of channels, sampling rate, sample range and data representation (coding format). For analog input channels, it has to be specified whether the sampling is single-ended or differential. For analog outputs, it has to be specified as whether the output clocking mode is simultaneous or sequential. Code shown below sets up all the above conditions. Number of input channels used is 15 (\(V_{as}, V_{bs}, V_{cs}, I_{as}, I_{bs}, I_{ar}, I_{br}, V_{dc}, V_{ag}, V_{bg}, V_{cg}, I_{ag}, I_{bg}, I_{ah}, I_{bh}\)). All the four available analog output channels are used (\(V^{s}_{dr}, V^{s}_{qr}, V^{s}_{dg}, V^{s}_{qg}\)). As mentioned earlier, the input channels are sampled at 1.5 Msps and output channels are sampled at 300 kspss per channel and the range is ±5 V. Data representation is chosen as offset binary. It means zero is offset in the middle of the range of positive binary numbers. Actual values can be then be calculated by subtracting the zero offset from the binary number.

```c
// Set input sampling rate to 1.5 M samples/sec
Board[CurrentBoard]->WriteLocal(RATE_A, 0x001E);
// Single-ended analog, Offset binary, +-5V I/O range
Board[CurrentBoard]->WriteLocal(BCR, 0x51);
// Set output rate generator to 300k samples/sec
Board[CurrentBoard]->WriteLocal(RATE_B, 0x00064);
// Set simultaneous out
ValueRead = Board[CurrentBoard]->ReadLocal(BCR);
Board[CurrentBoard]->WriteLocal(BCR, ValueRead | 0x0100);
```
The 16-bit bidirectional digital port is divided into two 8-bit ports. Each port can be configured as either input or output port. The digital port has one auxiliary input pin for triggering the interrupts. The digital port was used to measure the rotor speed. The HCTL-2016 module outputs a 16-bit word corresponding to rotor speed. But, the module has only 8 output pins. Therefore the data has to be read each byte at a time.

6.5.1.4 DFIG_Control Class

A class was created for this project called dfig_control. This class is defined in files cdfig.h and cdfig.cpp attached in appendix B. This class initializes/holds all the variables required and performs all the calculations required to generate the new output reference voltages for the back-back converters. Various functions required for vector are defined in this class. The function next_time_calculator(), computes the new output values at every interrupt. Before calculating the new output values, the class has to be supplied with the new input values acquired. Complete C code is attached in CD in pocket.

6.5.1.5 Graphical User Interface

A simple GUI is implemented as shown in fig. 6.20. As shown, it displays relevant data and has various options to control the program. The values that are displayed on the screen are either three-phase quantities in reference frame or dc quantities. Data such as the reference voltages for the converters can be observed and the controller can be stopped if the values seem to be going out of range. The values are refreshed every 10 ms when not storing data and every 1 s when storing data. Reference values and PI gains can be changed on the run to observe the response of the machine to the new values.
6.5.1.6 DOS Program

To summarize all the previous sections, the following are the functions that the DOS program has to perform to properly execute the vector control methods:

1) First, the program has to identify and initialize the PCI board. Several supplementary driver files are required to detect, calibrate and setup the board.
2) The program has to enable PCI interrupts on the board and interrupts must be setup to be generated when the auxiliary input goes from low to high.
3) Analog and digital I/O has to be setup as explained in section 6.5.1.3.
4) GUI has to be setup and display relevant data.
5) New data acquired is supplied to the dfig_control class and control calculations are performed every time an interrupt is generated.
6) Setup a method of saving data onto the hard drive in between interrupts.
6.5.2 Fuel Cell

National Instrument’s Labview was used to simulate the electrochemical model of the fuel cell for the simulator. Labview is primarily used for user-friendly GUI based data acquisition and as a virtual instrument. It is also used in real-time simulation and control of dynamic systems. But, due to the use of computationally intensive graphics, Labview is usually not preferred for hard real-time applications. But, the fuel cell simulator does not require a hard real-time environment as compared to DFIG. The response of the real fuel cell to changes in load or other parameters is in order of few seconds. So, Labview environment is quite sufficient in simulating the fuel cell. The simulator was run on a Pentium 2, 128 MB RAM personal computer. A constant 10 ms step time was used to acquire data, perform control calculations and update output control voltage.

6.5.2.1 Labview Program

Labview has a GUI similar to Simulink with library blocks that can be dragged and dropped into the system. Modeling is done in the form of a block diagram with various interconnected blocks implementing the modeling equations derived in section 4.2. The schematic of the fuel cell simulator is shown in fig. 4.4.

From equations 4.2 – 4.13, the model requires, apart from the operating conditions, fuel cell stack current as input. Therefore, the load current is sensed and used in the Labview program to establish the new stack voltage based on the electrochemical model. This voltage is used as a reference for the SCR bridge closed-loop control system. The bridge output voltage is measured and compared to the reference voltage generated from the fuel cell model. The resulting signal is used as the input to a PI controller. The PI output signal is then used to drive the SCR bridge, which is connected to three phase grid. The PI output cannot be directly connected to the gate voltage input of the bridge. As explained in section 6.3, the gate delay angle for the PCM-3 module varies in negative
proportion to the gate voltage and the range is $0 - 5$ V. So, the PI output voltage has to be properly conditioned before connecting sending it out on the output channel.

6.5.2.2 Hardware Setup

Labview DAQ card acquires the current and voltage measurement data from the sensors. Channel 0 and channel 1 single-ended analog input channels on the DAQ are used for this purpose. Using this data and the Avista SR-12 fuel cell parameters, the Labview program computes $v_{\text{cont}}$ for controlling the SCR bridge. This is sent on channel 0 analog output channel. The Labview program acquires data using the ‘AI Read One Scan.vi’ every step time and outputs the control voltage using the ‘AO Write One Update.vi’. Fuel cell voltage is read using the LEM LV-20 transducer and current is measured using the LEM LTS-15 transducer. The control voltage output is connected to the gate voltage input of the PCM-3 module via an analog isolation amplifier.

The actual fuel cell output voltage is pure dc. So, it is necessary to use a low pass filter at the converter output terminals to minimize the voltage ripple. The filter used is an LC passive filter, with an inductor of 17 mH and a capacitor of $850 \mu$F. The resulting corner frequency is 41.86 Hz. The fuel cell simulator is connected across dc link of the back-back converter system through Inductor $L_2$ (4.4 mH). The load current for the fuel cell model is measured at this point i.e. current injected into the dc link.

6.5.2.3 GUI

The Graphical User Interface developed in Labview for the fuel cell simulator is shown in fig. 6.21. This interface allows the user to control the simulation start and simulation end times and also monitor important data on-line. Operating conditions such as pressure, temperature etc, fuel cell parameters and control parameters can be changed.
on the run to observe the response of the fuel cell. Required data can also be stored onto the hard drive.

Figure 6.21 Labview GUI for the fuel cell simulator.

Complete circuit
CHAPTER 7
EXPERIMENTAL RESULTS

This chapter presents the final experimental results. As mentioned in chapter 6, the laboratory setup closely followed the simulation setup. This gives a fairly good idea of what to expect from the experiments. But, before the final experimental setup was run, all the equipment has to be tested. All the circuits were initially tested with known inputs to check if they are operating correctly. Then, the analog and digital I/O of the DAQ cards was tested. After all the components checked out ok, the machine was run in open-loop with REC connected in the rotor circuit. FEC was also tested in open-loop injecting power into the grid. Same procedure was followed with the fuel cell simulator. After obtaining expected results from open-loop tests, DFIG and fuel cell were in integrated and run in closed loop. In this chapter, open-loop results for DFIG and the fuel cell are presented. Closed-loop results showing active/reactive power control of DFIG and power flow from the fuel cell into the dc link are presented. Some of the problems faced are also discussed.

7.1 Open-Loop Results

First step when running an experimental setup is to test the setup with simple experiments. Open-loop tests were performed on the two converters and the fuel cell simulator. The open-loop tests provide a chance to debug the circuits or modify them for better performance in a safe manner. Various discrepancies were observed such as unbalanced grid voltages, large harmonics in rotor currents, variation in stator resistance etc. Appropriate modifications were made to the system to compensate these anomalies. Gains of current and voltage sensors were also adjusted based on observed data.
7.1.1 DFIG Open-Loop Test

The induction machine was run in open-loop similar to the simulation setup in section 5.2. REC was connected to the rotor terminals and was programmed to inject positive sequence currents of 1 Hz frequency. The dc link voltage was maintained at 75 V by an external dc power source. Modulation factor for REC was 0.5. Fig. 7.1 shows the response of the induction machine to positive slip input. The machine was initially run in squirrel cage mode with rotor windings short circuited and was connected to the REC at 1.7 s. As expected the machine stabilized at the new speed.

![Figure 7.1 Rotor speed for positive slip input.](image)

Fig. 7.2 shows the stator and rotor currents induced during open loop operation. The experimental response matched almost exactly with the simulation results shown in fig. 5.6. In simulation, the dc link voltage was maintained at 50 V. But, losses in the machine and the converter were not implemented in the simulation. One important thing that can be observed from fig. 7.2 is the high percentage of third harmonic content in rotor currents even though the star point is floating. The currents almost look like square waves. This will cause problems when transforming the a-b-c currents to d-q reference frame. The d-q reference currents will no longer be dc quantities. There will always be ripple in the transformed currents which will cause problems in closed loop control of
rotor currents. The harmonic content can only be explained as wear and tear in the rotor windings. The machine setup in the Electric Machines lab at CSM is over 50 years old. Harmonic content aside, the induction machine behaved as expected. The speed data from the optical encoder was fairly constant.

Another observation that was made was that the ‘three-phase grid’ voltages were unbalanced. The voltages come from an auto-transformer in the electric machines lab and not directly from the grid. The magnitude of phase ‘c’ voltage was slightly higher than the other phases. So, all the three phase voltages have to be measured in contrary to what is shown in fig. 3.5. Also, the phase sequence of the voltages was negative. So, the setup was modified to take this into account.
7.1.2 FEC Open-Loop Test

Next, FEC was also tested in open-loop. The test can be used to observe the accuracy in aligning the grid voltage vector along the reference d-axis. This makes sure that the voltages induced at the inverter output terminals are in sync with the grid voltages. Also, the currents through the transformers can be observed. Again, the dc link voltage was maintained at 75 V and modulation factor of 0.6 is used. The grid voltage was decreased to 40 V_{L-L} so as to be able to inject power into the grid in open-loop. The voltage vector angle is obtained from grid voltages as per equation 3.31.

Fig. 7.3 shows the response of the FEC. It can be seen from fig. 7.3 (a) that the d-axis voltage vector is constant. This tells that the voltage angle calculation was accurate. Fig. 7.3 (b) shows the inverter voltage and current waveforms. The voltage waveform is

![Figure 7.3 (a) d-axis grid voltage (b) FEC voltage and current (- current, - voltage).](image)
measured before the 1:4.34 turns ratio transformer. The converter was able to inject about 25 W of power into the grid. This is very low compared to the actual power that will be injected in closed-loop. But, these tests show that all the sensors, circuits and DAQ card are working properly.

7.1.3 Fuel Cell Simulator

The fuel cell simulator was also tested without connecting it across the dc link of the DFIG system. A resistive load of 10.29 Ω was connected across the output terminals instead. The schematic for this setup is again fig. 4.4. Load current and load voltage data required for the simulator are read using the Labview DAQ. Fig. 7.4 shows the response of the simulator. Stack voltage (shown in blue in fig. 7.4 (a)) is calculated based on the

Figure 7.4 (a) – Stack voltage, – converter voltage (b) – Gate voltage, – output current.
load current (shown in green in fig. 7.4 (b)). PI controller in the simulator compares the stack voltage with the actual converter voltage. The gate voltage for the SCR bridge is increased until the converter output voltage stabilizes at the new stack voltage level. This process takes about 4 s, which is close to the actual response of the Avista SR-12 fuel cell. The simulator was able to inject about 400 W of power into the resistive load.

The response of the PCM-3 SCR rectifier module to gate angle voltage can also be seen from the figure. The relationship between the gate voltage and the output is initially non-linear. But, after the gate voltage reaches 1 V, the output voltage varies linearly with the gate voltage input.

7.2 Closed-Loop Results

With everything working fine in open-loop, next step is to close the loop. As in simulation, the induction machine was initially tested with just REC connected in the rotor circuit fed by an external dc power source. After obtaining expected results, the dc power source was removed and FEC was connected. Finally, the fuel cell simulator was integrated across the dc link.

7.2.1 Start-up Procedure

The experimental setup has many components and running all of them together might not be safe. Initial transients might damage some of the components. So, a start-up procedure is formulated to start the experiment in a safe manner as explained below:

1) The vector control methods require an initial voltage on the dc link capacitor. From figures 6.1 and 6.17, this is done through the charging resistor $R_1$ and an external battery. $S_1$ is kept open until the capacitor is completely charged.
2) The induction machine is started in squirrel-cage mode with the dc motor as the prime mover.

3) The computer running the vector control methods is started and dc power supplies for all the circuits are tuned on.

4) Double-throw switch $S_2$ and breaker $S_3$ is operated to connect the rotor terminals to REC. The FEC is not yet connected and the REC is fed by the battery. Power flow in the rotor circuit is unidirectional and machine operated in sub-synchronous mode.

5) After the DFIG stabilizes, breaker $S_4$ is turned on and FEC is connected to grid terminals. The reference dc link voltage for FEC vector control is the set at the battery voltage.

6) Now, $S_5$ is opened to turn off the battery. DFIG is now running with both the back-back converters.

7) Next step is to connect the fuel cell simulator across the dc link. The Enerpro SCR bridge is turned on and the Labview program is run. The simulator can be commanded to inject any current into dc link. Switch $S_6$ is turned on when the voltage across the simulator output terminals reaches the dc link voltage.

7.2.2 DFIG

This section presents the experimental results of closed-loop operation of DFIG without the fuel cell. Vector control schemes derived in chapter 3 were implemented to control the active and reactive power generated by the induction machine. Some of the differences compared to the Matlab simulation are: the dc link voltage was maintained at 100 V for better control over reactive power and harmonic compensation was not implemented in the experimental setup. Reasons for not implementing harmonic compensation are explained later in this section.

Fig. 7.5 shows the response the induction machine to step changes in active and
reactive power commands. The following are the step changes in rotor currents from initial values of $i_{dr} = -2$ A and $i_{qr} = -2$ A

- At $t = 9$ s, step change in $i_{qr}$; $i_{qr} = 2$ A.
- At $t = 21$ s, step change in $i_{dr}$; $i_{dr} = 0$ A.
- At $t = 33$ s, step change in $i_{qr}$; $i_{qr} = 4$ A.
- At $t = 39$ s, step change in $i_{dr}$; $i_{dr} = 2$ A.
- At $t = 60$ s, step change in $i_{dr}$; $i_{dr} = 0$ A.
- At $t = 66$ s, step change in $i_{dr}$; $i_{dr} = 0$ A.
The REC controller follows the reference currents quite well. At around $t = 50$ s, the induction machine was generating about 1000 W of active power. The controller was not commanded to supply more reactive power to the stator because generating reactive power from the rotor side is not very efficient. From equation 3.21, before reactive power is generated from the stator, the rotor circuit has to supply the entire magnetizing current. The magnitude of magnetizing current, referred to rotor, is approximately 8.1 A. This high current would result in increased losses in the rotor circuit as well as in the IGBT converter. In fig. 7.5 (b), the REC commanded to supply to part of the reactive power required by the stator and rest is absorbed from the grid.

One of major problems faced in this project was the lack of a speed control loop on the dc motor. This problem was not anticipated until the entire setup was complete. Actual wind turbines have huge inertia and will naturally damp any oscillation in speed. In simulation too, inertia was quite high. But, in the experimental setup, the dc machine was rated at just 1 H.P. and thus has small inertia. To increase the inertia, fly-wheels were attached to the rotor shaft. This increased the inertia slightly but not nearly enough to damp out oscillations in rotor angular speed as shown in fig. 7.5 (a). It can be seen from the figure that the ripple in rotor currents follows the ripple in rotor speed. The ripple is more prominent in $i_{dr}$ as compared to $i_{qr}$. It can also be seen from the figure that when the rotor speed is constant, there is no ripple in the rotor currents.

The oscillation is speed combined with non-sinusoidal rotor currents were the two reasons based on which harmonic compensation was not implemented. The reference currents for active filter operation would contain $5^{th}$, $7^{th}$ and $11^{th}$ harmonic currents i.e. the rotor reference current would be a fast-varying signal. With the experimental setup as it is, it would be very difficult to control active and reactive power as well as generate compensating harmonic currents.

The controller, however, does a very decent job in controlling the active and reactive power generated from the stator side. All the other parameters in the machine are as expected. Fig. 7.6 shows the stator flux magnitude and the electrical speed of the stator.
Figure 7.6 (a) Stator flux magnitude (b) Stator flux electrical speed.

flux vector based on equations in 3.3.1.2. As explained, a low pass filter is used to approximate the integration of stator voltages.

Fig. 7.7 shows the response of the FEC to the changes in active and reactive power commands. The main purpose of the FEC is to keep the dc link voltage constant regardless of direction or magnitude of power flow in the rotor circuit. It can be seen from fig. 7.7 (a), the FEC maintains the dc link voltage at a constant value during all the step changes in the rotor currents. The converter also controls the reactive power flow from the grid to the dc link i.e. in the rotor circuit. With d-axis grid voltage orientation, the reactive power flow is directly proportional to \( i_q \). The reactive power command is set to zero for unity power factor. The FEC also maintains the q-axis current constant at 0 A. This reactive power command could be changed to compensate for the reactive power.
Figure 7.7 Response of FEC.
(a) DC link voltage (b) Reactive power in rotor circuit.

absorbed by the stator as only part of the reactive power required is supplied by the rotor circuit. The above results show that the vector control schemes implemented are able to control the required parameters.

7.2.3 DFIG and Fuel Cell

Since the DFIG and the fuel cell were working quite well, the next step is to integrate the fuel cell across the dc link of the back-back converter system. The maximum voltage of the SR-12 fuel cell is 41 V and the dc link voltage is at 100 V. So, as in the Matlab simulation, a boost converter was implemented in Labview. From schematic 4.4, the load current or the current in inductor L2 is controlled in a closed-loop using a PI controller. In
this case, the stack voltage is not directly obtained from the load current but from duty cycle ratio of the boost converter. Without closed-loop control of output load current, it would not be possible to inject a predetermined amount of current into the dc link. The current injected would then depend on the difference in the dc link voltage and SCR bridge voltage. Without the boost converter operation, the fuel cell only injected ripple currents into the dc link which lead to more oscillations in the rotor currents.

Fig. 7.8 shows the instantaneous active power flow in the rotor circuit. This power profile was recorded at the FEC output terminals. The following are the commands used:

- Stator active power command, $i_{qr}$ is maintained at 3 A.
- Stator reactive power command, $i_{dr}$ is maintained at 1 A.
- DC link voltage maintained at 100 V.
- Rotor circuit power factor command is maintained at 0 A.
- At $t = 8$ s, point (a) in fig. 7.8, fuel cell is tuned on and commanded to inject 1 A.
- At $t = 42$ s, step change in fuel cell load current is made; $i_b = 2$ A.
- At $t = 78$ s, fuel cell is disconnected from the dc link.

The experiment was started with DFIG running in sub-synchronous mode and was commanded to generate $\sim 720$ W of active power. This would mean that the active power would be absorbed form rotor side for the machine to operate in generating mode. As shown in fig. 7.8, the machine absorbs about 30 W of power from the grid through the rotor circuit. At the instant (a) shown in figure, the fuel cell is turned on and the boost converter is programmed to inject 1 A into the dc link or 100 W of power. As mentioned earlier, the response of the SR-12 fuel cell stack is slow to changes in load. The simulator stabilizes in about 10 s and the voltage of the bridge is same as the dc link voltage. The simulator injects about 100 W of power into dc link. Of this 100 W, 30 W is fed into the rotor as required and the remaining 70 W is injected into the grid.

The dc link voltage and reactive power flow in the FEC in shown in fig. 7.9. The FEC
does a very good job in keeping the dc link voltage constant. Small perturbations can be observed in the dc link voltage waveform at the instants when the changes in dc link current are made. But, the voltage recovers very quickly. The maximum ripple in the voltage is only 4 %, which is quite good. The reactive power command, however, is not as constant as the dc link voltage. This will again be blamed on the oscillations in rotor speed. This is explained later in this section.

At time instant (c) in fig. 7.8, the fuel cell current command is changed to 2 A. Now, the fuel cell injects 200 W of power into the dc link. The FEC controls the dc link voltage by forcing the capacitor current to zero. When the fuel cell injects current into the capacitor, the FEC will redirect the current either into the rotor or grid so as not to allow the dc link voltage to build-up. So, in this case, the FEC directs 30 W of power into the
rotor and remained in the dumped into the grid. At time instant (d), the fuel cell is disconnected from the dc link. Now, the FEC goes back to supplying 30 W to the rotor from the grid. So, in this way fuel cell can be useful in supplying power to the induction machine when there is not enough mechanical power. Also, it has been shown that power can be injected from a dc power source into the grid without using a separate inverter.

Fig. 7.10 shows the response of REC. It can be seen from the figure, that the currents have high ripple content. Again, the ripple in the currents follow the oscillations in the rotor speed. When the speed is constant, there is no ripple in the rotor currents and they follow the reference currents exactly. The ripple in the reactive power reference, \( i_q \), in fig. 7.9 (b) also follows the ripple in speed. These results show that if there had been a speed control loop on the dc machine, the results would have been a lot better.
Fig. 7.11 shows the fuel cell output current and output voltage. This data was obtained from Labview. So, the graph is on a slightly different time scale. Transients the fuel cell output voltage can be observed at the instants when it is connected and disconnected from the dc link. There is only a small transient when the current level is changed from 1 A to 2 A. The stack voltage is generated using the fuel cell stack current which is given by $i_{FC} = i_b / (1-D)$ (refer section 5.5.1) where $D$ is the duty cycle of the boost converter.
7.3 Comparison of Simulation and Experimental Results

Simulation and experimental setups have been designed to be as similar as possible so that the results can be compared with each other. However, experimental results cannot be expected to match the simulation results exactly. In simulation, many simplifying assumptions were made and few of the components are approximated as linear models. Core and rotational losses were neglected and saturation effect is not taken into account. There were no harmonics in the machine currents. Grid voltages was perfectly balanced. The transformers were approximated as constant gain devices and there are no losses in the converters. And, there is no offset or noise in voltage and current signals.

Open loop test results for the induction machine and the fuel cell confirmed that the models approximated the real devices very well. The response of the induction machine
model was very similar to that of the real machine. For active and reactive power control, in spite of the above differences, simulation results compare well with the experimental results. The induction machine generated about 1000 W of active and was also able to reduce the amount the reactive power it absorbed from the grid. Large inertia on the shaft maintained the speed constant in simulation and it was possible to generate reactive power and also operate as an active filter. Huge third harmonic component in the rotor currents also degraded the performance of the REC. With non-sinusoidal currents, the transformed currents will have an ac ripple.

With the fuel cell connected across the dc link, FEC performed very well. The experimental results are very similar to the simulation results. The converter was able to redirect the power injected by the fuel cell either into the rotor (depending on power requirement) or in the grid. The dc link voltage was maintained constant during all changes. The reactive power flow in the rotor circuit was also maintained at a constant value. Overall, the simulation setup gave a fair idea of what to expect and experimental setup performed as expected validating the proposed integrated system.
CHAPTER 9
CONCLUSION

9.1 Summary

Novel integration of a doubly-fed induction generator system with a fuel system has been proposed. The proposed scheme makes it possible for the fuel cell to inject power into the grid using the back-back converters of the DFIG system. Also, the low voltage DC link makes the system more cost effective as the cost of converters will be reduced. Transient d-q axis model of a DFIG system was derived. Vector control methods to control active and reactive power generated by the induction machine as well as to generate load harmonics to compensate for a non-linear load were developed. A dynamic electrochemical model of PEM fuel cell system was developed.

Simulation models of DFIG and fuel cell were developed in Matlab/Simulink. The models were integrated and simulation results were presented. The results showed that the proposed theory is valid. Results showing the operation of a DFIG as a power source and as an active filter have been presented. Results showing the interaction of DFIG and fuel cell with each other and with the ac grid were studied.

Experimental setup was built to validate the simulation results. Both simulation and experimental setups were designed to be as similar to each other as possible. However, there were some important differences that could not be rectified. The rotor currents were not sinusoidal which resulted in noisy d-q rotor currents. Another important difference was that in the experimental setup, the inertia on the shaft was quite small. This resulted in oscillations in rotor speed. With these two drawbacks, it was decided not to implement harmonic compensation in the experimental setup. Except this, all of the other objectives were implemented.
Open-loop tests showed that simulation models approximated the real devices very well. Experimental results showed active and reactive power control in the induction generator. The FEC maintained the dc link voltage and the reactive power flow in the rotor circuit. The experimental setup performed very well when the fuel cell was connected across the dc link. FEC routed the fuel cell power either into the machine or into the grid depending on the requirement. Overall the results obtained were quite satisfactory.

9.2 Future Work

Although every attempt was made to make the thesis as complete as possible, there is still always room for improvement. Harmonic compensation was not implemented in the experimental setup. It would be interesting to see if including a speed control loop on the dc motor would improve the performance of the REC controller.

Another important observation that was made was the dependence of reactive power flow on the dc link voltage. Higher the dc link voltage, the better the reactive power control.
REFERENCES


APPENDIX A
PCB DESIGN AND LAYOUT

It was decided to have all the circuits on PCBs (printed circuit boards) instead of protoboards as the Powerex IGBT modules are very sensitive to noise. Protoboards and solder less breadboards are prone to both external noise and noise within the boards itself. Wiring connections can cause real difficulties by including unintended circuit elements such as parasitic capacitances etc. So, when designing low-noise circuits on protoboards, lot of care is required so as to keep noise to a minimum. Also, protoboards are clumsy with tangled wires and crossovers that can make debugging or modifying the circuit very time consuming. So, for all the above reasons, PCBs were used to implement the dq⁸-abc, SPWM, IGBT and sensors circuits. dq⁸-abc and SPWM circuits are implemented on the same PCB, IGBT and sensor circuits are implemented on different PCBs. Ivex was used for PCB design and layout.

Layout is basically done in two steps. First, the schematics of the circuits are drawn in Windraft and then they are transferred to Winboard for layout. Ivex library does not have footprints for specialized components such as the IGBT modules, current/voltage sensors and connectors. So, before proceeding with schematic creation in Windraft, these footprints have to be created in Winboard. These modules are then transferred to Windraft and schematics for the circuits can be created. After designing the schematics, a netlist is generated for each PCB circuit. These netlists are then loaded into Winboard. The modules have to be rearranged and the wires have to be re-routed making sure that there are no unintended crossovers on the same layer. Also, the thickness of the wires has to be increased based on the current levels through them. After routing, gerber and drill files have to be generated for each board to be sent to a PCB manufacturer. Fig.A.1 shows the complete PCB design process. These are explained in the following sections.
A.1 Schematic Design

For small circuits with standard components, the first four steps in the PCB design may be skipped and the complete design can be done in Winboard. But, for large circuits with specialized components, designing and testing the circuits before layout becomes necessary. Windraft provides a PSPICE like environment for schematic design. It has an extensive library for standard components. But, the library is quite old and does not have footprints for many components that were used in this project. These footprints were created in Winboard using the dimensions from the datasheets. The size, shape and type of drill holes and solder pads have to be specified here. Fig.A.2 shows the footprint for the IGBT module created in Winboard. Similarly, footprints for current sensors, voltage sensors and connectors were created.
These footprints are then transferred to the Windraft library and names are assigned to each pin for schematic design. Next step is to design the schematic by picking the parts from the Windraft library. Many Windraft parts have a default footprint assignment. But, it should be verified that these dimensions correspond to the actual physical components that will be soldered onto the PCB. For large designs, that is if the schematic is too large to fit in one sheet, multiple sheet files must be interconnected in a hierarchical design. Values and names may be assigned to components and signals here so that they can be displayed as silk on the PCB. After the schematic design is complete, electrical rules check utility can be used to check if the schematic contains any wiring violations. Due to license limitations Spice simulation could be performed. But, before the schematic creation in Windraft, all the circuits were tested in PSIM. After schematic creation, a netlist has to be created for each board to be exported to Winboard. A netlist is an ASCII file that lists the interconnections of the schematic diagram by names of the signals, modules and pins.

A.2 Layout and Routing

The basic steps necessary to create a PCB in Winboard are as follows:

1) Load the netlist.
2) Develop a routing plan. Arrange the modules.
3) Place ground and power copper zones.
4) Find and correct any routing errors.
5) Generate final gerber and drill files.

After the netlist is loaded in Winboard, number of layers used must be specified. All the PCBs in this project have two layers: copper (bottom) and solder (top) layers. A routing plan must be developed before any tracks are placed. The routing plan determines
which wiring connections are to be routed with copper tracks and which layers they are to be routed on, and which wiring connections are to be connected with zones (copper pours) and which layers the zones are to be placed on. The modules have to be re-arranged so that routing tracks would be easier and also based on thickness of the tracks. After re-arranging the modules, board edges, mounting holes and targets can be added to the board file.

Winboard has few tools to help routing copper tracks. ‘Ratsnest’ can be used to display all the wiring connections exported from Windraft. The user can then select each track and specify layer, width, via diameter and drill size. Default values could be used for wires carrying signals. But, for wires carrying signal power or high currents, track widths have to be increased. PCBs manufacturers usually specify minimum track width, minimum isolation between tracks and maximum and minimum drill sizes. So, before proceeding with layout, these values should be noted so they can be used later in Design Rules Check.

The wires have to be routed so that there are no crossovers on the same layer. When working with only two layers, the technique of using vias is very useful to avoid crossovers. Via is a vertical track between the two layers that allows a single track to pass through multiple layers. After routing of copper tracks is completed, copper pours for ground and power zones can be placed. After the zones are complied, Winboard connects the ground and power connections in the modules to the respective zones. After routing and layout is completed, Design Rules Check can be performed to identify routing mistakes. The procedure will check for crossovers on the same layer, isolation between tracks and drill sizes. Final step in PCB design is placing the silk screen for component and signal identification. Default texts, pin and module numbers exported from Windraft could be placed here. Fig. A.3 shows the complete Winboard layout diagram for the IGBT circuit. The tracks in green are the tracks on the solder layer and the red tracks are tracks on the copper layer.
After the layout process is done, gerber and drill files are to be generated to be sent to a PCB manufacturer. Five gerber files and two drill files for each PCB are usually required. Two gerber files for copper tracks on each layer, two gerber files for solder mask on each layer, one gerber file for the silk screen, a NC drill file containing the size and placement information for drill holes and a through hole file. Final completed PCBs are shown in figures A.4 and A.5. Fig. A.4 shows the top view of the PCB with the IGBT circuit and fig.A.5 shows the bottom view of the same PCB. Fig. A.6 shows the PCB with components soldered.
Figure A.4 Solder layer view of the PCB with the IGBT circuit

Figure A.5 Copper layer view of the PCB with the IGBT circuit
Figure A.6 Picture of PCB with dead time and IGBT interface circuit.