CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

Speed Control of Induction Motor using FPGA based NI-GPIC Board

A graduate project submitted in partial fulfillment of the requirements

For the degree of Master of Science in Electrical Engineering

By

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Abstract

Speed Control of Induction Motor using FPGA based NI-GPIC Board

By

Ammar Quaid Surti

Master of Science in Electrical Engineering

Induction motors have been used in a wide range of home and industrial applications for the past several decades. In homes, induction motors are used in fans, water pumps, washing machines, dish washers and garbage disposals. Industrial applications of induction motors are endless. They are used for conveyor belt movements, robotic arms, continuous process control, etc. For these applications, controlling the speed and torque of induction motor is very important. Old control systems were not power efficient and had a number of flaws in their controls. Most flaws were due to carbon setting on the control circuitry contacts causing problems in properly transmitting signals between points.

Current control systems are mostly digitized and have a better response overall. The detailed study of induction motors have helped researchers understand and design better control systems that could consume less power and be more efficient.

This project is designed to control a 3-phase induction motor through a newly designed development board from National Instruments, SbRIO 9606 GPIC Board (National Instruments, 2015) [13]. The control is designed using Labview software and the new FPGA toolbox (Corporation, 2014) [4] by Brian MacCleery (Principal Product Manager for Clean Energy Technology) and his team. This toolbox helps design the system graphically and writes the code automatically in the background to be compiled and run on the FPGA board. Methods used to control the induction motor are V/f control. Also, a comprehensive research has been done on controlling the motor through SVPWM (Space Vector Pulse Width Modulation).

With the V/f control method, we will monitor the RPM (revolutions per minute) of the motor with open loop and closed loop systems. We will also look into the effects of the modulation index on the system and how modulation index affects the power quality. In addition, we will monitor any faults caused in the system by high current overshoots while turning on the motor or during speed change of the induction motor. We will also monitor the effects of the carrier frequency on the power quality.

These experimental results are compared with the theoretical results for the verification of V/f control.

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The board we have in the lab is the NI sbRIO 9606 board (National Instruments, 2015) [13] with the extended GPIC (General Purpose Inverter Controller) module (National Instruments, 2015) [14] connected to it (figure 1 and 2). This board contains two three phase IGBT inverters, two single phase rectifier bridges and two DC links (BMac, 2015) [2].

The NI SbRIO Board is powered with a 12VDC supply. We are provided with a DC power supply for the GPIC board separately. Also a 15VDC power is supplied to the board for the IGBT controllers.

The induction motor we have is a 3-phase motor along with a feedback encoder system which is connected to the GPIC board for sensing and getting the feedback for its speed. The connector used for this purpose is the LUMBERG KV81 circular connector. The sensor is provided with +5VDC, ground, and 2 digital I/O. Several of the LVTTL inputs on the GPIC are converted to 5 V TTL logic levels to support interfacing to optical quadrature encoders (A, B and Index pulse), which are decoded by the FPGA to calculate motor position and velocity.

The board has flexible connectivity and SMPS topology for many diverse applications (DC-AC, AC-DC, AC-DC-AC, etc.) (BMac, 2015) [2]:

- Two three phase IGBT input/outputs (total of 6 two-level IGBT half-bridges). Each IGBT is rated at a maximum for 10 Amps
- Two single phase AC inputs with full-bridge rectifiers
- Two sets of DC link capacitors with pre-charge contactors
- Contactor for connecting the DC-links together
- Terminals for connection of DC power supply or solar panels to the DC link
- Terminals that provide access to the voltage at the mid-point of the DC link capacitors
- On board current and voltage sensors for each half-bridge
- Removable pluggable connectors wire-poke terminals for easy wiring

![Figure 1: Top view of the sbRIO 9606 and GPIC board](image)
Figure 3 is the 24VAC transformer. The rated input of this transformer is 110VAC. The 24VAC is supplied to inverter A with an output to DC through the GPIC board.

Figure 4 shows the connection of the 24VAC transformer to the inverter A of the GPIC board. The connections are made to VgridA+ and VgridA-.
Figure 5 below shows the NI sbRIO 9606 FPGA board. This Research & Development Board is made up of two layers and the view below is of upper layer. The Spartan 6 FPGA processor as seen in this board is its main unit. Besides, we can see Ethernet connector, USB connector and serial connector mounted on the FPGA board.

Figure 5: sbRIO 9606 FPGA board mounted on the GPIC board

Wiring Connections

Below are the wiring connections to use for a 3-phase induction motor (figure 6). The connections on the research board are detailed below.

1. The Ethernet connection shows the connection between the NI sbRIO 9606 board to the computer at which Labview is acting as the control HMI.
2. The supplied voltage to the research board is via an ATX power supply. This power supply supplies multiple voltage ranges to the board including +5VDC, +12VDC, +15VDC and +3.3VDC.
3. The GPIC board is supplying +12VDC to the sbRIO 9606 board.
4. Connections from the GPIC board to the 3-phase induction motor.
5. Connection of the encoder from the 3-phase induction motor to the GPIC board.
6. A 15VDC floating supply input to the GPIC board.
7. 24 VAC voltage transformer is connected to inverter A.

Figure 6: Details of the wiring connections of the board
Figure 7 is the wiring connections to build the encoder cable which is compatible with the induction motor provided with the GPIC board. The connector is called the LUMBERG KV81 circular connectors with solder cap connections.

![Figure 7: Encoder connections](image)

The detailed connections for the Lumberg KV81 connector are shown in figure 8 (BMac, 2015) [2]. Along with the pin number we can see the type of signal and where the connections are to be made on the research board.

**AC 4-pole Induction motor fitted with Timken 1000 line encoder with A, B & index output channels to connector on mounting bracket.**

![Encoder connector pin out details](image)
Figure 9 shows the connected encoder to the research board.
Phase Induction Motor

The emphasis in this chapter is on understanding the behavior of induction motors and how the torque-speed characteristic affects the load on these motors.

Three-phase induction motors (figure 10) are the most common and frequently encountered machines in industry (Fathizadeh) [7]. The advantages of much motor are:

- Simple in design, rugged, low-price and easy to maintain.
- They have wide range of power ratings.
- They run essentially at constant speed from no-load to full load
- Its speed depends on the frequency of the power source
  - Requires a variable-frequency power-electronic drive for optimal speed control.

![Figure 10: Internals of the induction motor](image)

About Induction Motor

An induction motor has two main parts (Chapman) [3] (figure 11):

- A Stationary Stator. This has stator winding in them which induces a magnetism which causes the Rotor part of the motor to revolve.
- A Rotor. This is the revolving part in the induction motor that produces torque with respect to slip. The windings in the rotor are short circuited, unlike the windings in the stator which are independent to the three phases.

There are two types of rotors which can be placed inside a stator: cage rotor and wound rotor.

![Figure 11: Rotor and Stator of the induction motor](image)
Wound rotor induction motors are more expensive than the cage rotor induction motors as they require more maintenance with their brushes and slip rings (Chapman) [3].

How does an induction motor work?

An induction motor generally works when a three phase AC power is applied to the induction motor and its rotor starts rotating. When a three phase supply is connected to an induction motor, it is generally connected to the three phase stator field winding. This induces set of currents flowing inside the stator. These windings start behaving as electro magnets and produce 3 alternating and independent magnetic fluxes. The resultant of these fluxes is called the net flux. The magnitude remains constant but position keeps on changing in circular manner. The speed of the magnetic field’s rotation is given by (Chapman) [3]:

\[
    n_{sync} = \frac{120f_e}{p} \text{ rpm.}
\]

Where \( f_e \) is the frequency which generally is 50-60Hz, \( P \) is the number of poles in the induction motor and \( n_{sync} \) the synchronous speed in rpm (rotations per minute) (Chapman) [3].

Therefore, the rotating magnetic field in the stator passes over the bars of the rotor and an induced voltage is produced in the rotor. Hence, the magnetic flux of the rotor keeps changing, a current starts flowing in the rotor winding. When a current carrying rotor is placed in a stator magnetic field, using the Flemings right hand rule (Chapman) [3], the rotor experiences a force and starts rotating. The direction in which the rotor rotates is the same as that of the rotating magnetic field of the stator.

A different way to express the rotation of the rotor is with respect to the cycles of the AC power supply and how they produce a North and South Pole in the stator to make the rotor rotate. The coils of the stator are rounded in such a way that when a current flows in them, one coil is the North Pole and its pair is South Pole. The magnets polarity changes every half cycle of the AC power supply creating an alternative magnetic field. In the induction motor, the rotor is the rotating component. It also consists of a group of electromagnets arranged around a cylinder with the poles facing towards the stator poles. As we know, the rotor is located inside the stator, so as the magnetic field of the stator alternates due to the effect of the AC power supply, the induced magnetic field of the rotor attracts to the other end, hence causing the rotor to rotate.

Relation of rotor speed and slip

If rotor runs at the synchronous speed, which is the same speed of the rotating magnetic field, then the rotor will appear stationary to the rotating magnetic field and the rotating magnetic field will not cut the rotor and no induced current will flow in the rotor. Thus no torque is generated and the rotor speed falls below the synchronous speed. When the speed falls, the rotating magnetic field cuts the rotor windings and a torque is produced. So the induction motor will always run at a speed lower than the synchronous speed.
The difference between the motor speed and the synchronous speed is called the slip (Chapman) [3].

\[ n_{\text{slip}} = n_{\text{s}} - n_m. \]

Where, \( n_{\text{slip}} \) the slip speed of the machine is, \( n_{ \text{s} } \) is the speed of the magnetic fields and \( n_m \) is the mechanical shaft speed of the motor. If the rotor runs at synchronous speed, the slip is 0, and if the rotor is stationary, the slip is 1. So the value of slip is always between 0 and 1. Slip may be expressed as a percentage by the formula below (M.S.Aspalli, 2012) [11]:

\[ s = \frac{n_{\text{slip}}}{n_{\text{sync}}} \times 100\%. \]

The rotor frequency can be expressed as (Mohan, 2003) [12]:

\[ f_r = s f_e. \]

Here, \( f_r \) is the frequency at which the rotor is operating.

Substituting the above equations, the rotor frequency can be calculated as (Chapman) [3]:

\[ f_r = \frac{p}{120} (n_{\text{sync}} - n_m). \]
Power flow in induction motors

Figure 12: Power losses in Induction motor

Figure 12 (Induction Motor) [8] shows the losses in the induction motor while running.

1. Copper losses
   a. Copper loss in the stator \( (P_{SCL}) = I_1^2 R_1 \)
   b. Copper loss in the rotor \( (P_{RCL}) = I_2^2 R_2 \)
2. Core loss \( (P_{core}) \)
3. Mechanical power loss due to friction and windage

Torque Speed Characteristics

Input to the induction motor is a Three Phase AC supply, its output is mechanical power and for that we should know some terms and quantities related to mechanical power. Any mechanical load applied to the motor shaft will introduce a Torque on the motor shaft. This torque is related to the motor output power and the rotor speed (Chapman) [3].

\[
\tau_{load} = \frac{P_{out}}{\omega_m} \text{Nm}
\]

\[
\omega_m = \frac{2\pi n_m}{60} \text{ rad/s}
\]

When an induction motor is operating at no load, it is therefore very nearly at synchronous speed. At this point the slip is very small, and therefore the rotor frequency is also very small. The torque induced which keeps the rotor running is given by (Chapman) [3]:

\[
P_{in} = \sqrt{3} V_T I_L \cos \theta
\]
\[ \tau_{\text{ind}} = k B_r \times B_{\text{net}}. \]

And its magnitude is given by:

\[ \tau_{\text{ind}} = k B_r B_{\text{net}} \sin \theta. \]

Here, \( B_r \) is the rotor magnetic field and \( B_{\text{net}} \) is the net magnetic field. Since the rotor current is very small, the induced torque is also a small value, but it’s large enough to surmount the motor’s rotational losses.

If each term in the above induced torque equation is considered independently, we can drive the speed-torque characteristic curve (Induction Motor) [8]:

i. \( B_r \). The rotor magnetic field is directly proportional to the current flowing in the rotor (figure 13). With increasing slip (decreasing speed), the current flow also increases.

![Figure 13: Rotor magnetic field against motor speed \( n_m \)](image)

ii. \( B_{\text{net}} \). The net magnetic field in the induction motor is proportional to the voltage and, therefore, is approximately constant. Voltage actually decreases with increasing current flow, but this effect is very small and can be ignored in the graphical representation (figure 14).

![Figure 14: Net magnetic field against the motor speed](image)

iii. \( \sin \theta \). Keeping in mind the no load and full load magnetic fields inside the induction motor, we can conclude that the angle \( \theta \) is just equal to the power factor angle of the rotor plus 90°

\[ \theta = \theta_R + 90^\circ. \]
\[
\sin \theta = \sin(\theta_R + 90^\circ) = \cos \theta_R.
\]

This term is the power factor of the rotor. The plot of the rotor power factor and speed is shown below in figure 15:

Figure 15: Rotor power factor against the speed of motor

iv. The induced torque is the product of the three terms above. Therefore, the torque-speed characteristic of an induction motor can be built from the graphical representation of the individual terms and combining them together.

![Speed-Torque Curve for a Three-Phase Induction Motor](image)

Speed-Torque Curve for a Three-Phase Induction Motor

Figure 16: Speed-Torque curve for a three phase induction motor

The induction motor torque-speed characteristic curve plotted in figure 16 (Mohan, 2003) [12] provides several important pieces of information about the operation of induction motors. This information is summarized as:

1. The induced torque of the motor is zero at synchronous speed.
2. The curve is nearly linear between no-load and full load. In this range, the rotor resistance is much greater than the reactance, so the rotor current, the rotor magnetic field, and the induced torque increase linearly with the slip.
3. This *pullout torque* is 2 to 3 times the rated full-load torque.

   - A maximum possible torque cannot be exceeded. This torque, called the pullout torque or breakdown torque is two or three times the rated full load torque of the motor.

4. The starting torque of the motor is slightly higher than its full-load torque, so the motor will start carrying any load it can supply at full power.

5. If the rotor is driven faster than synchronous speed it will run as a generator, then the direction of the induced torque in the machine reverses, converting mechanical power to electric power.

Effect of Rotor resistance on the Torque-Speed Characteristics

Figure 17 represents how the rotor resistance can be effective to produce the torque-speed curve (Chapman) [3]. With less resistance as in R1, the mechanical speed of the motor is greater compared to the ones with higher resistance. However, the highest torque induced with different resistances remains the same.

Figure 17: Torque-Speed Characteristic curve with different values of rotor resistance
Speed Control of 3-phase Induction Motor

Stator of the induction motor is the point at which the power is supplied for the rotor to start rotating. So basically, we are looking into the stator voltage control to affect the overall control of the Induction Motor.

There are various ways to control the speed of the induction motor:

- Pole Changing,
- Variable supply frequency control,
- Variable supply voltage control,

The above methods are used for low power and low starting torques applications, for example, fans, pumps etc. These control methods have a couple of drawbacks with their approach, 1) they have torque that varies with the load and cannot work with heavy loads and 2) as we will discuss later on, varying only the frequency or voltage in the induction motor causes the air gap flux to become unstable and due to that the torque is affected.

Stator voltage control with industrial applications and applications where we need to vary voltage and frequency can be done with:

1. SPWM (Sinusoidal Pulse Width Modulation) control technique.
2. SVPWM (State Vector Pulse Width Modulation) control technique.

The design provided by PWM for 3-phase induction motor is the voltage per hertz method for closed loop. V/f control is most popular and is widely used in industrial applications. There are many advantages of using V/f control for induction motor:

- It provides fine range of speed.
- It gives good transient performance.
- It has a wider stable operating region.
- Voltage and frequencies reach rated values at base speed.
- The acceleration can be controlled by controlling the rate of change the PWM signal supplied to the IGBT power circuit.
Sinusoidal Pulse Width Modulation (SPWM)

The Sinusoidal Pulse Width Modulation (SPWM) is the most common and effective method to control the speed of the induction motor. This algorithm is applied to the power circuitry that is connected with the induction motor. The pulse width modulation is applied to the 2-level 3-phase IGBT switches to provide the induction motor with the sinusoidal waveform needed. V/f control is a method where this SPWM method is applied and put in practice. In this section we will study about SPWM and later see how it is implemented on the NI GPIC board and monitor its results.

While controlling the induction motor with V/f control, we need to consider 3 quantities and their relation and understand how they are linked with each other. Let us consider the voltage induced in the stator $V_t$, supplied frequency to be $f$ and the air gap flux to be $\Phi$. The link between these is:

$$V_t \propto f\Phi.$$

Thus, reducing the frequency without making changes to the supply voltage will result in a different air gap flux, and that reduces the torque of the induction motor. So therefore, whenever the frequency is varied in order to control speed, the supply voltage should also be varied in order to keep the air gap flux constant and therefore keeping the V/f ratio constant (Akin, 2013) [1]. The voltage and the frequency are directly proportional to each other. So in order to decrease the speed of the induction motor, the voltage is decreased, therefore, the frequency is also decreased simultaneously.

At steady state, the voltage applied to the three phase induction motor is (Yu, 1998) [17]:

$$V \approx \omega \Lambda.$$

Where $V$ and $\Lambda$ are magnitudes of stator voltage and stator flux respectively. Thus we get (Yu, 1998) [17],

$$\Lambda \approx \frac{V}{\omega} = \frac{1}{2n} \frac{V}{f}.$$

Here, the ratio V/f remains constant with changing $f$, then the flux remains constant too and the torque does not depend on the supply frequency. If we consider $a = f/f_{\text{rated}}$ being the ratio between rated frequencies and operating frequency of the induction motor, the torque can be calculated as (Eltamaly, 2015) [6]:

$$T = \frac{3}{\omega_m} \left[ \frac{V_{\text{rated}}^2 R_f}{R_s + \frac{R_f^2}{2} + (X_s + X_f)^2} \right].$$

If the ratio $a < 1$, the torque equation is (Eltamaly, 2015) [6]:

$$T = \frac{3}{\omega_m} \left[ \frac{V_{\text{rated}}^2 R_f}{a R_s \frac{R_f^2}{2} + (X_s + X_f)^2} \right].$$

At operating frequency higher than the rated frequency, the V/f constant changes to avoid insulation breakdown. This can be illustrated from the graph below:
The graph can be split in three regions with respect to the speed range of the induction motor (Akin, 2013) [1]:

- First from 0 to \( fc \), a quick start voltage is required, so the voltage drop across the stator resistance cannot be neglected and must be compensated for by increasing the stator voltage. Therefore, the V/Hz profile is not linear.
- Second, after frequency \( fc \), the V/f relation is constant and the slope represents the air gap flux density.
- Third, from \( f_{\text{rated}} \) and higher, the V/f graph does not apply because the stator voltage would exceed its rated value. Therefore, the resulting air gap flux would be changed and reduced. It causes the torque to reduce.

The V/f method uses pulse width modulation (PWM) technique to control the speed of the induction motor. For applying this method, we need to produce a variable amplitude AC. So a controlled sinusoidal voltage is compared with a triangular carrier wave to produce a PWM signal with varying voltage and frequency. When the two waves are compared, the resulting wave is the PWM signal. Figure 18 shows how the V/f control algorithm is implemented.

The same method is applied with the other two phases that are 120\(^\circ\) apart. The modulating sine wave is 120\(^\circ\) apart and is compared with the carrier triangular wave to produce the resultant PWM for the particular phase.
According to these PWM signals, the IGBT switches are operated. The positive part of the PWM is implemented by the upper level switches and negative part of the PWM is generated by the lower level switches.

Figure 19 shows the output wave form with respect to PWM waveform. By changing the PWM, the output sine wave can be altered. If the frequency of the PWM is changed, the output frequency of the sine wave also changes. In contrast, if the PWM width is changed, the output voltage supplied to the induction motor increases or decreases accordingly.

![Figure 19: Sinusoidal produced by the output PWM](image)

The block diagram of the closed loop control of the induction motor is shown below:

![Block diagram of the closed loop control of the induction motor](diagram)
Space Vector PWM (SVPWM)

The diagram below shows the three phases winding on the induction motor.

The currents produced by each phase can be expressed by these equations (Mohan, 2003) [12]:

\[
\begin{align*}
    i_A &= I_m \cos(\omega_e t) \\
    i_B &= I_m \cos(\omega_e t - 120) \\
    i_C &= I_m \cos(\omega_e t - 240).
\end{align*}
\]

The magnetic field produced in the stator winding by these three phase voltages can be expressed as follows:

\[
\begin{align*}
    MF_A &= K_i A \cos(\theta_{ae}) \\
    MF_B &= K_i B \cos(\theta_{ae} - 120) \\
    MF_C &= K_i C \cos(\theta_{ae} - 240).
\end{align*}
\]

Substituting values for \( i \) in MF equations:

\[
\begin{align*}
    MF_A &= F_{max} \cos(\theta_{ae}) \cos(\omega_e t) \\
    MF_B &= F_{max} \cos(\theta_{ae} - 120) \cos(\omega_e t - 120) \\
    MF_C &= F_{max} \cos(\theta_{ae} - 240) \cos(\omega_e t - 240).
\end{align*}
\]
Solving the equations with the cosine expansion (Mohan, 2003) [12]:

\[
MF_A = \frac{F_{max}}{2} \left[ \cos(\theta_{ae} - \omega_t t) + \cos(\theta_{ae} + \omega_t t) \right]
\]

\[
MF_B = \frac{F_{max}}{2} \left[ \cos(\theta_{ae} - \omega_t t) + \cos(\theta_{ae} + \omega_t t + 120) \right]
\]

\[
MF_C = \frac{F_{max}}{2} \left[ \cos(\theta_{ae} - \omega_t t) + \cos(\theta_{ae} + \omega_t t + 240) \right].
\]

The above equations produce pulsating magnetic fields in the stator windings. Each pulsating magnetic field can be split in two portions. One with the $-\omega_t t$ value is revolving in the anticlockwise direction and the other is revolving in the clockwise direction.

So thus, we get the combined revolving magnetic field by the following equation:

\[
MF = (MF_A^+ + MF_B^+ + MF_C^+) + (MF_A^- + MF_B^- + MF_C^-) = 3MF_A^+.
\]

\[
MF = \frac{3F_{max}}{2} \cos(\theta_{ae} - \omega_t t).
\]

Space Vector Transformation

We know that: $i_A + i_B + i_C = 0$

\[
i_\alpha = i_A + i_B (\cos 120) + i_C (\cos 240) = i_A - \frac{i_B}{2} - \frac{i_C}{2} = \frac{3}{2} i_A
\]

&

\[
i_\beta = i_B (\cos 30) + i_C (\cos 150) = \frac{\sqrt{3}}{2} (i_B - i_C)
\]

In matrix form:

\[
\begin{bmatrix}
  i_\alpha \\
  i_\beta
\end{bmatrix} = \begin{bmatrix}
  \frac{3}{2} & 0 & 0 \\
  0 & \frac{3}{2} & -\frac{3}{2}
\end{bmatrix} \begin{bmatrix}
  i_A \\
  i_B \\
  i_C
\end{bmatrix}.
\]
If we consider a star network load, we could assume that all three coils are connected to each other at a neutral surface. So we have 3-coils with each connected to three phases A, B and C (figure 20) with the other end of these coils connected to a common neutral (N). So the new equations representing $\alpha$ and $\beta$ are:

\[
V_{AO} + V_{BO} + V_{CO} \neq 0.
\]

\[
V_{\alpha} = \frac{1}{2}(2V_{AO} - V_{BO} - V_{CO}).
\]

\[
V_{\beta} = \frac{\sqrt{3}}{2}(V_{BO} - V_{CO}).
\]

We can represent this in matrix form as:

\[
\begin{bmatrix}
V_{\alpha} \\
V_{\beta}
\end{bmatrix} =
\begin{bmatrix}
1 & -\frac{1}{2} & -\frac{1}{2} \\
0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2}
\end{bmatrix}
\begin{bmatrix}
V_{AO} \\
V_{BO} \\
V_{CO}
\end{bmatrix}.
\]
Derivation of a voltage vector in the space plane

The above diagram shows the voltage vectors produced while designing a space vector modulation. Let’s consider the case at phase A which is (+ - -). This represents an inverter state, which represents a situation where the top switch of phase A is ON and for the Phase B, C the bottom switches are ON. Similarly we can do this for all the other 6 states and find out the corresponding ONs for the upper and lower switches for the power electronics. For every possibility, we have a vector value assigned through the phases. All the vectors are of magnitude $V_{dc}$.

There are two other states mentioned as “- - -" & “+++". "- - -". The former means that all lower switches are ON; this shows that the load is shorted. Similarly when the vector is +++ , all upper switches are ON and the load is shorted. In vector terms, this is known as a null vector or zero. These two states are called zero states because there is no transfer of power between the DC bus and the AC side of the circuit. The other six states are called the active states, which represent power flow between DC buses to the AC side.

In space vector based PWM, we use a revolving voltage vector as the reference, as shown above. In sine triangle PWM, we use 3-phase sinusoidal signals. If we transfer the sinusoidal in vector domain, it
is therefore a revolving voltage vector. The vector changes its position according to the set point. The vector moves on the circular axis and produces different combinations of switch timing. This timing is calculated according to the position of the vector.

Let’s consider that the small interval of time at which the above vector is positioned at the location is $T_s$.

This vector can be achieved by timing the horizontal phase for time $T_1$ and the 60 degree phase for time $T_2$ and also the active time for null vector as that will represent 0 during in the PWM waveform. This can be expressed as:

$$V_1 = V_{dc} \angle 0^\circ, \; V_2 = V_{dc} \angle 60^\circ.$$  

$$V_{ref}T_s = V_1T_1 + V_2T_2 + V_ZT_Z.$$  

By deriving expressions for $T_1$, $T_2$ and $T_z$, we come to the point where these timings are expressed by the equations below:

$$T_z = T_1 + T_2 + T_Z.$$  

$$T_1 = \frac{V_{ref} \sin(60-\alpha)}{V_{dc} \sin 60} \cdot T_s.$$  

$$T_2 = \frac{V_{ref} \sin(\alpha)}{V_{dc} \sin 60} \cdot T_s.$$  

$$T_Z = T_s - T_1 - T_2.$$
In Figure 21, the graph represents the working of the SVPWM in order to produce the voltage vectors. Every cycle has 2 null vectors with the time duration being half of Tz, and has 2 active vectors with time duration calculated by the formulas given above. In the beginning of the cycle, a null vector is provided to produce a negative part of the PWM signal for the phases. This means that all the bottom switches are ON in the power schematic, so all phases are equal to $-\frac{V_{dc}}{2}$.

The second section is where the state $+ - -$ is enabled. Here, phase A upper switch is ON and phase B and C are still in the negative loop of the DC bus. Same goes with the other states when they are activated. According to the state and their timing, each signal is provided to the individual phases to produce the 3-phase supply.
Co-simulation with Multisim and Labview

The first step towards achieving the target of controlling a 3-phase induction motor is to first simulate the response of the system using a technique called the co-simulation. This co-simulation uses the software Multisim (spice based circuit design tool) and Labview to get results of the different responses obtained by changing variables inside our model.

This new tool is intended to enable the development of power electronics control IP for Labview FPGA, enabling you to develop/test/debug/validate before compiling to physical hardware (Instruments, NI community, 2015) [10]

Introduction to co-simulation

The following procedure is followed to build the co-simulation applications.

1. The power based circuitry is designed in Multisim.
2. The Labview code to control the Multisim circuitry is developed and placed inside a Labview control design using a Multisim design reference block. This block are directly present in the Labview and just requires a drag/drop and configuration to support the corresponding Multisim file.

The two software’s swap data in a coordinated, variable time step manner, in which both solvers obtain convergence around an accurate simulation result, even in the case where coupled dynamics exist between the Multisim and Labview parts of the system.

![Figure 22: Data flow for co-simulation of induction motor](image)

AC Induction Motor Co-Simulation

Figure 23 shows the Labview control for the 3-Phase Induction motor co-simulations. You could clearly see a block in the Labview control file that imports the Multisim variables from the Multisim
circuit. The other blocks in the control are performing different tasks, like calculations, graphical results and other related tasks.

Figure 23: Labview build file for co-simulation

Figure 24 represents the Multisim circuit for the co-simulation of the 3-phase induction motor. From the figure, we can point out that the variables UAB, UBC, iA, iB, Te, Tm and W are referenced to the Labview block for control.

Figure 24: Multisim file for co-simulation
Figure 25 is of the front panel of the Labview control. Here the simulation will run and according to the parameters set, we will see graphical results of the line to line voltages, RPM of the motor and the slip value of the motor. The switch at the bottom of the front panel which is labeled as Stop will terminate the simulation when selected.

Figure 25: Waveform window for the simulation
Simulation Results

Exercise 1

For the first simulation, we have set few parameters according to our need. As you could see in Figure 26, the speed set point is 1450 RPM. Also we have an option to set the time at which the load could be applied on the motor. So in this case we have set it for 2.4 seconds and the load value is set at 100. PID gain values are constant for the whole simulation as these values give the best results for the motor. The simulation end time is set at 5 seconds.

In Figure 26 we see an overview of the simulation for 5 seconds with torque value of 100 applied at time 2.4 seconds. We could actually see a small glitch in values of the graphs at time 2.4 seconds. Figure 27 shows the zoomed in results of these graphs at the point of glitch.
In Figure 27, the first graph shows the voltage and current for phase AB. The lines in blue represent the voltage and the dotted lines in red represent the current consumed by the induction motor. Here you can notice that when the test torque is applied to the induction motor, the current consumption increases.

Also the torque graph shows a boost from 0 to 100 at time 2.4 seconds. In the third graph, the RPM of the motor drops from 1450 to 1434 when there is load applied to the induction motor.

Slip is an important part to monitor with high torques. If the torque is too high and if the slip value goes above 1, then the motor acts like a generator and could cause serious damage to the power circuitry and perhaps cause fire. In this case, as we increase the load, the slip which was 0, increased to a value 0.01448. You could see a small overshoot in the values. These overshoots can be controlled by applying different algorithms for the PI control and optimizing them with better values.
Exercise 2

For this exercise, we have further increased the value of the torque to see the response of the system. Here we have increased the value of $T_m$ to 200 and the time at which the torque is applied is changed to 4 seconds. Also in this case, we have increased the RPM for the steady state of the motor to be set at 1800 (figure 28).

![Simulation result for 1800RPM and torque value of 200 applied at 4sec](image)

Let’s first look into the first graph which is the voltage and current of the motor. We could noticeably see the raise in the current consumed by the induction motor when the torque value of 200 is applied to it at 4 seconds from startup. The RPM of the motor drops significantly from 1800 to 1740 and the slip value increases from 0 to 0.048.

We could therefore summarize that increasing the torque value will affect the slip and also the RPM of the induction motor in a noticeable manner. Also there is a rise in current consumptions and we need to keep in mind to add several heat sinks with our power transistors to bear those high currents for motor control.

More on how to implement co-simulation using LABVIEW and Multisim is given in the following link: [http://www.ni.com/white-paper/13663/en/](http://www.ni.com/white-paper/13663/en/). This gives in detail steps and guidance on to create Multisim circuitry and the procedure to link it with Labview and start testing in no-time.
Steps to Communicate with NI GPIC board

This chapter briefs the user of the NI SbRIO GPIC board with the procedure to follow for writing down the Labview code onto it. This chapter mentions all steps to follow for a successful running of Labview application on the NI GPIC board.

Step 1:

Connect the NI sbRIO9606 GPIC board with an Ethernet cable to your computer as described in the previous chapter, and then, open NI MAX facility provided my National Instruments software’s to install drivers for the board (NI sbRIO GPIC Evaluation Kit, 2015) [15]. When you open NI MAX, you will notice the Remote Systems extension on the left side of the window. Extend the Remote Systems icon and identify your NI sbRIO9606 board. The status of your board will show connected and running as in figure 29.

Select the software section under the board tab and install the drivers required by the board. The software’s needed to install the driver are also shown in figure 29.

Figure 29: NIMAX - software installation
Step 2:

The next step is to make sure that the board has its features enabled to work on Real Time and the FPGA startup App is enabled. For that, you should look at the bottom of the NI MAX software and select the controller setting tab. On this tab, you will see the startup setting on the NI sbRIO9606 board.

1. The safe mode: Makes sure that the system does not start on safe mode and works properly with all features enabled.
2. The console out provides diagnostic information from the controller when it is connected to a computer using the Ethernet cable. This could be helpful for troubleshooting different connection problems related to Labview and the NI sbRIO 9606 board.
3. IP reset is a feature where every time the board is connected to a computer, the IP address of the board will reset and subsequently will have to configure your Labview with the new IP address of the board.
4. Disable RT startup app, disables the real time processing between the controller board and the computer.
5. Disable FPGA startup App, disables the feature to auto load any FPGA applications from the computer to the controller board.

Options 1, 2 and 3 depend on the users’ application with the controller board. However, make sure that options 4 and 5 are unchecked, which means that the RT startup and FPGA startup are enabled. This can be seen in Figure 30.

Figure 30: NIMAX - Controller setting
Step 3

Download the zip file from the link below:

The user can download different files according to the Labview version they are using.

Unzip the above file to a short directory like c:/Powerdev or c:/GPICRef and not on desktop. The reason is that there are very long paths due to Xilinx coregent IP in the GPIC reference Design toolkit. The default windows zip file might give you an error message that the file is password protected, when in fact it’s just that the paths are too long for windows.

Launch the GPIC Reference Design VI file from the unzipped folder. This might take a few minutes first time as Labview needs to identify all folders and paths of the supported IP cores and toolboxes.

Figure 31 shows how the project file looks like when the VI file is launched on Labview.

![Figure 31: GPIC reference design project file](image-url)
Step 4:

This step involves identifying and linking Labview with the IP address of the controller board and therefore linking to the board. For this purpose, the user needs to visit NI MAX and note down the IP address on which the controller board is connected to the computer. Then pop up Labview and right click on the GPIC Inverter Research Board as shown in the Figure 32 and select properties. In the properties window, enter the new IP address of the controller board from NI MAX and click ok. This will now tell Labview to go to that IP address in the network to link to the board.

![Figure 32: Linking Labview with controller via IP address](image-url)
Step 5:

Now once the Labview and the controller board identify each other on the network, the user can proceed with building and deploying the design onto the controller board from Labview. But before that, there is one thing that very less people know about, and that is referring the source file for the real time with the startup VI of the controller. For this purpose, the user must enlarge the tree of the GPIC Inverter Research Board on lab view and then extend the Build Specifications icon. Right click on the RT GPIC 3-Phase DC-to-AC Inverter Control and select properties, shown in figure 33.

Under properties, select the source files and add the [RT] GPIC 3-Phase DC-to-AC Inverter Control in the Startup VIs (if not added already) as shown in figure 34. Click OK and exit the window.

Adding this source file informs the build file to refer to this [RT] file under the GPIC Inverter Research Board as a startup VI. This is important to let the controller know about design details that is running on the sbRIO 9606 board.

Figure 33: Build specification properties

Figure 34: Setting source for build file
Step 6

Next we need to build the project. Right click the build specification file and click on Build, as shown in figure 35. Building the project means that now Labview will compile the source files of the design, link object codes and generate any number of documents, reports or related files to be deployed on to the controller.

In addition, the user also needs to deploy the project onto the controller board. This is done by right clicking the build specification file and select deploy, as shown in figure 36.

After deploying the project on the controller board, the user needs to set the VI file to run on the controller as a startup file. So for that, the user needs to right click the RT file and select “Run as startup”. This is shown in Figure 37.

Figure 35: Project build

Figure 36: Deploying project

Figure 37: Setting the file to run at startup
Implementing GPIC Design Application with NI sbRIO 9606 GPIC Board

Let’s now look into the GPIC reference design application which is implemented onto the NI sbRIO 9606 GPIC board. The method to compile this application onto the FPGA board is mentioned in the above chapters. Follow the instructions and then open the desktop application of the model to start working and testing voltages and currents and responses for real time applications. Figure 38 shows which file to open in the “My Computer” extension. The file we are working is the GPIC 3-Phase DC to AC inverter control.

Figure 38: Desktop file to control and monitor responses from the GPIC board

Now once the file is open, let’s start understanding the reference module (figure 39). There are multiple options here in the module for testing and analyzing purpose.

- **RT controller IP address**: Searches the Ethernet network locally and find all RT networks connected locally. The **Connect** button connects the reference module to the IP address entered.
- The LED indicators are for different purposes regarding the status of the FPGA system. **Connected LED** turns ON if the desktop application is connected to the controller. **Stream Captured LED** shows if the feedback information is been received by the Labview module, and the **Fault LED** turns ON when there is a fault detected in the system.
- To start controlling the GPIC board remotely, click the Enable Control button.
- The FPGA state shows the current state of the FPGA board. Safe mode shows that the board is not being controlled remotely by any means. Once we enable control on FPGA, the state switches from safe mode to connect.
- The enable PWM button starts the PWM signal sending to the FPGA and we get a three phase output from our inverters.
When we enable the Log Data button, the entire Real time simulation results are saved. We could later on access the log files and check for results on different simulation values.

Inverter Type icon selects either Inverter A or Inverter B for control. On inverter A we have our 3-phase induction motor connected and on inverter B we have a filter connected to produce a 3-phase sinusoidal supply for different applications.

The graphical area gives us detail analysis on all the aspects of the simulation. On the right hand side we can see all the monitoring items for both the Inverter A and Inverter B applications. These items include PWN Vector, Grid Voltages, 3-phase output voltages and currents, feedback RPM of the motor etc.

At the bottom right side, we could see a closed loop button. Enabling this closed loop scenario, we enable the induction motor control via closed loop. Here we get the feedback from the motor, and use PI controller for optimizing the RPM of the motor to the set point.

![DC to AC inverter control desktop file](image)

Figure 39: DC to AC inverter control desktop file

Starting working with the reference module requires that we select the configured Real Time board IP address; in this case it is 169.254.66.100. The status LED on the FPGA will be blinking, once connected with the reference module, the status LED on the sbRIO 9606 turns solid. This can also be monitored on the Labview GUI when the connected LED turns solid.

LABVIEW GUI for of V/f control

As mentioned above while discussing about V/f control, Figure 40 shows the control implemented. Once the PWM is enabled the module in Figure 40 gets active and enables the case structure. Once this is enabled, the PI module and the “Closed Loop?” Boolean switch checks if the control is set to manual or automatic. If the system is set on automatic, the LVFPGA block is activated and takes in values for Kp, Ki and speed set point for the feedback loop control. Also, once the system is set on automatic control, the selector switch in the module selects the values from the LVFPGA block rather than the values from the manual control. The output of this module is the sinegen frequency.
The sinegen freq from the previous module is input here to the sawtooth generation block. The output of this block is a sawtooth wave. There is a selector switch that determines whether the output should be a sinegen or a PLL. The PLL block uses grid (line to line) and PLL PI gains as input. This block tracks the phase and frequency of a three-phase signal. This operation is useful for FPGA control applications of a three-phase system. The output phase of the three-phase Phase-Locked Loop is in pi radians (Instruments, 3-Phase PLL Express VI, 2015) [9]. The outputs of the PLL/Sine Generation module are the three phases; Sine_u, Sine_v and Sine_w (figure 42).
The outputs from the previous modules are entered in the module in Figure 43 as inputs. This module compares the sine waves with the triangular wave to produce the PWM signal to drive the 2-level IGBT switches on the GPIC board. Soon after the comparison, we receive a PWM signal that is then passed through a rising edge detector that breaks the PWM into positive and negative parts and adds a delay between them to drive it onto the IGBT switches.

Verifying results for V/f control

As discussed earlier regarding the V/f control and how the voltage and frequency are directly proportional to affect the air gap flux in the induction motor, here that claim will be observed by observing the PWM vector produced by comparing the sine wave and the triangular carrier wave.

In Figure 44, the RPM set for the open loop system is 1000, and the PWM vector and phase_u voltage is monitored. As seen below, there is around 1.25 PWM cycle per 0.05 sec and that represents the frequency of the phase voltage. The duty cycle in those PWM waves represents the voltage.
Figure 44: PWM vector for RPM set at 1000

In Figure 45, the open loop RPM is set at 1500 and the PWM vector and the phase voltage is monitored. If this is compared with Figure 44, we can see that in 0.05 seconds there are 2 PWM cycles representing that the frequency of the sine wave increases with respect to the RPM of the induction motor. Also the PWM duty cycle of the PWM waves have changed a little for the change in voltage values to keep the air gap flux constant.

Figure 45: PWM vector with RPM set at 1500

Another example for the verification of the v/f control is shown in Figure 46 where the speed of the induction motor is increased to 2500 RPM. Here, significant difference can be seen in the voltage and frequency. Analyzing the PWM wave, we can see that the frequency is increased in the 0.05 seconds monitored. Also, we can see the voltage decrease to keep the air gap flux constant. Hence proving the claim above that:

\[ V_1 \propto f\Phi. \]
Method of applying SVPWM with Labview

To apply SVPWM with Labview, we need to design 5 major modules. (D. N. Sonawane, December 2010) [5]

1. Transformation module
   a. In this module, the values of the three phase voltages are transformed to two dimensional plane of $\alpha$ and $\beta$.

2. Sector determination module
   a. The input to this module is $\alpha$ and $\beta$ values. According to a set of rules defined by the user for the system, a sector is selected for which the values match, and according to that sector, the switching times of the IGBT’s are calculated.

3. Switching time calculation module
   a. This module calculates the timing for each switch. T1, T2 and TZ. These timing are then fed to the IGBT’s and the gates are turned on for that particular time to produce the voltage vector.

4. Symmetric PWM generation module
   a. This module is the heart of this algorithm which is responsible for generation of six symmetrical PWM signals. This module takes in switching time and the sector number produced by previous blocks. Figure 21 represents the output of this module.

5. Dead time generation module
   a. The dead time module adds a delay between each switch turning on and off. If there is no dead time in the system, turning on and off a signal at the same time will cause a short circuit which might damage the power electronics. Adding a dead time is effective as a system security.
Inverter B (3-Phase DC to AC conversion)

Below in figure 47, we can select either inverter A for induction motor control or inverter B for 3-phase AC output.

![Inverter B Configuration](image)

**Figure 47: Select inverter type**

After the connection is established, we can start seeing the grid voltages that is feeding our own system on the graphical region. After clicking the enable control, another LED on the FPGA turns on stating that now we could control the FPGA board remotely through Labview. Also at this point the FPGA state switches to “enabled”.

When switching on the PWM for the system, we will start monitoring the three phase produced. The algorithm applied for 3-phase output using PWM is the sine triangle PWM. Here the Sine wave and the reference triangular wave are compared to produce a PWM for the 3-phase voltages.

The graphical monitoring system shows us the grid voltage which is supplied by the wall transformer. And also after the PWM is enabled, we can see the line to line or line to neutral voltages. The line to line voltages are bipolar (figure 48) and the lines to neutral voltages are uni-polar (figure 49). We can select either of the two voltages to be displayed on the graphical interface using the toggle switch.
The PLL (phase lock loop) toggle switch locks phase onto the grid. This is done using phase shift technique and synchronizing the zero cut from the external grid voltage supplied through the wall transformer. Figure 50 shows the voltages with sinegen switch and figure 51 shows the voltages with PLL enabled.
If we see closely, we can see ripples in the voltages and the currents at carrier frequency of 3000Hz. If the carrier frequency is increased, the power quality enhances. Therefore, if the carrier frequency is increased, it results in reduced ripple voltages and currents. But this better power quality comes with a price of bad efficiency in the system. Also during high carrier frequency, the temperatures of the IGBTs rise significantly due to high switching losses and will require more cooling units to support the power circuit. Hence, at 3000Hz carrier frequency, we get a more efficient system but a poor power quality.

According to certain AC standards, the total harmonic distortion of any three phase system should be less than 10%, so increasing carrier frequency improves the ripple factor. Here are a few examples of the three phase voltage and currents with different values of the carrier frequency. Figures 52, 53 and 54 show the output voltage comparison with different carrier frequencies.
Figure 52: PWM carrier frequency set at 1000Hz

Figure 53: PWM carrier frequency set at 2000Hz

Figure 54: PWM carrier frequency set at 5000Hz
The open loop output RPM is measured with respect of the Induction motor speed. In this case when we are dealing with just the 3-phase voltages, we can divide the RPM by 30 to get the output frequency.

\[ \text{Output Frequency} = \frac{\text{RPM}}{30} \text{ Hz.} \]

Our usual output frequency should be 60Hz, so in this case we have set out open loop output RPM at 1800.

The modulation index of the system can also be changed to produce different results for the three phase output. Changing the modulation index will make changes to the output amplitude. Increasing or decreasing the modulation index will result in the linear increase or decrease in the amplitude of the 3-phase voltages. If the modulation index goes more than 1, the system is said to be over modulated. This technique is used to get more power out of the inverter but in return the power quality goes down. Below in Figure 57, increasing the modulation index over 1 results in non-sinusoidal 3-phase current and they are highly distorted. Figure 55 and 56 represent voltages with modulation index of 1 and 0.5 respectively.

![Image](image1)

**Figure 55:** Live results with modulation index set as 1

![Image](image2)

**Figure 56:** Live results with modulation index set as 0.5
At the inverter output, we can use a filter consisting of inductors, capacitors and resistors, to get the desired sinusoidal wave output. Below is Figure 58 with and without the filter installed at the output of the inverter B of the GPIC board.

Figure 59 and 60 show the zoomed in output voltages with respect to the rising and falling of the PWM waves generated at the outputs.
Inverter A (3-phase induction motor)

We can select the inverter A in the same reference design on Labview without stopping the GUI. Just click on the inverter type and select inverter A for the induction motor control.

As we enable PWM, we see that the DC link voltage is dropped significantly. The motor is set to hard start on its current setting. Figure 61 shows the DC voltage at motor startup.
The DC link drops when we increase the RPM of the motor and vice versa (figure 62 and 63).
Increasing the carrier frequency from 2000 Hz to 5000 Hz gives us better power quality but there is more power loss in the IGBT switches and that energy is transmitted as heat from the switches. This could damage the power circuitry and can cause fire in the system. Figure 64 and 65 show the output sinusoidal with carrier frequency of 2000 Hz and 5000 Hz, respectively.

Figure 64: Power quality when carrier frequency set at 2000Hz
Open Loop System

Figure 66 shows the setting and variables available for open loop system experiments.

In Figure 67, the open loop system is implemented. If we monitor closely, the set point open loop RPM is 1800 and the RPM the motor is running on is 1785.45. This shows the error value in the open loop system.
Closed Loop control

Figure 68 shows the closed loop setting available to experiment. The PI controller is used to regulate to the set point. The Lumberg KV81 connector is providing a feedback of the speed to the FPGA controller and according to the PI controller, we are regulating the speed to the set point in the system.

Figure 69 shows the PI controller values that are used to stabilize the system. Different values of Kp and Ki can be experimented.
In Figure 70, the closed loop RPM is monitored. The RPM set point is 1800 and the motor is also running on the same RPM as the set point. This is because of the PI control which reduces any error between the set point and the running values of the motor RPM.

Infecting the system with a fault

Status of System can be accessed by selecting status tab on top of the “Inverter Type”. In the status tab we can monitor the system status. Also we have options to look at the CPU usage, IP address, MAC number of the connected system, Fault ID and other important aspects regarding the connected
system. Also in the status tab we can find the location where the GPIC data and the fault data are stored (figure 71). These files saved are in .tdms format and can be accessed by Microsoft excel, MATLAB and other data analysis software.

![Status tab to access GPIC log data and fault data](image)

Figure 71: Status tab to access GPIC log data and fault data

A fault in the system is induced purposely to test the response. The RPM of the motor is decreased from 3000 to 1800 and we can see in Figure 72 that error is represented by a red light on current Iu (A).

![Red light representing Error on Iu (A)](image)

Figure 72: Red light representing Error on Iu (A)
In Figure 73, we can see that the current $I_u$ (A) has crossed the set point of 10A and generated an error in the system.

![Figure 73: Fault induced when $I_u$ (A) reaches 10A](image)

Monitoring the DC link, at motor RPM of 3000, the DC link voltage was low (pulled down) than that of at RPM 1800, and then the RPM pops back up when the inverter trips due to a fault as shown in Figure 74.

![Figure 74: DC link voltage pops back up after system shutdown due to fault](image)
Study of motor V/I during startup and stop

If you notice in Figures 75 and 76, there is a large inrush of current at machine start up. This is because the excitation voltage that we are applying to the motor is not in phase with the motor, unlike the one we demonstrated in the co-simulation. So we are going to get a large excitation because of the hard start of the motor.

Figure 75: Phase current on machine startup

Figure 76: Large inrush of phase current when machine starts
When we disable the PWM for the machine to stop, we can see in Figure 77 that the current decays instantly in the stator, and the excitation voltage goes away. But we still see voltage at the motor terminals because the rotor currents are still circulating and decaying exponentially (Figure 78). If we ground the system, we won’t be seeing this exponential decay, instead the system will go to 0.
Labview Code Modules

V/f control modules for induction motor control

Figure 79 shows the simulated 3-phase grid voltage generated by using Vgrid_uv.

Figure 79: Simulating 3-phase grid voltage

Figure 80 shows the fault handling loop set at 40MHz

Figure 80: Fault handling loop

Figure 81 shows the module in which the IGBT temperatures are monitored. This is done by scanning the analog inputs from the FPGA board.
Figure 81: Temperature monitor for IGBTs

Figure 82 shows the encoder interface to labview. Here the analog inputs are scanned and the position, speed and acceleration of the motor is displayed.

Figure 82: Feedback from the induction motor processing module

The figure below shows the module that stores a buffer in FPGA RAM before and after a fault occurs.

Figure 83: Fault data logging module
Space Vector PWM control modules for induction motor

Figure 83 shows the module created to generate the SVPWM. Here the simulated 3-phase sine wave generated is crossed through the Space vector equations to get the Space Vector PWM.

![Figure 84: Generating SVPWM](image)

Figure 84 shows the module that takes in analog values from the FPGA board and displays it on Labview. These analog values are also used for generating the SVPWM.

![Figure 85: Taking analog values from the FPGA board](image)

Figure 85 shows the module that takes in analog values from the FPGA board and displays it on Labview. These analog values are also used for generating the SVPWM.
Figure 86 shows the module created to convert the SVPWM achieved from the module in figure 84 to a signal that is fed to the IGBTs on the GPIC board.

![Figure 86: Converting PWM to feed to IGBT switches](image)

As mentioned for the v/f control, figure 87 produces a simulated 3-phase grid voltage from taking in the analog input grid voltage and adding delay to its phases.

![Figure 87: Grid voltage conversion](image)

Once the process in figure 87 is done, the grid voltages pass through the module in figure 88 to generate the 3-phase sinusoidal voltage that is then inserted in our SVPWM generation module shown in figure 84.

![Figure 88: Generating 3-phase voltage with phase shift on grid voltage](image)
Figure 89 shows the resulted phase voltage after applying the Space Vector PWM algorithm. Channel 1 of the oscilloscope was connected to phase A and channel 2 connected to phase B, the resultant CH1-CH2 is shown is the figure.

Figure 89: Phase voltage generated with SVM
Works Cited


