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A Complete Low-Cost Design and Analysis for Single and Multi-Phase AC Induction Motors Using an 8-Bit PIC16 Microcontroller

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INTRODUCTION

This document provides a detailed analysis of driving a single and multi-phase AC induction motor (ACIM) using the PIC16F1509 microcontroller. Laboratory data is presented alongside the simulated data in an extensive reasoning of the entire design. The purpose of this application note is to show how to add speed control and soft-start to a single and multi-phase AC induction motor by using a three-phase inverter circuit. A low-cost solution is delivered, complete with a bill of materials (BOM), schematic, code and PCB artwork files. After analyzing this document, the reader can easily integrate the reference design and associated materials into a competitive product. The design does not include power factor correction because of the low-cost initiative.

The target application of this design is a garage door opener with a motor size of less than 1 Horsepower (HP). Motors that are larger than this may require significant changes to the existing BOM and circuit layout on the high-voltage side. Hardware optimizations for different types of motors and input voltages are detailed.

Laboratory results from running a ¼ HP permanent split capacitor (PSC) motor directly from the mains at 120V 60 Hz with a run capacitor are directly compared to the identical motor being driven via a multi-phase inverter board. A dynamometer and a power analyzer are used to characterize the reference design. The rest of this document will analyze these findings along with other supplementary inverter features such as isolated I/O, variable frequency (V/f) control, feedback and voltage regulation. The entire procedure and materials described in this document will provide the reader with enough material to design a repeatable experiment.

Three-phase applications can also utilize this board with minimal software changes; however, this document does not provide a detailed analysis on the results. Instructions on the setup and testing procedure of a three-phase motor are covered in this application note.

Here is a short summary of the inverter board benefits when used to drive a single-phase motor:

- Elimination of relay and run capacitor – a potential reliability improvement
- Speed/torque control
- No heat sink for up to ½ HP
- Same inverter supports single-phase and three-phase with one line of code change
- Isolated user interface
- Independent winding drive (load balancing)

The theory on how induction motors work and their construction will not be covered here. For further information on this topic, please refer to AN887 in Reference 2. For a complete listing of Microchip AC induction motor application notes, please visit www.microchip.com/motorcontrol/.

The last chapter of this document contains a list of recommendations that the reader may want to further investigate.

FIGURE 1: AC INDUCTION MOTOR WITH THREE-PHASE INVERTER BOARD
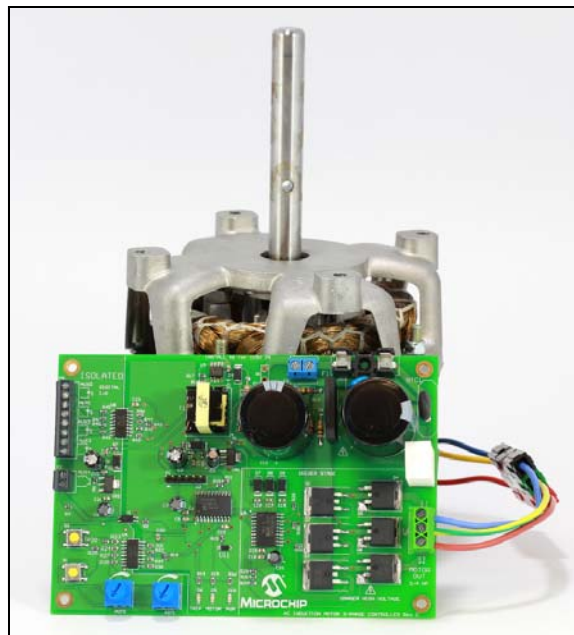
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TRADITIONAL SINGLE-PHASE AC INDUCTION MOTOR TOPOLOGY

The PSC single-phase induction motor is often the simplest and most widely used motor of this type (see **Section "References"**). It has low starting torque and current; however, it incurs inefficiencies from the expensive, non-polarized run capacitor. This capacitor commonly fails before the rest of the motor, so there is a concern for maintenance because of this dependency.

Topology

A PSC single-phase induction motor is also less commonly referred to as a two-phase motor since it is unable to turn without sufficient phase shift between the two windings. A capacitor can be placed in-between the input signal and the windings in order to produce an approximate 90-degree phase shift.

FIGURE 2: TRADITIONAL SINGLE-PHASE AC INDUCTION MOTOR TOPOLOGY

Note: The capacitor provides the necessary phase shift to produce a rotating magnetic field.
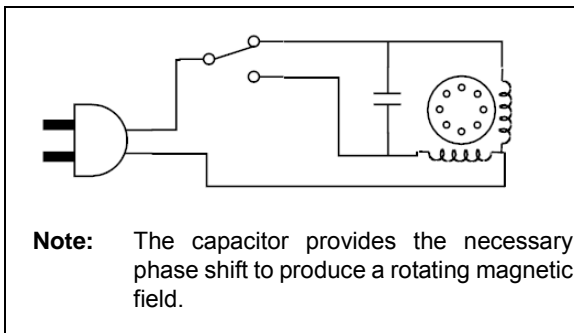
The switch is often replaced with a relay that can control the direction by swapping which phase leads or lags the other. The value of the capacitor is typically specified by the motor manufacturer and is sometimes in the range of 5-50 uF for motors that are less than 1 HP. The capacitor is carefully chosen in an attempt to correct the power factor for maximum power efficiency. The voltage rating is typically high at around 220-450V, depending on the input voltage. The capacitor must not be polarized, since it is across an alternating voltage. If this capacitor fails, the motor will cease to turn. The importance of selecting the correct capacitor is therefore critical.

Losses

A practical capacitor has resistance and radiates heat as it consumes the RMS AC ripple current within its equivalent series resistance.

The permanently installed capacitor trades off starting torque capability at standstill with ripple torque reduction at running speed. Because of the high V_A rating of the capacitor, capacitors are often selected to meet the minimum starting performance requirements, resulting in poor running efficiency.

For motors that do not have identical windings, it is necessary to feed the two phases with different voltages. This asymmetry is due to the presence of the capacitor, which forms a resonant circuit with the motor's inductance. Consequently, this raises the voltage across one of the windings and causes uneven current flow.

INVERTER BRIDGE SINGLE-PHASE AC INDUCTION MOTOR TOPOLOGY

Topology

A three-phase inverter can be used as a substitute to the permanent capacitor as seen in Figure 3.

FIGURE 3: SINGLE-PHASE INVERTER WITH THREE HALF-BRIDGES

Note: Six PWM signals are used to drive the connected squirrel cage PSC motor.
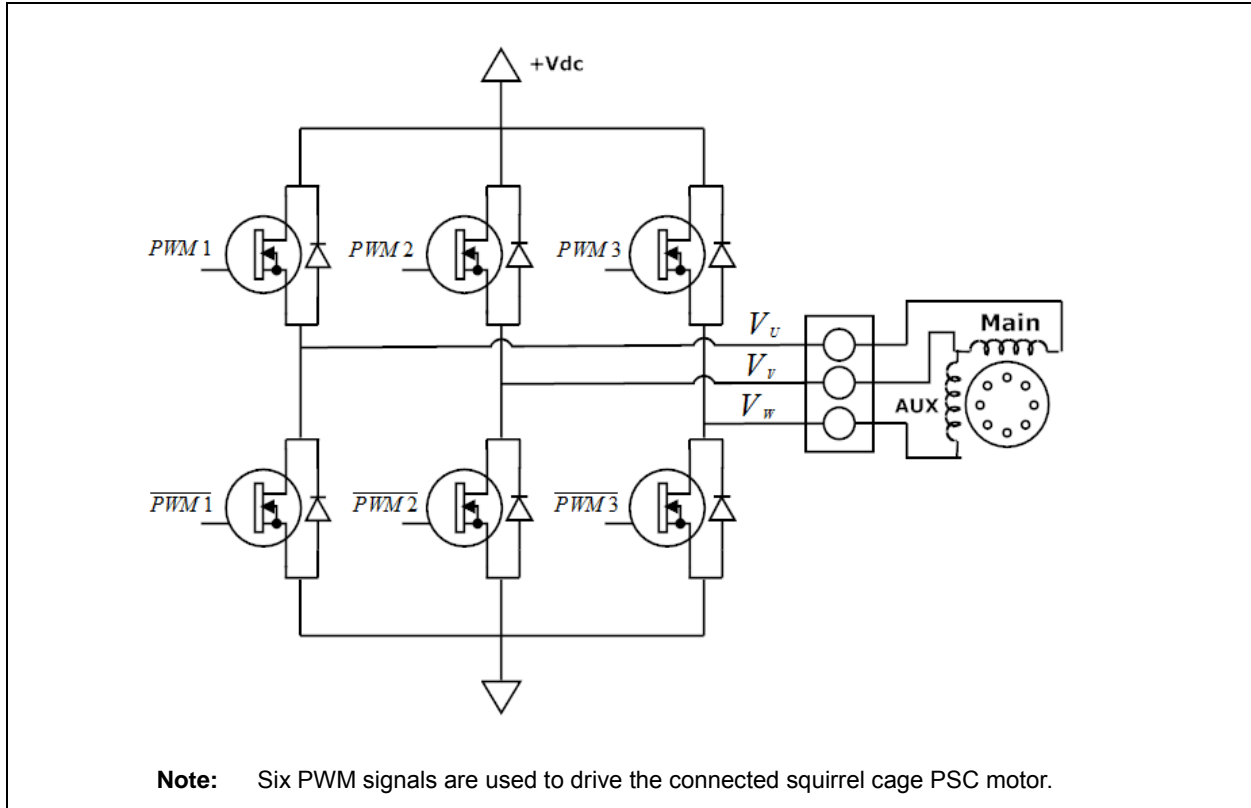
This topology has the benefit of being able to adjust the speed of the motor and apply the appropriate amount of voltage on each winding so that the weaker winding is not overdriven. V_{DC} is created after rectifying the AC input. See Figure 31 for the entire system overview. Variable Frequency Drive (VFD) is the control algorithm used to ramp up and down the motor. For more information on V/f control, please see Reference 3.

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Phase Derivation

The motor will still spin without the capacitor if the coils are driven out of phase from one another. This can be achieved by creating three phases in software. These three-phase voltages can then be referenced from one another to create two resultant waveforms across the two motor windings. Equation 1 shows how one of the phases (Vv) is taken as the reference (neutral) to create two waveforms. The following equations are explained in more detail in Equations 4 through 6 in AN967 (see Reference 6), which outline each of the three phases in the time domain.

EQUATION 1: MOTOR WINDINGS EQUATION

$$V_{MAIN} = V_U - V_V$$

$$V_{AUX} = V_W - V_V$$

> **Note:** The phasors for each phase are explained in more detail in Figure 11 in AN967 (see Reference 6).

V_U, V_V and V_W are the three phases that are created in software utilizing the PWM technique. Equation 2 shows a general time domain expression of a sinusoidal wave that will be used to graph and analyze the voltages on the motor.

EQUATION 2: GENERALIZED SINUSOIDAL EXPRESSION

$$A_T = A_M SIN(\omega T \pm \theta) + V_{DC}$$

Symbol	Description
A_t	Time-Varying Waveform
A_m	Waveform Magnitude
V_{DC}	Direct Current (DC) Offset

Equation 3 shows the individual inverter phases after applying the general representation of a time varying sine wave.

EQUATION 3: INDIVIDUAL PHASE EXPRESSIONS

$$V_U = \frac{V_{DC}}{2} SIN\left(\frac{\pi}{180}T\right) + \frac{V_{DC}}{2}$$

$$V_V = \frac{V_{DC}}{2} SIN\left(\frac{\pi}{180}T - \frac{\pi}{2}\right) + \frac{V_{DC}}{2}$$

$$V_W = \frac{V_{DC}}{2} SIN\left(\frac{\pi}{180}T - \pi\right) + \frac{V_{DC}}{2}$$

The phase amplitude is equal to the rectified DC voltage. There is a DC offset of $V_{DC}/2$ since the sine wave must swing an equal proportion in both the positive and negative direction. The $P_I/2$ term indicates a phase shift of 90 degrees, as seen in Figure 4.
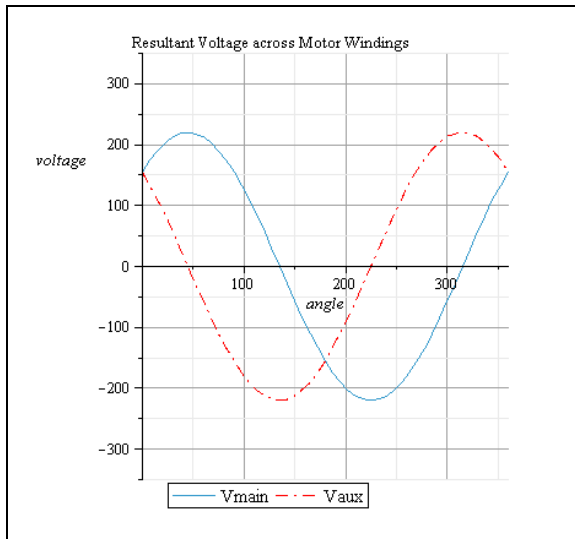
FIGURE 4: THREE PHASES FROM THE OUTPUT OF INVERTER

> **Note:** V_U and V_W are each 90 degrees out of phase from the middle winding, V_V.
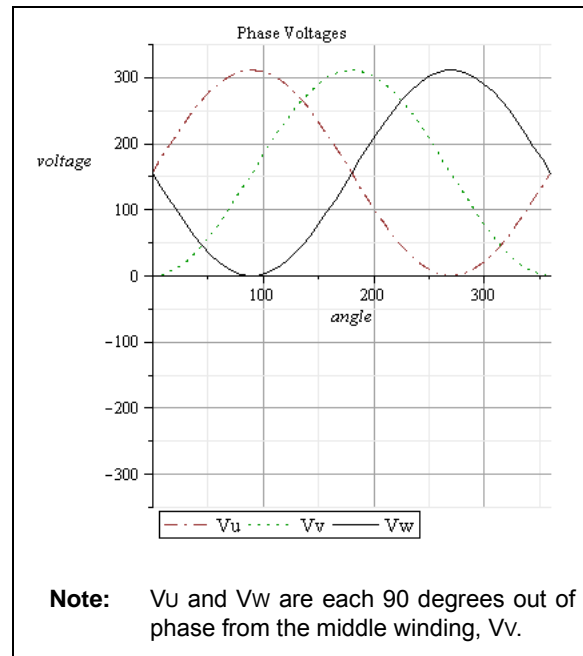
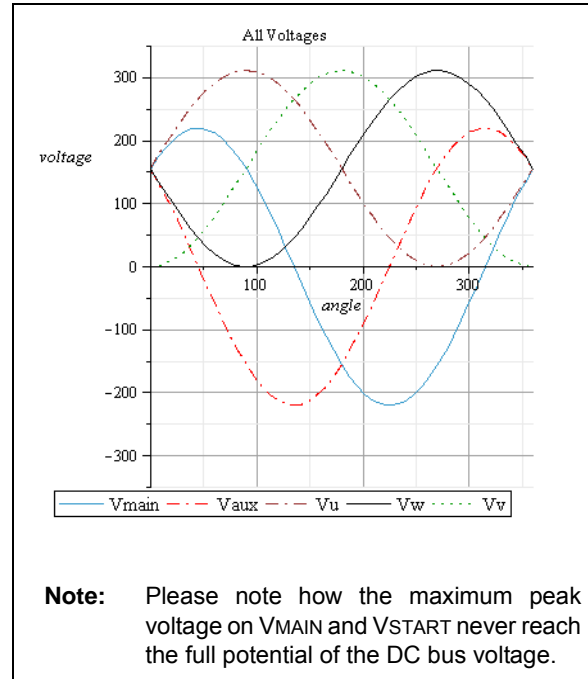Phase V_V is considered the neutral one. Each winding has V_V as its reference.

Figure 5 shows the two resultant waveforms that are realized across the two windings of equal magnitude.

FIGURE 5: VOLTAGES SEEN ACROSS THE TWO MOTOR WINDINGS

As Figure 5 shows, the peak voltage is much lower than the original 311V. After substituting values into Equation 1 from Equation 3 and locating where the maximum voltage occurs in the auxiliary and main waveforms, the peak voltage evaluates to $\left(\frac{1}{\sqrt{2}} \bullet V_{DC}\right)$, or 70% less than that of connecting the motor directly to a 220 VRMS source with capacitor. The two resultant AC waveforms across the motor's stator are only utilizing 70% of the available DC supply. Figure 6 shows the three phases from Equation 3 alongside the two-motor waveforms from Equation 1.

FIGURE 6: ALL-PHASE VOLTAGES

Note: Please note how the maximum peak voltage on V_{MAIN} and V_{START} never reach the full potential of the DC bus voltage.

The resultant waveform across the motor does not utilize 100% of the input DC bus voltage.

Space vector PWM is therefore used to recover this missing percentage of voltage; however, this strategy only works for three-phase motors that have each of their windings 120 degrees out of phase from one another. Another strategy that can be used is to add the third harmonic to the sine wave so that close to 100% of the DC voltage can be utilized. Please see AN955 for more details on sine PWM generated phases with 120 degree phase shift. The software included with this inverter board contains a look-up table with the modified values.

Figure 7 shows the current through the windings.

FIGURE 7: CURRENT THROUGH COILS USING A CURRENT PROBE
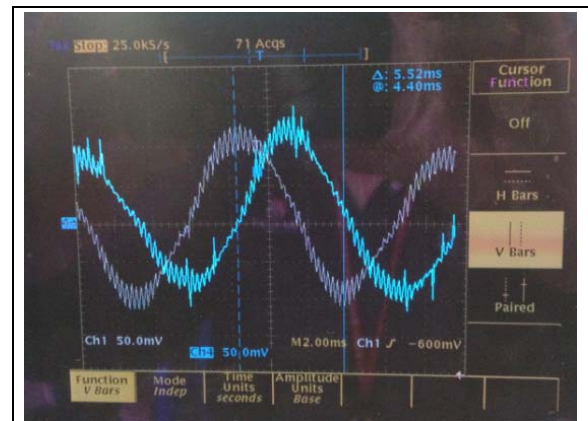
The two current phases in Figure 7 are approximately 90 degrees out of phase from one another.

PSC AND INVERTER COMPARISON FOR SINGLE-PHASE MOTORS

Introduction

This section explains the scientific comparison between the PSC run method versus the inverter method with no run capacitor. Table 1 shows a summary of the tests conducted.

TABLE 1: SUMMARY OF TESTS

Test	Purpose
Torque	To characterize the effects of Variable Frequency Drive on the motor's torque.
Acceleration and Speed	To identify which method turns the motor shaft the fastest and how quickly the load will accelerate.
Efficiency	To compare the real component of the output power to the input power and to measure the power factor and other inefficiencies.

These three tests cover the largest design considerations in motor control. None of the tests require a special setup from the other tests. Each analysis in the three separate tests uses the same subset of data.

Equipment

Table 2 lists the equipment used during the tests.

TABLE 2: CURRENT THROUGH COILS USING A CURRENT PROBE

Purpose	Model
Three-Phase Power Analyzer	Yokagawa WT1806
Braking Source (Dynamometer)	Magtrol Hystersis 715-D
Programmable Controller (Dynamometer)	Magtrol DSP6001
PC Control Testing Software (Dynamometer)	Magtrol M-TEST7
1800w AC Power Supply	California Instruments 2001RP

A single motor from WEG was used during the experiment. Its nameplate readings can be seen in Table 3.
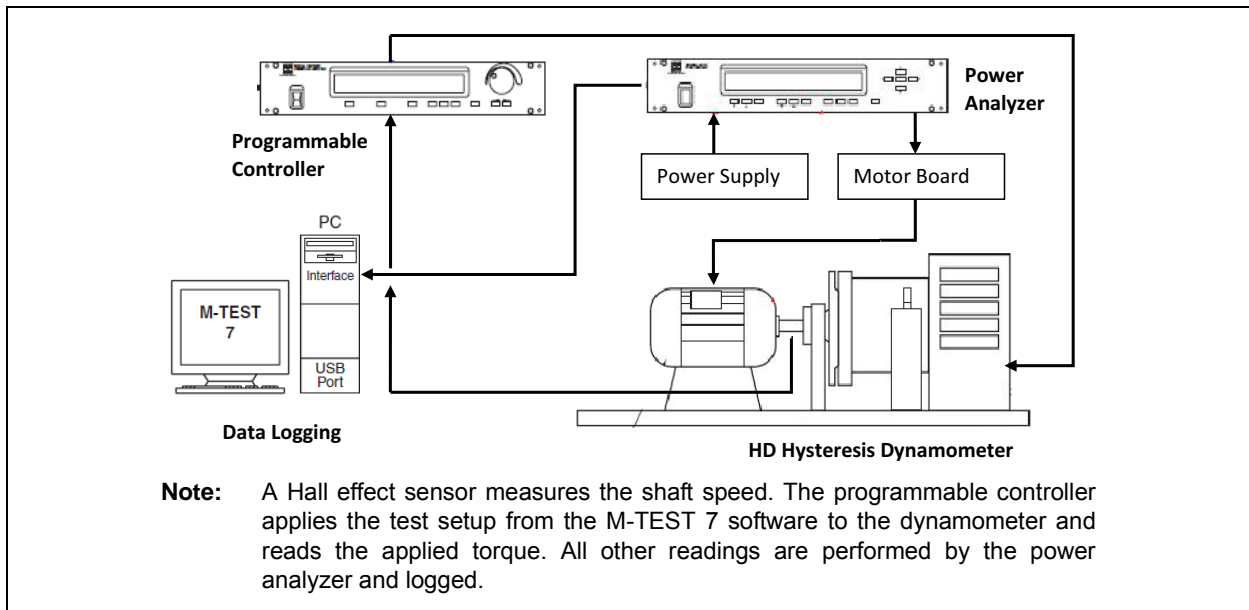
TABLE 3: MOTOR NAMEPLATE READINGS

Property	Value
Size	1/4 HP
Type	One-phase ACIM
Poles	4
Frequency	60 Hz
Voltage	220V
Current	1.2A
Run Capacitor	12 uF
Speed	1645 RPM
Main-Winding Resistance	13Ω
Auxiliary-Winding Resistance	13Ω

This particular motor has a balanced winding configuration. Both windings are identical in terms of resistance and inductance. The results shown in this document will differ from other motors constructed in other various ways.

Test Setup

The entire test setup can be seen in Figure 8.

FIGURE 8:   TEST SETUP ON THE DYNAMOMETER

Note: A Hall effect sensor measures the shaft speed. The programmable controller applies the test setup from the M-TEST 7 software to the dynamometer and reads the applied torque. All other readings are performed by the power analyzer and logged.

The input to the system is single-phase, two-wire (1P2W) voltage at 220V, 60 Hz. The power analyzer is also configured for 1P2W on its single element input. The output from the power analyzer is fed into the two terminals on the inverter. The inverter has an optional voltage doubler that is not used during the tests since the input voltage is greater than 115V. Three wires are then connected to the motor windings as seen in Figure 3.

The PC interface runs the M-TEST software which configures the programmable controller and hence, the dynamometer. When a test is running, the programmable controller adjusts the dynamometer to apply a specific braking force. Before initiating a test, the motor is brought up to its maximum free running speed. When the maximum speed for a specific frequency is reached, the test begins. The duration of the test depends on the starting speed of the motor.

The M-TEST software runs a dynamic ramp test with inertia cancellation on the motor. A ramp test decrements the motor speed in steps of 50 RPM until it reaches a minimum of 150 RPM. A single locked rotor reading is extrapolated using 20 data points.

All tests lasted under 60 seconds because of the risk of damaging the insulation of the motor as a result of large prolonged currents in the stator.

Note: Please refer to the motor manufacturer's recommendations on the subject of prolonged stress testing (locked rotor).

The inverter board's properties for the entire test duration are listed in Table 4.

TABLE 4:   INVERTER BOARD MODULATION PROPERTIES

Property	Value
Switching Frequency	7.82 kHz
Sine Table Look-up Values	64
Dead Band	420 ns max.

When the test is complete, the power analyzer and motor feedback readings are consolidated into a spreadsheet and plotted with MATLAB®.

Results

This section presents the quantitative data taken from the power analyzer. Table 5 shows a summary of the tests performed.

TABLE 5: SUMMARY OF TESTS

Test	Purpose
Torque	To characterize the effects of Variable Frequency Drive on the motor's torque.
Acceleration and Speed	To identify which method turns the motor shaft the fastest and how quickly the load will accelerate.
Efficiency	To compare the real component of the output power to the input power and to measure the power factor and other inefficiencies.

These three categories of tests use the same data points but present different pieces of it.

The main advantage of using an inverter board over the traditional PSC method is that the user can control the voltage and drive frequency. Multiple modulation frequencies are tested on the inverter board to characterize the effects on the motor, such as maximum torque, speed and efficiency.

The voltage and frequency can be adjusted with the inverter board. A 1:1 voltage-to-frequency ratio means that the voltage scales with the frequency in an exact linear fashion. The inverter board can control these two parameters independently of one another to create unique results. A maximum voltage-to-frequency ratio implies that the voltage is kept at its maximum whilst the frequency is adjusted.

Table 6 shows what frequencies are tested and their maximum torque results when both a linear 1:1 voltage-to-frequency and maximum voltage-to-frequency control algorithms are used for frequencies lower than 60Hz.

TABLE 6: INVERTER BOARD TESTS WITH 1:1 AND MAX V/f CURVE

Frequency (Hz)	Starting Torque (Nm)	Max. Torque (Nm)	Max. Speed (RPM)	Max. Efficiency (%)	Max. Output Power (W)	Notes
30	0.472	0.472	819	30.0	29	1:1 V/f
40	0.664	0.664	1170	29.5	42	1:1 V/f
50	0.765	0.777	1430	34.8	66	1:1 V/f
60	0.742	0.788	1770	37.7	87	Inverter
60	0.830	1.63	1760	47.1	227	PSC method
70	0.670	0.724	2020	39.2	94	—
80	0.53	0.576	2310	37.8	87	—
90	0.375	0.436	2530	33.3	77	—
120	0.195	0.218	3340	28.6	56.6	—
30	2.12	2.49	905	29.6	106	Max. V/f
40	1.61	1.62	1170	35.8	109	Max. V/f
50	1.16	1.16	1490	38.7	105	Max. V/f

In short, the inverter is capable of lifting a larger size load at start-up; however, its rate of work is much slower than that of the one-capacitor motor. The rest of this section will cover a more detailed analysis of the data in Table 6.

TORQUE

The starting torque is one of the most important characteristics in a motor application. If the motor is unable to lift the load at 0 RPM (locked rotor), then none of the other properties matter, since the load will not move.

Figure 9 shows the torque curves plotted against the speed of the motor's shaft.

FIGURE 9: TORQUE CURVES FOR LINEAR 1:1 V/f
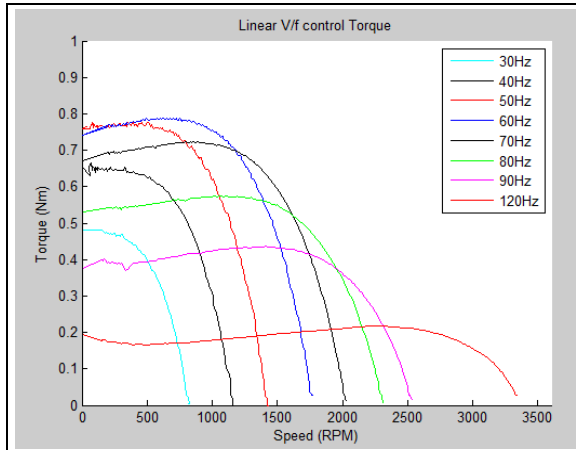
From the curves, it is apparent that the motor has the highest starting torque of around 0.75 Nm between 50-60 Hz in line with the motor design. Frequencies above and below 60 Hz have lower torque profiles. The V/f slope determines this profile for frequencies below the rated frequency of 60 Hz. Ideally, a 1:1 ratio between the voltage and frequency should yield a constant torque as seen in Figure 10.

FIGURE 10: V/f RELATIONSHIP TO TORQUE
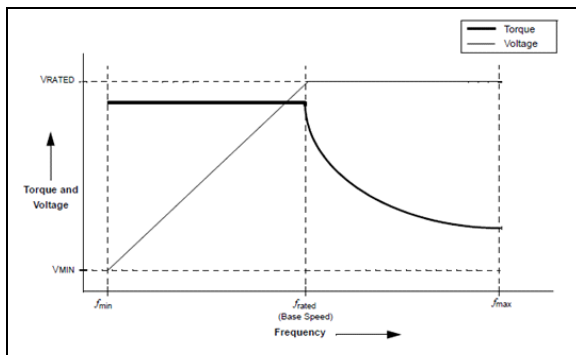
However, the low frequency plots in Figure 9 do not show a constant torque curve. To understand this phenomenon, the theory on Variable Frequency Drive must first be discussed.

VARIABLE FREQUENCY DRIVE

The torque developed by the induction motor follows Equation 4 below.

EQUATION 4:

$$T = K_1 \phi_M I_2$$

Neglecting the voltage drop caused by the stator impedance, the magnetizing flux is found to be:

$$\phi_M = K_2 \frac{V_1}{F_1}$$

Where:

| Symbol	Description	Units
T	Torque available on the motor shaft	Nm
ϕ_m	Magnetizing Flux (Wb)	Wb
I_2	Rotor Current (A) ~ proportional to Load	A
V_1	Stator Voltage	V
$K_1 K_2$	Constants ~ proportional to Motor Design	—

Given a constant torque load, then, proportionally varying voltage amplitude and frequency will result in constant flux and, therefore, constant torque while the current remains unchanged. For more information, please refer to the WEG technical guide listed under Reference 8.

In a real application, the actual voltage/frequency ratio is usually restricted to a certain range and is not a perfect 1:1 ratio. One such restriction is the motor voltage. Overvoltage will damage the insulation of the stator and cause premature malfunctioning of the motor.

From the rated frequency upwards, the voltage is kept constant while the frequency is increased. This causes the flux to decrease and the motor torque starts to decrease gradually. For more information please refer to the WEG technical guide under Reference 8.

Frequencies lower than 60 Hz require a fine tuning of the voltage-frequency ratio because of losses in the motor and inaccuracies in the motor drive. The plots in Figure 9, which do not show a constant torque profile, are created using a 1:1 ratio. Figure 11 shows the V/f profile with a slope close to zero by keeping the voltage at its maximum while adjusting the frequency. Frequencies below the optimal 60 Hz are kept at maximum voltage.

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FIGURE 11: **MAXIMUM V/f CONTROL TORQUE CURVES**
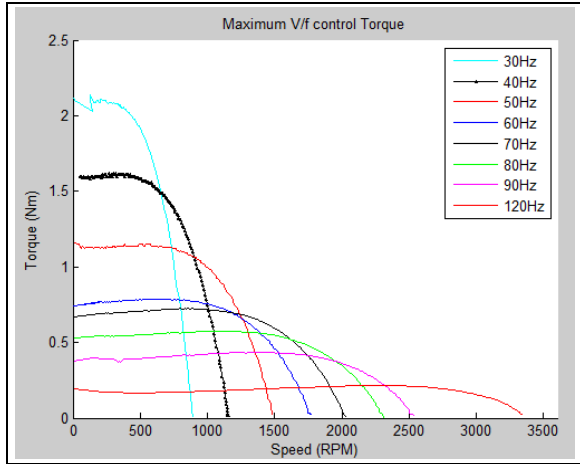
It should be apparent from Figure 11 that, when the V/f slope is lowered from 1:1 to close to 0:1, the torque rises dramatically as the frequency is decreased. A low frequency causes a decrease in an inductor's impedance. The high voltage applied to this lowered impedance raises the current in the stator which produces higher torque.

In order to get a linear torque curve with this specific motor and inverter board, the V/f profile should be fine-tuned in code until all frequencies below the optimal frequency share the same shifted torque profile. Figure 12 shows a typical plot of torque curves for a typical NEMA type A motor.

FIGURE 12: **TYPICAL VARIABLE FREQUENCY TORQUE CURVES**

Note: Curves below the optimal 60 Hz have greater starting torque.
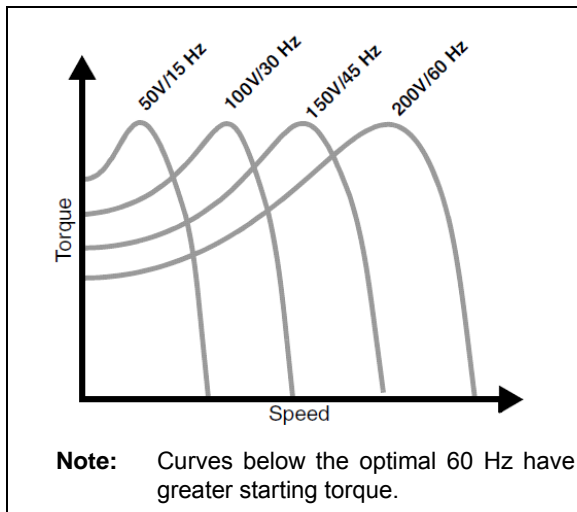
If maximum torque is desired, the rate of frequency increase should be adjusted to *jump* curves so as to take advantage of the breakdown torque, as shown in Figure 13.

**FIGURE 13:** **CONSTANT TORQUE PROFILE**
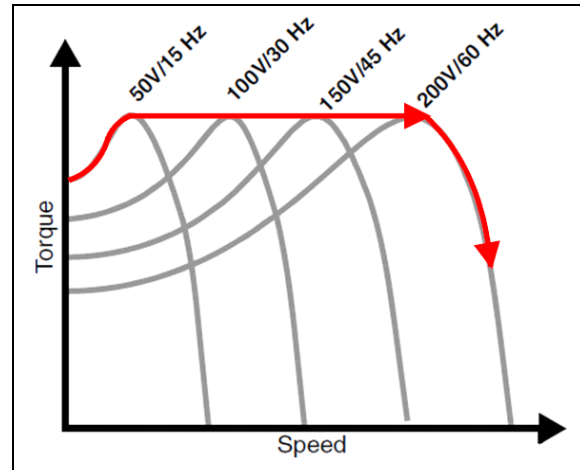
The red line shows how the software should control the frequency and voltage in order to ride along the tops of each torque curve. This will maximize the delivered torque at a constant rate.

Figure 14 shows the torque curve for the traditional PSC method at 60 Hz compared to the 60 Hz inverter method.

FIGURE 14: **TORQUE CURVES OF THE CAPACITOR RUN VERSUS INVERTER RUN**
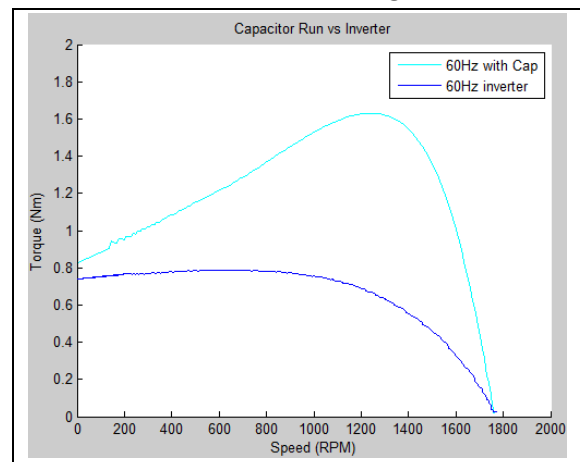
The shapes of the curves between the two methods differ greatly. The capacitor method shows a slightly larger starting torque and will accelerate faster than the inverter board at 60 Hz. The inverter board produces a curve similar to that of a class D design motor, whilst the PSC run topology produces a similar class A torque curve. An unequal voltage magnitude caused by the permanent capacitor creates an unequal magnitude of magnetizing flux within the stator. The inverter board attempts to create an equal amount of current in each winding, since this particular motor has identical impedance in each. The shape of the torque curves are not similar because of these discrepancies in the driving topologies.

Looking at the starting torque when the rotor is locked, the inverter would be unable to lift the same-sized load as the PSC method if the inverter were programmed to simply turn the motor at a 60 Hz modulation frequency. However, the inverter board can use Variable Frequency Drive to lift an even larger-sized load as seen in Figure 11. The designer must also take into consideration the trade-offs of large starting torque versus efficiency and speed.

Operating the motor above its rated output torque for a prolonged period of time will reduce the motor's lifespan due to larger-than-rated currents in the stator. Figure 15 shows a hypothetical motor operation where the load requires a large starting torque to overcome stresses such as static friction. This is considered a hard-start.

**FIGURE 15:** **HARD-START PROFILE**
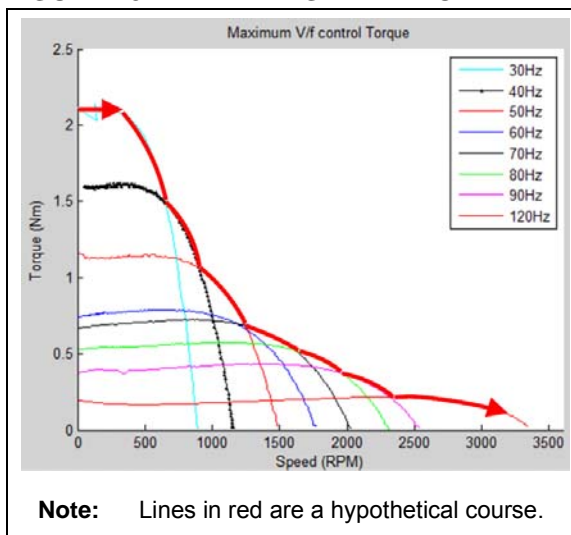
> **Note:** Lines in red are a hypothetical course.

An important consideration is to determine at what point to stop incrementing the frequency. If the load requires a minimum of 0.4 Nm torque to lift, then the inverter board should be configured to stop its hard-start at around 80 Hz. As described in **Section "Efficiency"**, the full load torque should be matched with the correct curve, so as to maximize the efficiency when the motor has been spun up to its running speed. If the frequency is increased too fast, the motor will stall and it is unrecoverable until the V/f curve is reset and adjusted accordingly.

Figure 16 shows a soft-start, which lowers the initial stress of the motor as it spins up to its running speed.

FIGURE 16: **SOFT-START PROFILE**
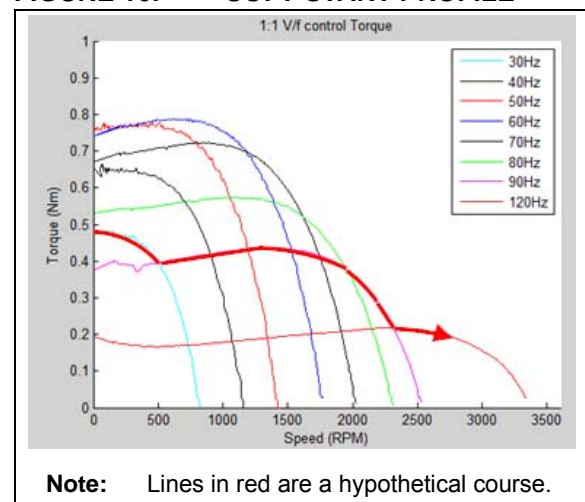
> **Note:** Lines in red are a hypothetical course.

Varying the V/f profile should be adjusted according to each specific application. It may be more practical and easier to pick one frequency curve and stay on it.

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Summary

1. Starting Torque

The inverter board presents the highest amount of starting torque, which is arguably the most important design property in applications where the load is fixed and requires a large amount of starting torque. The inverter board must configure the V/f slope accordingly to achieve these large torque values. A drawback of this modification is that the stator consumes very large currents and the maximum speed of the motor will be slow if the curve is followed to normal run location. The designer should be aware of the motor specifications before modifying the applied voltage and frequency.

2. Nominal Run Speed (60 Hz)

As seen in Figure 14, the PSC method yields greater starting torque and run-time torque over the motor's full range of operation. The PSC method would be a cheaper and more powerful alternative in terms of output torque if the inverter board did not take advantage of manipulating the voltage and/or frequency and it just ran the motor at its nominal frequency.

3. Torque Range

Settings to accommodate motors that only require low torque can be easily adjusted with the inverter board. This typically prolongs the motor's lifespan, it conserves energy and displaces heat to its surroundings, such as a garage. The inverter can change the frequency and voltage, which is not possible with the limited on and off control of the PSC. With the permanent capacitor, the motor must be sized larger than what is needed and may spend its lifetime not operating at its fully rated load.
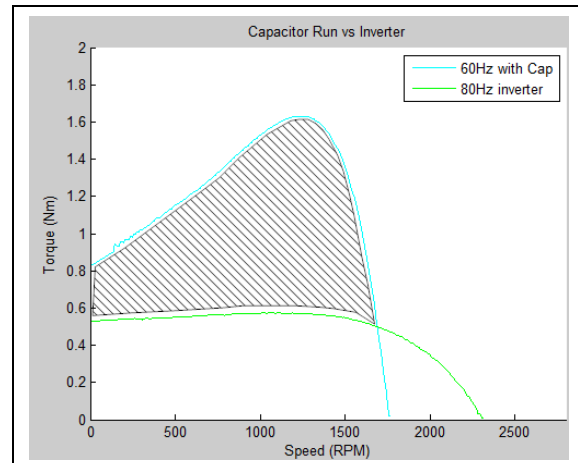
ACCELERATION AND SPEED

The most obvious benefit of V/f control is that the designer can control the speed at which the motor shaft spins. The faster it spins, the sooner the load can be pushed or pulled to its destination. Getting the gate up faster than the competition is a critical design win in a garage door or gating system application.

- Angular acceleration $\propto$ applied torque
- Accelerating torque $\propto$ available motor torque – load torque

Large torque will accelerate the motor's shaft at a faster pace for a given speed. Figure 17 shows the run capacitor method at 60 Hz compared to the inverter board at 80 Hz.

FIGURE 17: ACCELERATION FROM TORQUE PROFILES

The shaded area represents more torque available for acceleration than the other curve below it. Even though the 80 Hz curve reaches up to 2300 RPM, the motor will take longer to reach that speed compared to the capacitor method. An application where the load must be moved a large distance would benefit from riding along the 80 Hz curve since it will be cruising at a higher speed on average. Short distance applications may benefit from using the 60 Hz curve with the capacitor method, since the 80 Hz curve will take a longer time to ramp up its speed.

Please note that this particular motor has four poles. At 60 Hz, its synchronous speed can be calculated as in Equation 5.

EQUATION 5:

$$N_S = \frac{120 \cdot F}{P} = \frac{120 \cdot 60}{4} = 1800 \text{ RPM}$$

Symbol	Description	Units
N_S	Synchronous Speed	RPM
f	Applied Power Frequency	Hz
P	Total Number of Poles	—

The synchronous speed of the motor can also be qualitatively identified by looking at Figure 16 and locating where the torque curve approaches a value of '0'. After synchronous speed is achieved, the frequency is increased while keeping the voltage constant. This lowers the available torque on the motor shaft, but increases the speed at which it turns. To take advantage of the increase in speed, the designer should appropriately size the motor and stepping speed, so as to reach a suitable ending speed. Recall that if the soft/hard-start increases too rapidly or follows a curve that cannot continue to lift the load, the motor will follow the curve back towards (0 RPM) and it will stall, as shown in Figure 18.

FIGURE 18: INCREASING THE FREQUENCY TOO RAPIDLY

Note: Lines in red are a hypothetical course.
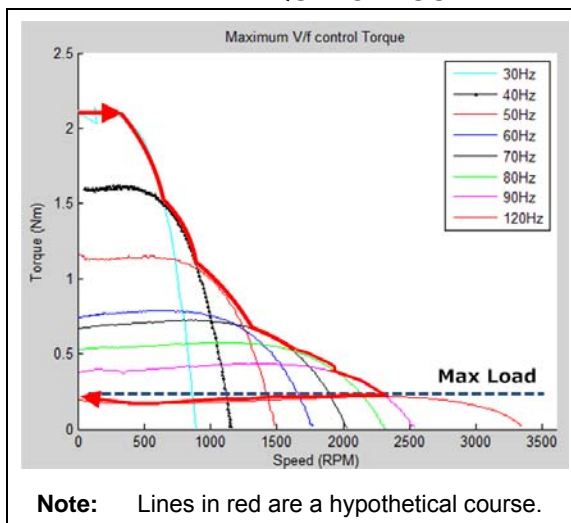
If the maximum load line is crossed because of the frequency jumping too soon, the motor will stall by following its current curve back to 0 RPM (i.e., insufficient torque available to drive the load).

Please see **Section "Software"** to learn more about the available settings to prevent the motor from stalling.

Summary

1. Speed Range

The inverter board allows the motor to out-pace a replica motor that is driven by the PSC method. The PSC method can only be driven at one frequency and, hence, it cannot exceed its synchronous speed.

2. Acceleration

The difference between the maximum torque at a specific speed and what the load actually needs will determine the rate at which the motor is able to lift the gate. A large delta will get the gate up faster to a certain speed.

EFFICIENCY

The system efficiency, as defined in Equation 6, is analyzed in this section.

EQUATION 6:

$$\eta = \left(\frac{P_M}{V_{RMS} \cdot I_{RMS}} \right) \cdot 100$$

Symbol	Description	Units
η	Overall System Efficiency	—
P_m	Motor Output	W
V_{rms}	Input RMS Voltage	V
I_{rms}	Input RMS Current	A

Note that efficiency is governed by the output power of the motor shaft divided by the real component input power to the system. The losses of the motor as well as the inverter board are lumped together in this model. Future tests may also want to place a one-phase three-wire (1P3W) measuring element in-between the inverter board and the motor to further characterize the losses. Please see **Section "Recommendations"** for more information on other suggestions for future tests.

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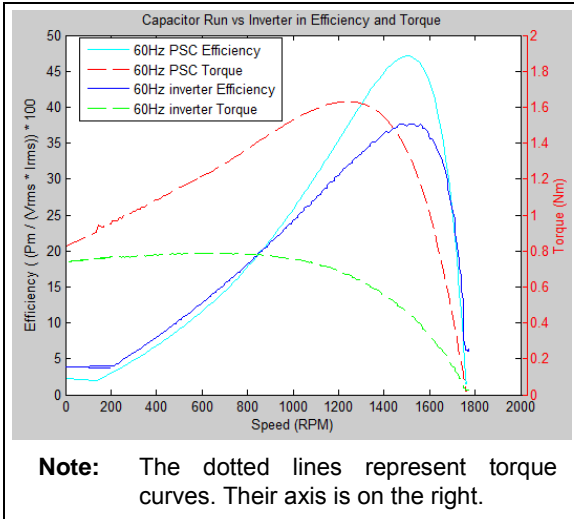shows the efficiency of the PSC and inverter board at 60 Hz.

FIGURE 19:   EFFICIENCY OF THE PSC METHOD VERSUS THE INVERTER
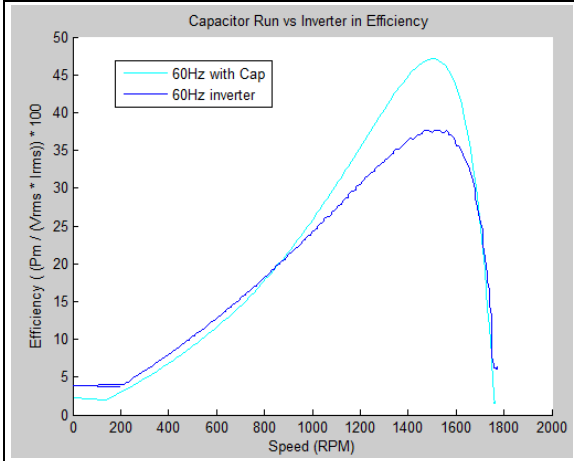
The system running at 60 Hz with the PSC method (see Figure 19) is approximatively 10% more efficient than with the inverter method.

Figure 20 shows the efficiency and torque plotted on the same graph.

FIGURE 20:   EFFICIENCY AND TORQUE

Note: The dotted lines represent torque curves. Their axis is on the right.

The motor's peak efficiency is at nearly the same points in both methods. A typical induction motor will run most efficiently at a few percentage points from its synchronous speed. Please note the motor is not running at its maximum efficiency when the torque is also at its maximum.

Another important characteristic is the input and output power of the motor. Figure 21 shows the efficiency along with the input power.
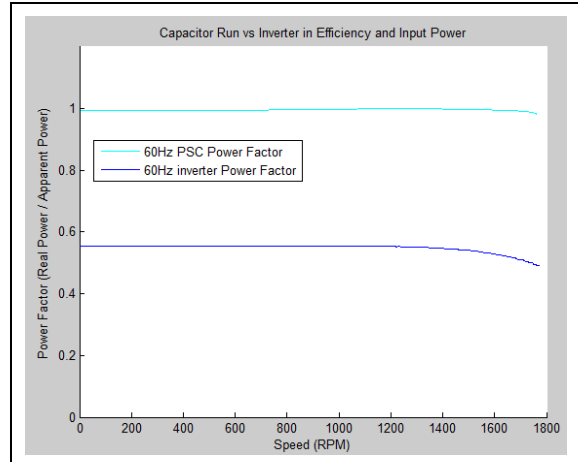
FIGURE 21:   EFFICIENCY WITH INPUT POWER
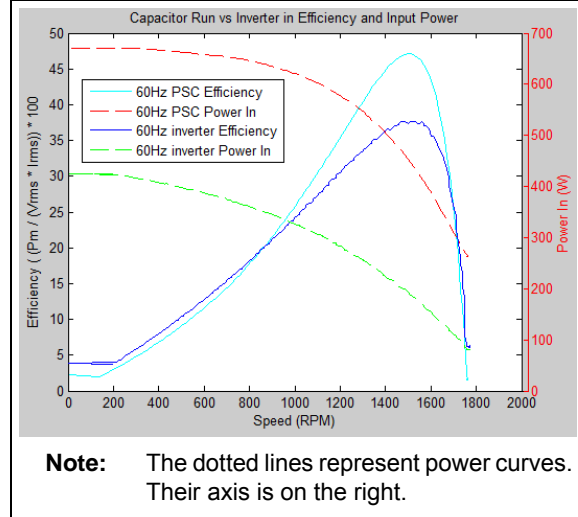
Note: The dotted lines represent power curves. Their axis is on the right.

Further analysis shown in Figure 22 shows that much of the input power is not consumed and it is rather wasted as reactive power.

FIGURE 22:   POWER FACTOR

More than half of the energy is stored in capacitive and inductive elements in the inverter board. The PSC method has a power factor (PF) close to '1' due to the close matching of the capacitor in relation to the motor's inductance. There is also no power stage with the PSC method to support typical circuitry such as a microprocessor and sensor inputs. The power factor comparison is therefore favoring the PSC method due to its basic, atypical setup.

The poor power factor can be attributed to the rectification stage of the inverter board's power supply, as shown in Figure 23.

FIGURE 23: FULL-WAVE BRIDGE CURRENT CONSUMPTION
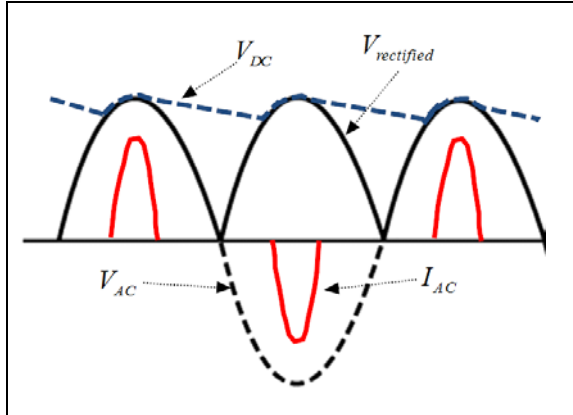
The two large DC capacitors only consume current when the DC voltage lowers below the peak voltage of the AC input. Therefore, there are large peaks of current in short bursts when the incoming voltage charges the capacitors. The current drawn will have significant harmonic content due to the presence of the switching elements.

The motor will also induce reactive power into the input system which reduces the overall efficiency of the system. The designer may want to install passive power factor correction to improve the design.

This causes the voltage and current consumption from the power utility company to be inefficient. The power factor correction is not installed because of the low-cost nature of the inverter. An improved power factor will greatly increase the real component of the input power.

Infrared imaging was used to compare stator losses in the motor with the two methods. There is no load connected to the motor, which is set to run at 60 Hz 220V.
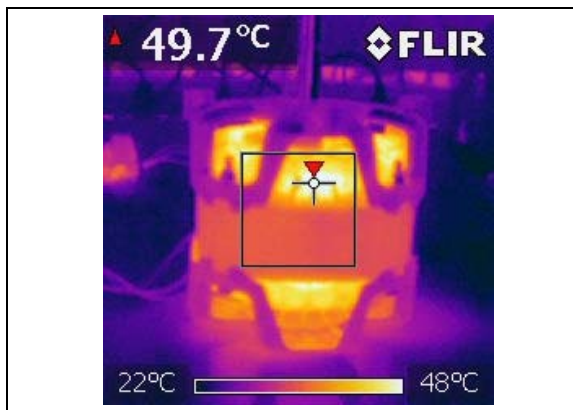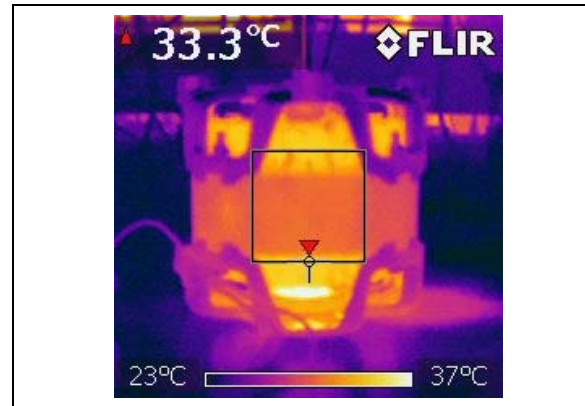
**FIGURE 24: MOTOR WITH PSC**

FIGURE 25: MOTOR DRIVEN BY INVERTER

As shown in Figure 24 and Figure 25, under the same input conditions, the motor driven with the run capacitor has its stator running warmer compared to the inverter method. The temperature range on the bottom indicates an overall increase of the entire picture. The arrow in the box simply indicates the warmest part in the box. The designer must take the current and overall power input/output curves into consideration before arriving at the conclusion that the PSC method produces more losses in the stator. An induction motor fed by PWM voltage presents a lower efficiency level than when fed by purely sinusoidal voltage, because of the increased losses caused by harmonics in the PWM.

Additional analysis into the harmonics produced by the switching elements on the inverter should be performed in order to characterize the stator losses. See **Section "Recommendations"** for further tests that can improve the data.

The current in both systems is also analyzed (see Figure 26 through Figure 28).

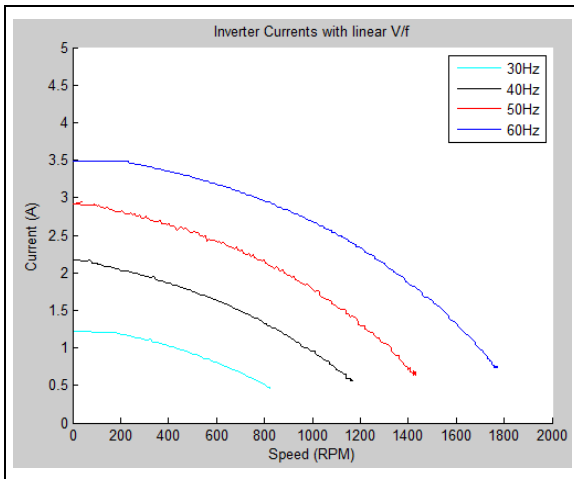**FIGURE 26: TOTAL CURRENT CONSUMPTION AT 60 HZ**
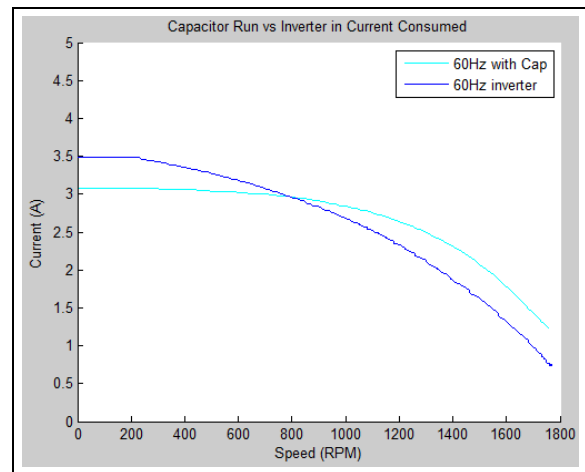
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The amount of current consumed by the overall system in both methods is similar, but the inverter has an approximate 500 mA more when the motor starts. The current in the inverter would theoretically double if the voltage doubler was used for 115V systems.
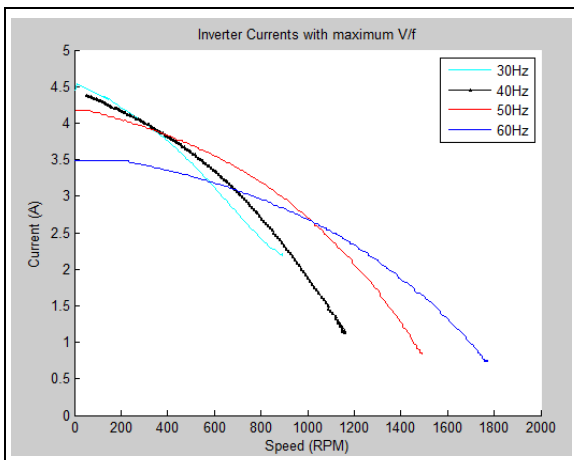
For operation under 60 Hz, the current reduces as dictated by the V/f slope.

FIGURE 27: **TOTAL INVERTER CURRENT CONSUMPTION AT 1:1 V/f**

However, if the voltage is kept at a constant maximum and the frequency decreases to 30 Hz, the current increases dramatically, as seen in Figure 28.

**FIGURE 28:** **TOTAL INVERTER CURRENT CONSUMPTION AT 0:1 V/f**

Because of the inductive load, a decrease in frequency lowers its impedance and causes a large increase in current. The limiting factor in the inverter board is the ripple current in the DC capacitors. Please see Table 19 for more information regarding design limitations.

The mechanical output power of the motor is also compared to that of the PSC run method, as seen in Figure 29.

FIGURE 29: **OUTPUT POWER AT 60 Hz**
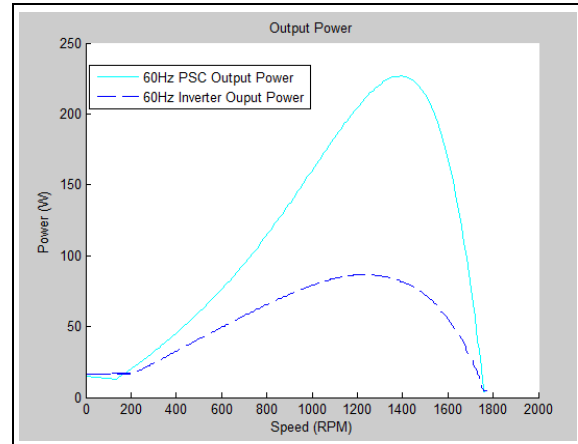
The inverter has reduced output power capability. The designer should consider this when the inverter is to be placed in a direct substitution of a PSC application. This is primarily caused by the 30% V_{DC} utilization loss, as shown in Figure 6, as well as by harmonic losses and a low power factor. The output power does not increase much at maximum voltage in lower frequencies.

FIGURE 30: **OUTPUT POWER OF INVERTER**
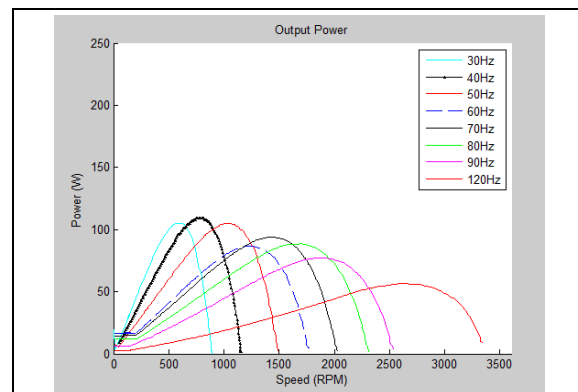
Note that Figure 29 and Figure 30 use the same Y axis scale.

Summary

1. Overall Efficiency

The PSC run motor is approximately 10% more efficient, as seen in Equation 6. Losses in the inverter run motor can be attributed to the inverter itself and to the switching elements.

2. Power Factor

The PSC method has an almost unity power factor. The inverter board has a reduced power factor and, therefore, it wastes energy in the power grid. Power factor correction may be added to correct this.

3. Output Power

The PSC run motor has much greater output power at around 230W. The motor is a 1/4 HP, so the expected output power is at least 746/4 = 186W. The inverter board yields slightly under 100W. A drop-in replacement scenario should note this key difference. Although the inverter board can lift a heavier gate at faster speeds, the rate of work is considerably less when driving a split-phase motor with no run capacitor.

INVERTER BOARD

Introduction

The inverter board is constructed as an application-specific platform rather than a general purpose demo board. However, it does provide numerous inputs and outputs (I/O) for the user to interact with and modify. The inverter is strictly engineered to drive a single-phase or three-phase AC induction motor. Most of the parts in the bill of materials in **Appendix A: "Bill of Materials"** have been optimized to drive up to a ½ HP motor, whilst some parts, such as the IGBTs, are higher-end and give the designer more flexibility. After reading this section, the reader should understand the limitations of this inverter, as well as its optimizations in software and hardware.

Overview

Figure 31 shows a top-level overview of the overall system.

FIGURE 31:   SYSTEM OVERVIEW
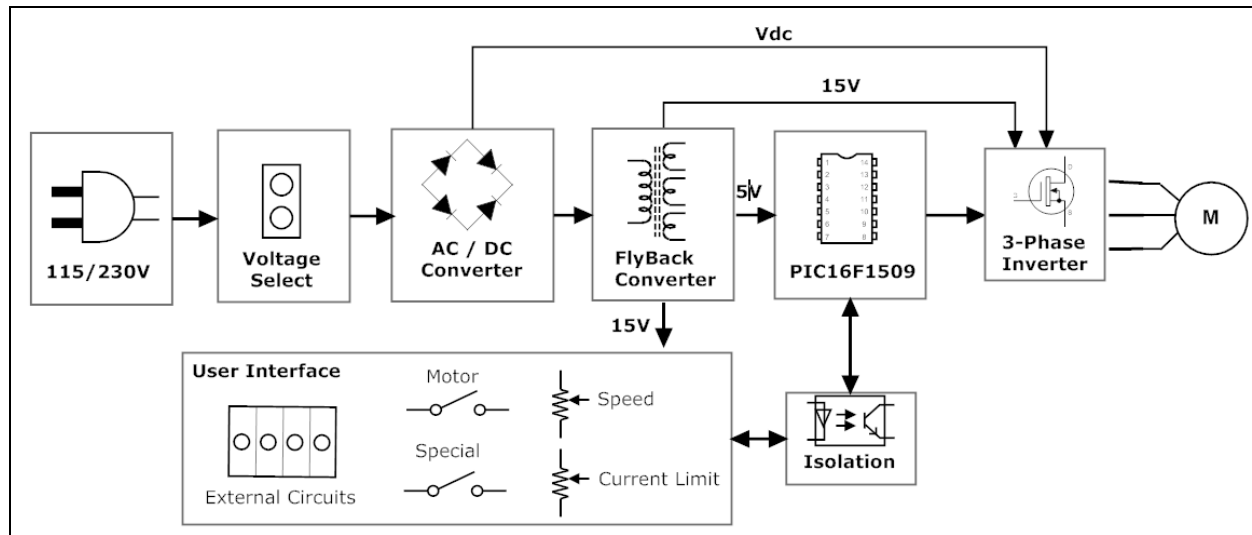
The input voltage is first doubled if the jumper is inserted for 115V systems with a 220V motor.

> **Note:** Please see Table 20 for configuration settings. Incorrect jumper settings may cause the board to malfunction.

It is then rectified to a DC bus voltage. This DC voltage is then used in a flyback converter to generate two 15V DC regulated supplies. Each 15V power source is then down-converted to 5V from a linear regulator. The user interface uses optocouplers as isolation for safety issues. The printed circuit board has a clear indicator in silkscreen that designates what is safe to touch. PIC16F1509 has six PWM lines driving the three-phase inverter, which are connected to the motor. The modulated sine wave is created from the rectified

DC bus voltage. As the motor spins, the microcontroller monitors the speed and current limit settings, as well as the feedback current, to ensure overcurrent protection.

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Quick Start

The board's operation should first be validated as seen in **Section "Acceptance Test"**. After validation passes, the user can use the inverter board as described in Table 7.

TABLE 7: QUICK-START INPUTS AND OUTPUTS

Element	Purpose
S0	Start/Stop Motor
S1	Start/Stop Motor
POT0	Controls the speed and direction of the motor
POT1	Current Limiter of the motor
W1	Jumper to select between 115V or 230V input. Jumper should be inserted for 220V motors on 115V input (see Table 20)
P3	Input Single-Phase AC Mains Voltage
P4	Motor Output Terminals
P2	Auxiliary Output
P5	Auxiliary Inputs
F1	Motor Fuse
P1	In Circuit Serial Programming™ (ICSP™) Header

The following basic steps show how to get an induction motor spinning:

1. Note the size and type of motor to be attached to the board.
2. Program either the single-phase hex file or the three-phase hex file onto the board by using the header at P1. 5V must be supplied by the PICkit™ 2 during programming.
3. Remove the PICkit 2 from the ICSP™ header.
4. Place a fuse into the fuse holder at F1 that can pass the rated motor current.
5. Connect the three motor wires to terminal P4. Refer to Figure 3 for single-phase motor connections.
6. Connect your input voltage of either 115V or 230V to terminal P3. Refer to Table 20 for jumper settings.
7. The PWR green LED should now be on.
8. Place the wiper in POT1 to its halfway point.
9. Place the wiper in POT0 fully clockwise.
10. Press either S0 and S1 to start the motor.
11. The motor should slowly ramp up to its maximum speed at 120 Hz modulation.
12. Slowly turn POT0 counterclockwise to slow the motor to a halt. Turning it fully counterclockwise will turn the motor in the opposite direction.
13. Adjusting POT1 will trigger an automatic shutdown if the trip point threshold is met. The trip LED will illuminate when this happens.
14. The user must press S0 or S1 to start up the motor again after an emergency shutdown event.

Feature Summary

The inverter board was designed with flexibility in mind; therefore, some of the features listed in Table 8 can be omitted to optimize performance with cost.

TABLE 8: DESIGN SPECIFICATIONS

Design Specifications	
Motor Type	Single-phase and three-phase 1/3HP AC induction motors
AC Input Voltage	115 $\rightarrow$ 230V, single-phase
Control Method	V/f, with soft-start/stop, current feedback; Space Vector Modulation (SVM) for three-phase motors
Motor Rated Voltage	120V or 220V
PWM Switching Frequency	3.9 kHz $\rightarrow$ 15 kHz
Motor Frequency Range	15 Hz $\rightarrow$ 120 Hz
Heat Sink	No
Isolation	Yes
Overvoltage Protection	Yes
Undervoltage Protection	Yes
User Configurable Speed	Yes
User Configurable Current Trip	Yes

Most of the inputs/ outputs (I/O) are used by the default code since an optimal microcontroller was selected. There is still plenty of space for the developer to use custom modifications. The I^{2}C™ lines are also free to use for any added slave devices. Table 9 shows how much code space and how many modules are used to meet the design specifications.

TABLE 9: RESOURCES USED

Resource Type	Used	Available to User
Program Memory	2833 (words)	5359 (words – 65.4%)
Data Memory	289	223 (bytes – 43.6%)
CPU Processing (F$_{PWM}$ = 7.8 kHz, F$_{OSC}$ = 16 MHz)	70%	30%
PWM Channels	3	1
CLC Modules	3	1
ADC Channels	2	6
Timers	2	3
Comparators	0	2
I^{2}C™/SPI	0	1
External Interrupts	4	6
I/O Lines	16	1
EEPROM	0	0

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Microcontroller

Figure 32 shows the pin designators and their purposes, with the exception of programming functionality.

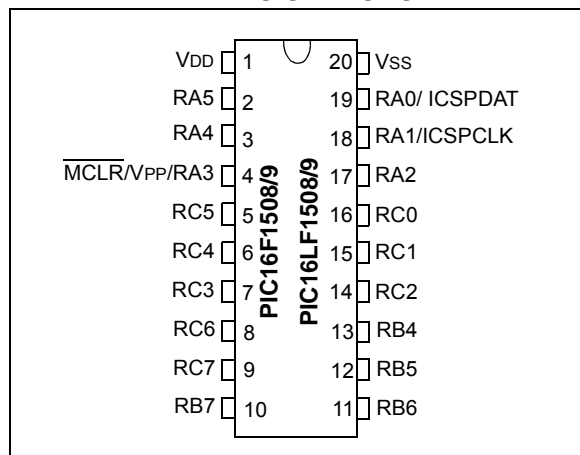**FIGURE 32:**   **PIC16(L)F1508/9 PIN DESIGNATORS**

Table 10 shows a complete listing of pin functionality.

TABLE 10:   PIN FUNCTIONALITY

Pin	Input/ Output	Digital/ Analog/ Both	Purpose	Notes
RA5	OUT	Digital	PWR LED	
RA4	IN	Both	Push Buttons	2 x Shared In
RA3	IN	Digital	Dedicated Input	Dedicated In
RC5	OUT	Digital	Motor PWM	
RC4	OUT	Digital	Dedicated Output	
RC3	OUT	Digital	Motor	
RC6	IN	Analog	Current Sense	
RC7	OUT	Digital	Motor LED	
RB7	OUT	Digital	Motor	
RB6	OUT	Digital	I^{2}C™ Clock	Unused
RB5	IN	Both	Auxiliary Inputs	3 x Shared In
RB4	Both	Digital	I^{2}C™ Data	Unused
RC2	IN	Analog	Motor Speed	
RC1	OUT	Digital	Motor PWM	
RC0	OUT	Digital	Motor PWM	
RA2	OUT	Digital	Motor PWM	
RA1	Unused	Analog	Unused	Unused
RA0	IN	Analog	Motor Current Limit	

User Interface

The inverter board has numerous inputs and outputs. Some of these are multiplexed onto a single pin in order to accommodate a larger number of I/O. All of the user interface requirements are isolated via two four-channel optocouplers and a one-channel optocoupler. Table 11 lists the user interface inputs and outputs.

TABLE 11: USER INTERFACE INPUTS AND OUTPUTS

Isolated User Interface		
Qty.	Multiplexed	Purpose
2	Y	Push Buttons
1	N	Speed Control
1	N	Current Limit Control
1	N	Dedicated Digital Output
1	N	Dedicated Digital Input
3	Y	Auxiliary Digital inputs

The board provides two switch buttons and two potentiometers. There are also headers that provide connections for external I/O, such as garage door trip sensors. The two potentiometers have their transistor in the optocoupler circuitry biased in its amplifying region. The output is therefore approximately linear, since the optocoupler LED does not have a linear I-V curve. Large currents in the 30 mA range are consumed for each POT.

The digital push buttons and auxiliary inputs are biased to cause an interrupt-on-change (IOC) when either of them is used. This alleviates the CPU from constantly checking the voltage level on the pins. Whenever an IOC is detected, an ADC reading must be taken in order to determine which input caused the interrupt.

FIGURE 33: MULTIPLEXED PUSH BUTTONS CIRCUIT
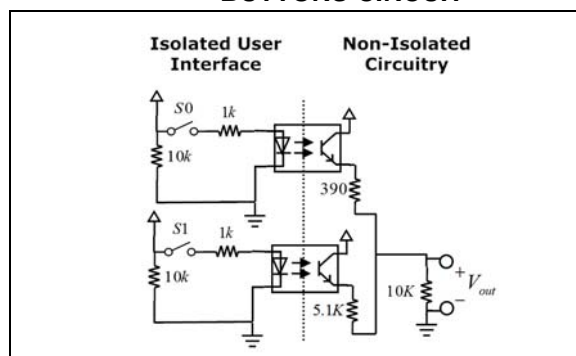
Figure 33 shows an example circuit that has two multiplexed signals (S0 and S1) on a single input pin to the microcontroller. The 390 and 5.1K resistors form a voltage divider with the 10K resistor. When switch 0 (SW0) is pressed, it is considered active and the output voltage reads close to 5V, as seen in Equation 7.

EQUATION 7: S0 IS ACTIVE

$$V_{OUT} = 5V \bullet \frac{10K}{(10K + 390)} = 4.8V$$

When switch 1 (SW1) is pressed, the output voltage is 3.3V, as seen in Equation 8.

EQUATION 8: S1 IS ACTIVE

$$V_{OUT} = 5V \bullet \frac{10K}{(10K + 5.1K)} = 3.3V$$

The large voltage difference between these two voltages enables the ADC to distinguish between which switch is active. The electrical specifications for the PIC16F1509 and all of the enhanced mid-range devices specify a maximum input low voltage of 0.8V and a minimum high voltage of 2.0V, as seen in the design parameter number 41 (D041) under the Electrical Specifications chapter (see DS40001609). This means that for IOC to work correctly, an input should be higher than 2V when active and lower than 1V when inactive.

SOFTWARE

The code has numerous comments surrounding all functions and important properties to help the reader easily modify the operation. Some of the code used in this application is taken from Microchip AN984 (see Reference 7). The modulation routines in particular are based around this reference. Parts of the text will be replicated throughout this chapter for convenience. Table 12 lists the important developer information of the software.

TABLE 12: BUILD INFORMATION

Property	Description
Language	ANSI C89 C
Compiler	XC8 V1.22 PRO
IDE	MPLABX v1.80

Summary

Table 13 lists the states in the main state machine inside of main.c. The main loop consists of a simple state machine.

TABLE 13:   STATE-MACHINE STATES

State	Description
INIT	The inverter is initialized and the motor is stopped.
IDLE	Motor is off while polling for button presses.
MOTOR_STARTING	Enter here while performing soft-start.
MOTOR_ON	After the motor has been soft-started, the program enters this state. This state will continuously poll all auxiliary inputs, switches and speed/current potentiometers.
MOTOR_STOPPING	Enter here when program has been instructed to stop the motor. Soft-stop is performed gradually here until the motor has been stopped completely, or it brakes.

Upon entry, the motor starts in its IDLE state where the microcontroller initializes pins and stops the motor. If SW1 is pressed, the motor starts and transitions into its MOTOR_STARTING state. The motor starts using the soft-start method where the frequency and voltage are adjusted in a linear fashion in order to slowly bring the motor up to operating speed.

The state machine then transitions into the MOTOR_ON state when soft-start is complete. The motor speed and current trip points are continuously polled in the main loop. If an overcurrent scenario is detected, the MOTOR_STOPPING state is entered and the motor is stopped and status LEDs blinked in a pattern to designate that a Fault condition has occurred. If SW1 is pressed, the motor is stopped by either braking or by soft-stop. The state machine returns to state IDLE.

A structure diagram of the important files and their methods and properties are shown in Figure 34.

FIGURE 34:   STRUCTURE DIAGRAM
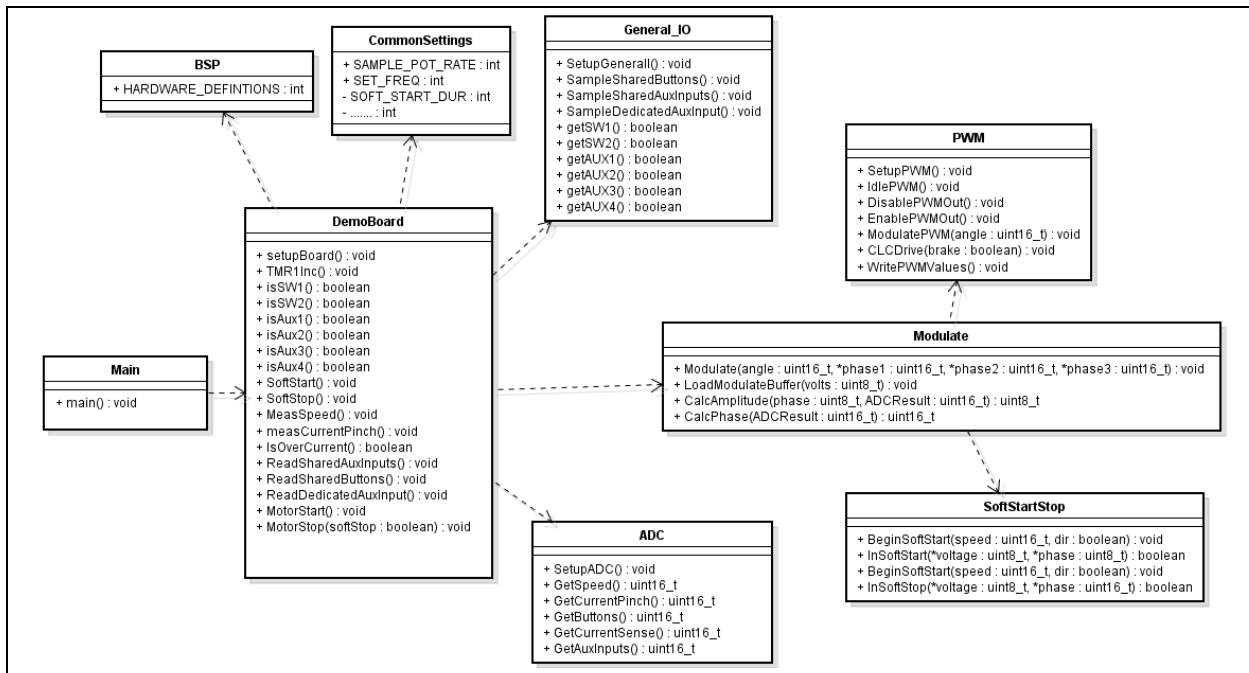
main.c

It consists of state machine and global ISR flags. The PWM routine is given priority. No blocking code other than this routine is within the ISR. All other interrupts are serviced outside of the interrupt vector to give precedence to the modulation routines.

demo_board.c

This file acts as a facade to the main.c file. A facade is a software design pattern that provides a unified interface to multiple complex subsystems. In essence, it alleviates the complex logic from the main.c file. The majority of the methods called from the main loop to this file are abstracted away to other files.

bsp.h

The board specific header file contains all hardware definitions. This is referenced in most other files.

common.h

This file is the only file that should be modified to fine-tune the general settings, such as switching frequency, timer intervals, trip points, etc. Any other modifications to the system may require adjustments elsewhere. This file is included in every source file.

generio_io.c

This file handles all user interface components, such as buttons, switches, auxiliary I/O and potentiometers. The ADC files are also referenced here for multiplexing purposes.

modulate.c

It calculates the adjusted sine wave when given a Volt and phase parameter and it saves all 64 values in a pre-filled buffer. The soft-start routine pace of increment is limited by how fast this routine can complete, since the voltage and phase parameter often change. When the motor is steadily running, the buffer will not change often, since the two inputs are typically constant.

pwm.c

This does the actual loading of the PWM registers from the phase structure. The CLC is configured here to generate three complementary PWMs.

soft_start_stop.c

This file contains math-intensive operation methods. Before doing a soft-start/stop, the speed POT position is measured. This position divided by the number of steps for any given sequence, SOFT_START_DURA-TION, will be added every SOFT_START_DELAY. Figure 35 shows a flowchart for the while(1) loop in main.c.

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**FIGURE 35:   MAIN ROUTINE FLOW DIAGRAM**

© 2014 Microchip Technology Inc.
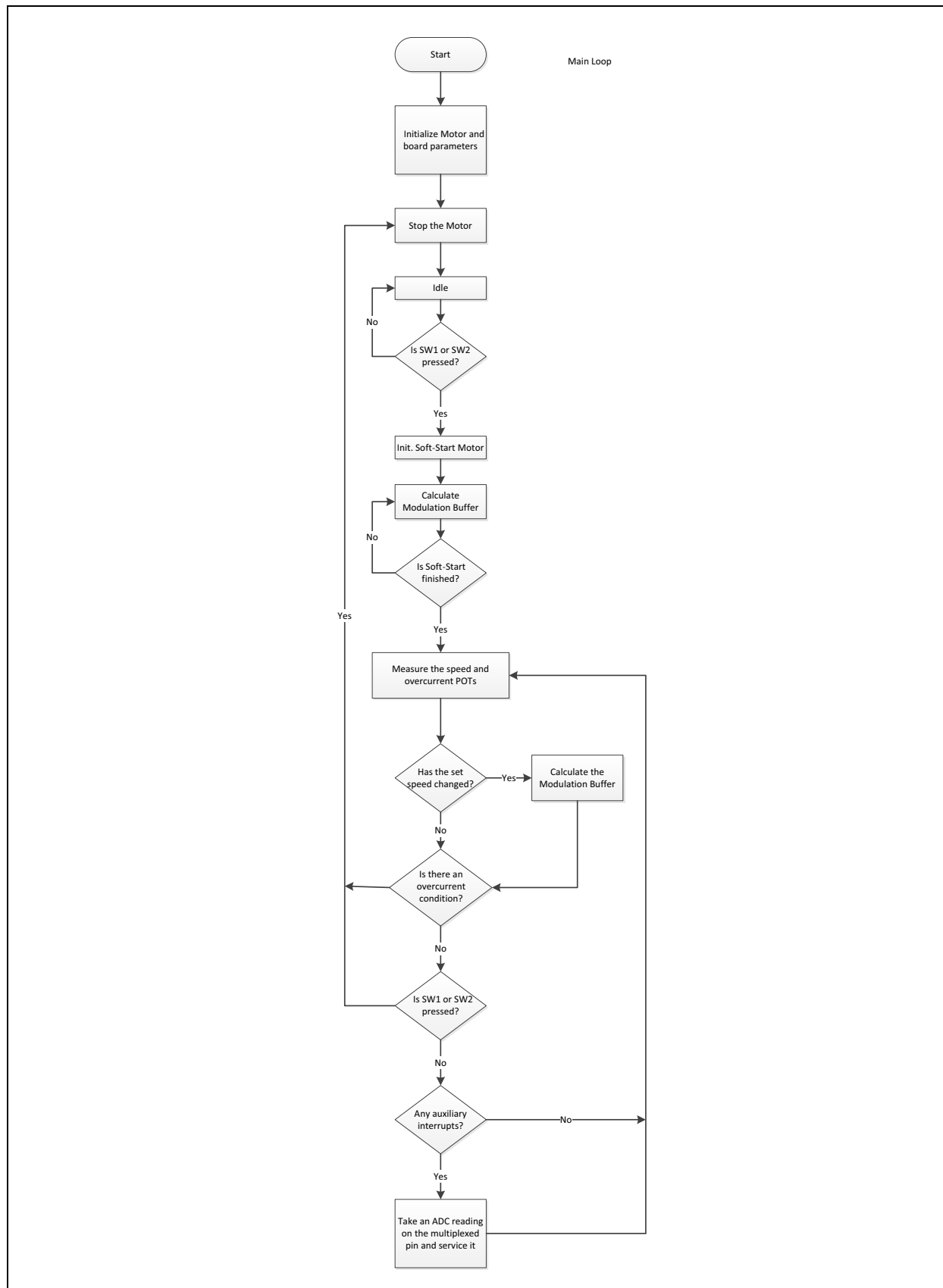
With the exception of the time-keeping TMR1 overflow and modulation TMR2 overflow, all other ISR flags are serviced outside of the ISR vector. Figure 36 shows a flowchart of the ISR.

FIGURE 36: **ISR FLOWCHART**
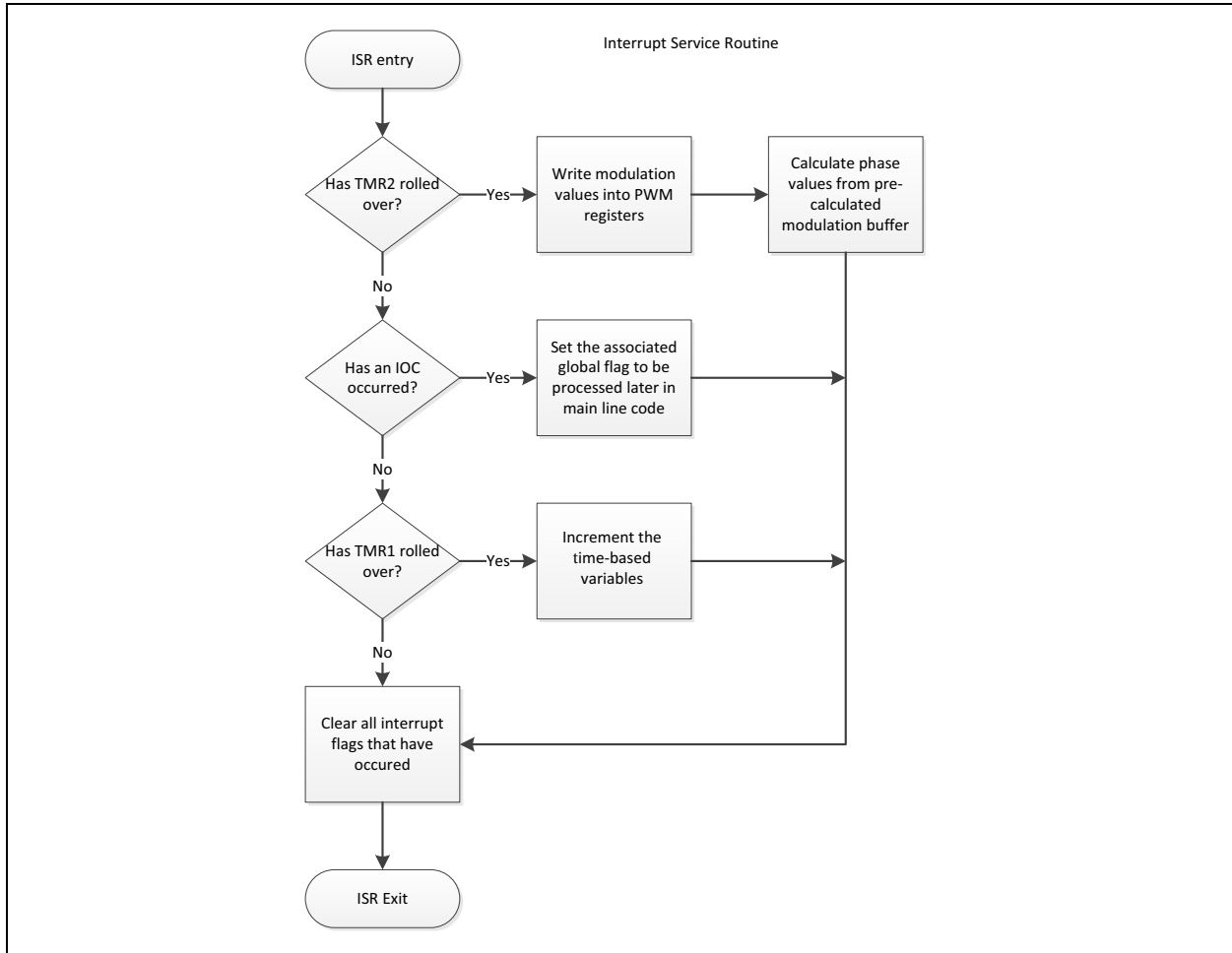
The primary focus of the software is driving the three-phase inverter. The PWM and CLC hardware modules are utilized to complete this task. The majority of the software processing power is spent calculating the next PWM values and polling for user inputs, such as trip sensors and speed control. Figure 37 shows the general overview of the driving stage.

FIGURE 37: **SOFTWARE PWM DIAGRAM**
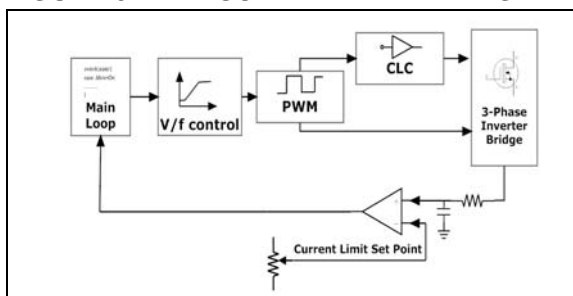
Software Modulation

This section describes the modulation technique and its associated routines. These sections are the primary focus of the code.

MODULATION VARIABLES

A global structure, `mod`, is kept in RAM, which specifies the pulse width and offset of the PWM modules. Table 14 lists the three modulation structure members.

TABLE 14: MODULATION STRUCTURE MEMBERS

Member	Size	Purpose
phase	uint16_t	Present Phase Offset
deltaPhase	uint16_t	Phase Increment (Frequency)
voltage	uint8_t	Pulse Width (Voltage)

Phase

This value represents a full 360 degrees of angle, where 0x0000 = 0 degrees and 0xFFFF = 359.9 degrees.

deltaPhase

The `deltaPhase` value is adjusted accordingly to the `voltage` parameter. The voltage parameter is derived directly from the ADC reading of the speed POT. This variable is added to the frequency variable, `phase` value, every TMR2 overflow to get an adjusted modulation angle value.

Voltage

The voltage is modified by the ADC reading of POT0. It has a maximum value of 127 and a minimum value of 0. A value of 127 indicates that the PWM signal will have a duty cycle close to 100% when the sine wave is at its peak value. The voltage sampling rate can be modified in the `SAMPLE_POT_RATE` as seen in Table 14. The 64-byte sine wave table is then multiplied by this amplitude factor and added to 50% duty cycle. These scaled values are saved in a 64-byte array in RAM for quick access in the ISR. It should be noted that the V/f processing is only executed when the motor voltage is changed such as in soft-start.

Checks are in place to ensure that the voltage does not go below the pre-configured minimum value.

Generating the Sinusoidal Waveform

The sinusoidal PWM (SPWM) look-up table method is the easiest way to generate a sine wave. The calculations are done in an Excel sheet and then pasted into the static program memory on the microcontroller. The sine values are read from the table at predefined intervals to create a specific modulation frequency.

A Sine Pointer variable, `deltaPhase`, can be adjusted to scale how fast or slow the modulation moves through the look-up table. `deltaPhase` is then added to the `Phase` variable. If the variable `Phase` is kept increasing/decreasing at a constant rate, then the resulting sine wave modulation frequency will be kept constant. This variable can therefore be left to overflow.

Each time a new value is needed from the look-up table, the upper eight bits of the pointer variable are used as the pointer index. The lower eight bits of the pointer variable can be viewed as fractional bits.

To set the modulation frequency with a PWM frequency of 16 kHz, please see Equation 9.

EQUATION 9:

$$F_{RESOLUTION} = \frac{F_{PWM}}{2^{16}} = 0.244 \frac{HZ}{BIT}$$

Essentially, every increment of `deltaPhase` will adjust the modulation frequency by 0.244 Hz. Changing the PWM frequency will result in a different resolution.

To find the Table Pointer delta value that will provide a 60 Hz modulation frequency, use the formula in Equation 10.

EQUATION 10:

$$DELTAPHASE = \frac{F_{MOD}}{0.244} = \frac{60}{0.244} = 246 BITS$$

If value 246 is added to `delta` at each PWM interrupt, then the resultant modulation will be 60 Hz.

To generate multiple-phase outputs, simply add a constant offset value to the Phase Pointer. The source of this method is AN984 listed under Reference 7. For more information, please refer to pages 5, 6 and 9 of the above-mentioned application note.

V/f PROFILE

The two subroutines, `CalcAmplitude` and `CalcPhase`, calculate the two parameters that generate the values for the PWM signals. `CalcPhase` takes the scaled POT0 reading as an input and returns a value between 0 and 512.

The amplitude calculation checks the minimum and ideal frequencies to ensure that the voltage is held within the correct zone (constant voltage past ideal frequency).

PWM MODULATION

This is called every TMR2 overflow. The `angle` parameter has only its upper six bits used as the pointer index into the pre-calculated and scaled sine table in RAM. Only the upper six bits are used since the total size of the table is 64 bytes ($2^6 = 64$). The returned value from the sine table is assigned to the first PWM pointer variable. The same routine is followed to get the second and third phase outputs after the angle parameter is incremented according to the predefined phase offset. A value of 0x4000 between modulation outputs will generate a 90-degree phase shift.

`LoadModulateBuffer` is called to calculate the scaled PWM values. It takes a single parameter, `volts`, with which to multiply the default sine table. It then adds `HALF_DUTY`.

DRIVING FREQUENCY

An article published by WEG, a major motor manufacturer (see Reference 7), points out that there is no simple interrelation between the insulation life and the switching frequency. General experiences have shown the following pattern:

- If f_S < 5 kHz the probability of insulation failure occurrence is directly proportional to the switching frequency.
- If f_S > 5 kHz the probability of insulation failure occurrence is quadratically proportional to the switching frequency.

High-switching frequencies can also cause bearing damages. However, a switching frequency increase results in the motor voltage FFT improvement and, therefore, it tends to improve the motor thermal performance besides reducing noise.

System Configuration Settings

The inverter board code contains numerous settings that are easily changeable by modifying a single `#define`. The entire configuration is within a `common.h` file. Other `#defines`, which depend on the inputs from the `common.h` file, are located within the project. These `#defines` should be modified with extreme care.

GENERAL

Table 15 lists the settings associated with the general operation.

TABLE 15: GENERAL CONFIGURATION SETTINGS

Name	Description
`DEBUG`	If this is commented out, it will disable CLC4 from outputting PWM4 on Aux4 (P2). This is used primarily as one of the tests in the acceptance document (see **Section "Acceptance Test"**).
`TMR1_TIMER_SET`	TMR1 is used as a generic timer and multiple items rely on this as a heartbeat.
`SAMPLE_POT_RATE`	The frequency at which Speed and Current Pinch POTs are sampled as a function of `TMR1_TIMER_SET` (ms)
`_XTAL_FREQ`	The microcontroller operational frequency. Changing this will require vast changes to the calculations of the PWM frequency and other dependences.

MODULATION

The modulation routine has a few associated system settings (see Table 16). The soft-start/stop routine lengths and delays, as well as the modulation frequency, can be modified here. The default code already contains three predefined frequencies of:

1. 3.9 kHz
2. 7.8 kHz
3. 15.6 kHz

Different frequencies can be configured, but changes to the modulation routines and sine wave values will need to be made. The frequencies above were selectively chosen so as to minimize the overhead in calculations by using powers of 2 (shifts only) for multiplication and division.

TABLE 16:   MODULATION-RELATED SETTINGS

| Name	Description
FREQ_XXXX	Predefined PWM switching frequencies
SOFT_START_DURATION	Amount of times Timer1 rolls over before incrementing soft-start V/f profile
SOFT_START_DELAY	TMR1_TIMER_SET (ms) per each count
SOFT_STOP_DURATION	Amount of times Timer1 rolls over before decrementing soft-stop V/f profile
SOFT_START_DELAY	TMR1_TIMER_SET (ms) per each count
MODULATION_MAX	The maximum modulation frequency
MODULATION_IDEAL	The ideal modulation frequency for the motor
MODULATION_MIN	The minimum modulation frequency

USER INPUT/ OUTPUTS

The ADC is used on multiplexed pins to distinguish which I/O has been activated. An isolated user input is labeled as being active when the input on the isolated side is driven high at typically 5V. Table 17 shows the relative user configurable #defines.

TABLE 17:   SETTINGS FOR THE USER I/O

Name	Description
BOARD_V	Microcontroller voltage on V$_{DD}$
S1_V	The expected voltage on pin RA4 when S1 is pressed
S2_V	The expected voltage on pin RA4 when S2 is pressed
AUX2_V	The expected voltage on pin RB5 when Aux2 is active
AUX3_V	The expected voltage on pin RB5 when Aux3 is active
AUX4_V	The expected voltage on pin RB5 when Aux4 is active
ADC_STOP_POS	The upper limit for Idle operation
ADC_STOP_NEG	The lower limit for Idle operation

The speed reading returns a signed integer that is then compared to the `ADC_STOP_NEG/POS` `#defines`. Rotating the POT counter clockwise from the fully clockwise position will decrease the motor from full speed to idle and then full speed in reverse, as seen in Figure 38.

FIGURE 38: **ADC TO MOTOR READINGS**

Note: The ADC value is printed above.
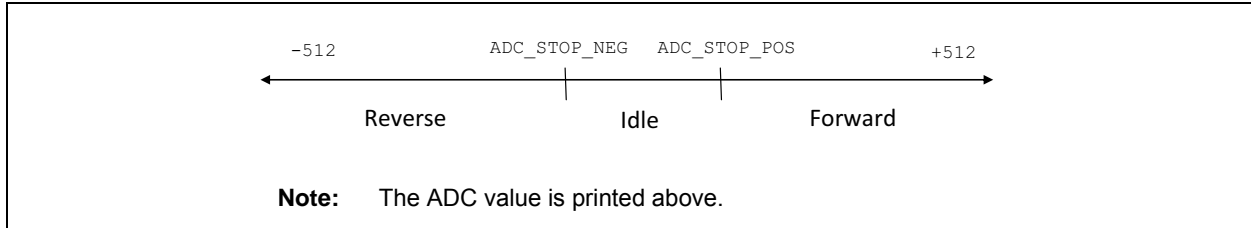
The biasing of S1 and S2, as well as all of the auxiliary inputs, is designed to allow the greatest voltage differential between the shared active elements. This is achieved by carefully-selected resistors in a voltage divider network.

MOTOR FEEDBACK

The only feedback to the system is the small RC feedback network that is connected in between the motor and GND. This network provides a small voltage reading that is proportional to the current in the motor, as seen in Table 18.

TABLE 18: **MOTOR FEEDBACK SETTINGS**

Name	Description
CURRENT_TRIP_V	In Volts, when generating a Fault condition. Use this setting if the user wishes to reallocate the current trip POT to some other usage.
CURRENT_TRIP_AVG	Number of ADC measurements to average for the current trip. Make this a multiple of 2 for code speed.

HARDWARE DESIGN CONSIDERATIONS

This inverter is constructed to run up to a ½ HP motor; however, components that can exceed those levels are used. A low-cost solution is one that selects the minimum amount of parts with as little performance overhead as possible to run the application. Table 19 highlights some components that limit the flexibility of the inverter board.

TABLE 19: HARDWARE COMPONENT LIMITATIONS

Component	Limit Description	Approximate Limit Value	Derivation
Diode Bridge	Maximum Input Current	10A	Data sheet
DC Ripple Capacitors	Maximum Input Current	2.5 A$_{rms}$ through each capacitor	Data sheet
Flyback Converter	Input Voltage	250VAC	Data sheet
Flyback Transformer	Secondary Output Current	200 mA	Data sheet
Feedback Resistor	Motor Current	4.5A	$(I_R{}^2 \bullet 0.22\Omega) < 5W$
Various Terminal Connectors	Input/Output Voltage on each terminal	Variable	Data sheet
IGBTs	Switching Frequency and Motor Current	F_{switch} < 25 kHz and I_{drain} < 5A without a heat sink	See **Section "Motor Feedback (Current Sense)"**

 * The derivation source comes from the component's respective data sheet.

Figure 39 shows a thermal image of the inverter when running the motor at 220V 60 Hz with no load.

**FIGURE 39: INVERTER BOARD DRIVING MOTOR WITH NO LOAD**
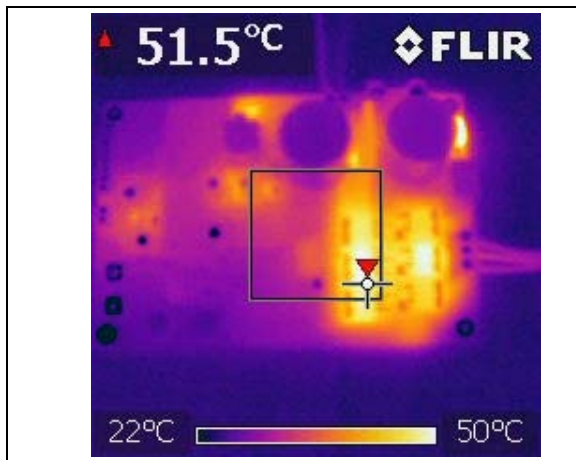
Notice how the IGBTs and NTC are the hottest components on the board. The IGBTs are rated up to 150°C and the NTC up to 200°C. The other parts that are warm include the linear regulators, flyback converter and diode bridge. This design ensures that under full load, none of the components will be performing out of specification. The designer may wish to optimize some of the parts for his/her application, such as the IGBTs and diode bridge. This section will explore design limitations and optimizations that can be made.

DC Bus Voltage Capacitors

The default DC bus capacitors have a capacitance of 560 uF and a ripple current rating of 0.235A. Ripple current is the amount of RMS AC current flowing through the capacitor's plates as seen in Figure 40.

FIGURE 40:   RIPPLE CURRENT
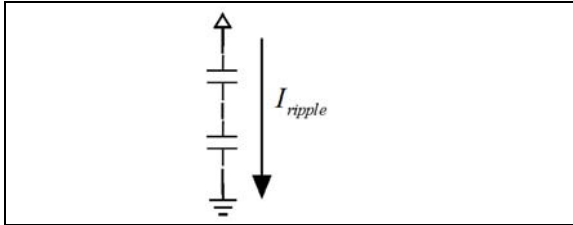
The ripple current rating is a direct correlation with its Equivalent Series Resistance (ESR). Current passing through the capacitor will cause a voltage drop across its internal resistance which then causes the capacitor to heat up. Too much heat dissipation will prematurely damage the capacitor.

The amount of ripple voltage on each of the capacitors should be carefully monitored when the motor size is increased and the V/f profile is modified.

The ripple current is related to the ripple voltage. Given the input frequency, capacitor bank size and load current, Equation 11 outlines the magnitude of ripple voltage.

EQUATION 11:   VOLTAGE RIPPLE ACROSS CAPACITORS

$$I_{CAP} = C\frac{DV}{DT} = C\frac{\Delta V}{\Delta T} = C \bullet \Delta V \bullet F$$

Rearranging:

$$\Delta V = \frac{I_{LOAD}}{F \bullet C}$$

Symbol	Description	Units
ΔV	Ripple Voltage which is equal to the difference between $V_{AC_{max}} - V_{AC_{min}}$	V
I_{load}	Total load current as seen by the capacitor	A
f	Input frequency as seen by the capacitor	Hz
C	Total capacitance of the bank	F

A ¼ HP motor that was used throughout the tests will consume approximately 1.4A at 60 Hz as seen in Figure 26. The input frequency, or charge/discharge rate, for the capacitors and total capacitance bank varies depending on whether the voltage doubler jumper is inserted.

The voltage doubler consists of two capacitors that can optionally be configured by a single jumper (W1) to double the input voltage, as seen in Figure 41.
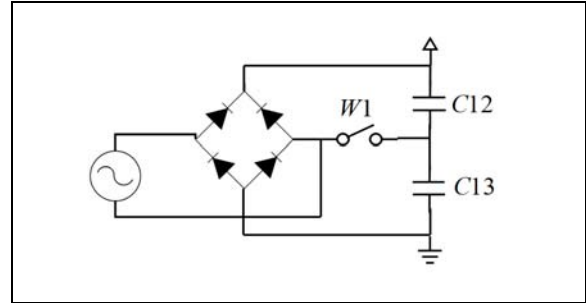
FIGURE 41:   VOLTAGE DOUBLER

Table 20 shows when to connect to the jumper.

TABLE 20:   JUMPER SETTINGS

Jumper In (W1)	Input Voltage (V)	Motor Rated Voltage (V)
✓	115	230
✗	115	115
✗	230	230

WITHOUT VOLTAGE DOUBLER

When the voltage doubler is not engaged, the effective capacitance of the two large capacitors in series creates a total capacitance as shown in Equation 12.

EQUATION 12:   TOTAL CAPACITANCE WITHOUT DOUBLER

$$\frac{1}{C_{TOT}} = \frac{1}{C_{12}} + \frac{1}{C_{13}}$$

Note: C12 and C13 are the two large capacitors. Please refer to **Appendix B: "Complete Inverter Board Schematic"** for the schematic.

Since the capacitors are of the same value, the total capacitance is (560 uF/2), or 280 uF.

The output frequency from the full-wave rectifier is double the input frequency, as shown in Figure 23.

Equation 13 shows the voltage across both ends of the capacitors combined will equal the peak voltage of the input.

EQUATION 13:   VOLTAGE ACROSS BOTH CAPACITORS IN SERIES

$$V_{DC} = (V_{12} + V_{13}) = (V_{IN} \bullet \sqrt{2})$$

AN1660

Given the above calculations at 220V input, the ripple voltage is as shown in Equation 14.

EQUATION 14: RIPPLE VOLTAGE

$$\Delta V = \frac{1.4A}{120Hz \bullet 280\mu F} \approx 42V\ (13.5\%)$$

WITH VOLTAGE DOUBLER

If the W1 jumper is inserted, then the voltage across both ends of the capacitors will be as seen in Equation 15.

EQUATION 15: CAPACITOR VOLTAGE WITH VOLTAGE DOUBLER

$$V_{DC} = (V_{12} - V_{13})$$

$$= (V_{IN} \bullet \sqrt{2}) - (-(V_{IN} \bullet \sqrt{2}))$$

$$= (V_{IN} \bullet \sqrt{2}) \bullet 2$$

The DC voltage is effectively double that of the input voltage, but at a cost of increased ripple voltage and current.

> **Note:** There is no protection for placing input voltage higher than120 and placing W1 on the jumper. If this happens, the capacitors are at risk of irreversible damage since their voltage rating will be exceeded.

Each capacitor will only see one half of the sine wave cycle. Therefore, the ripple voltage for the voltage doubler scenario will have a frequency that reflects the input frequency on a 1:1 ratio (see Equation 16).

EQUATION 16: RIPPLE VOLTAGE WITH VOLTAGE DOUBLER

Assuming identical capacitors at 120V input:

$$\Delta V = \frac{1.4}{60 \bullet 280\mu F} \approx 84V\ (27\%)$$

With the voltage doubler, the ripple voltage is doubled.

> **Note:** Keep in mind of the typical 20% tolerance value on the capacitance when doing calculations.

Driver Stage

The driving stage uses an International Rectifier three-phase gate driver for high-voltage applications. It has integrated dead time and drives six external, N type IGBTs/FETs in bootstrap operation. The inverter was designed and tested with IGBTs; however, FETs can easily be placed on the same footprint. The default IGBTs are rated up to 10A on their drain with a very low V_{ce} saturation.

The design consideration between selecting FETs or IGBTs is usually a function of switching frequency and current. Table 21 compares a design decision between placing an FET or an IGBT down.

TABLE 21: IGBT AND FET COMPARISON

Type	Part #	I_{max}	$R_{DS(ON)}$/ $V_{CE(ON)}$
IGBT	IRG4BC20KD-SPbF	16A	NA/ 2.27V
FET	IRFIB7N50APBF	6.6A	0.520 Ohm/ NA

IGBTs are inherently more expensive, so the design for a ½ HP motor should use FETs with a low R_{ds_on}.

From the IR IGBT's data sheet, Thermal Resistance (Junction to ambient) is 40°C/W for a TO-263 package, and T_J is limited to 150°C. The IGBT in this particular D2Pak can, therefore, dissipate up to 3.15W before it requires a heat sink for an ambient temperature of 25°C.

Hence, without a heat sink, the IGBT can only pass 1.38A to the emitter through its collector $(3.15W = 2.27 \bullet 1.38)$. The FET can handle 2.46A without needing a heat sink $3.15W = 0.520 \bullet 2.46^2)$. It is critical that the designer should note that the data sheet specification of maximum current does not imply that the device can handle that amount without a heat sink or in a warm ambient environment. Figure 42 shows that the losses for an IGBT scale linearly, whilst the FET scales at a power of two.

FIGURE 42: IGBT VERSUS FET IN CURRENT AND POWER CONSUMPTION
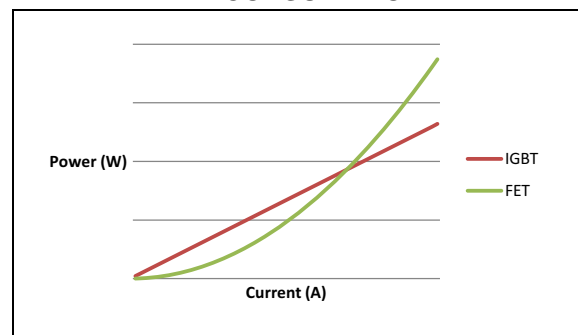
Lower current applications will benefit from using FETs, while higher current applications with larger motors should use IGBTs.

Figure 43, from an IR application note, AN980 (see Reference 5), shows that the cost decision point for choosing IGBTs over FETs coincides with a motor of 1HP.

FIGURE 43: **PER UNIT DOLLARS VERSUS MOTOR SIZING**
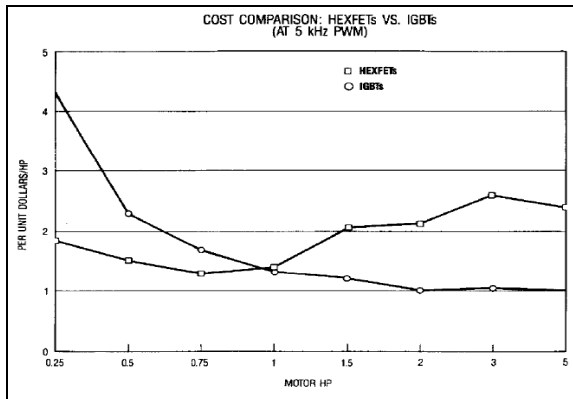
Motors that are less than 1 HP in size should use FETs, according to the International Rectifier application note. The designer should determine the trade offs of the two elements.

Essentially, there is a trade off between the cost of the silicon and the aluminum needed for the heat sink. Cheaper FETs/IGBTs need more dissipation caused by higher losses versus expensive parts that need no external dissipation. As pointed out in the IR application note, "Often it is more cost-effective to choose silicon rather than aluminum."

SMD thermal dissipation is an alternative route to using a heat sink, albeit at a cost of heating up other components on the inverter.

Besides the switching elements, another design issue is the selection of gate resistors and bootstrap diodes and capacitors.

The gate resistors were selected at 22 Ohms in order to lower the dV/dt which reduces the negative voltage spike caused by fast transitions. The designer should be careful not to make this transition too slow in proportion to the switching frequency; if this condition is not met, the element will never switch full on or off. Please see Reference 11 from Avago Technologies for information in selecting the correct gate resistor.

1.0 uf 25V capacitors were chosen as the bootstrap capacitors. The voltage across the capacitor must not be lower than Vg_on in between switching times; the gate will fail to fire if this condition is not respected. The diodes must be fast-acting in order to preserve the charge on the capacitors.

Do not replace the fast-acting with general purpose diodes. The diodes must be fast-acting in order to charge the bootstrap capacitors efficiently without losing leakage current from fast-switching cycles.

Inrush Current

An inrush limiter is used to limit the initial current that is drawn from the AC supply from tripping a household circuit breaker. This negative temperature coefficient (NTC) thermistor suppresses the high inrush current surges that occur when charging the low-impedance DC smoothing capacitors of C12 and C13. Once the capacitors are energized, the resistance of the NTC will decrease rapidly to a very low value.

A few items of data are needed to scale an inrush current limiter:

1. Load capacitance of device to be protected
2. Steady-state current (I_{MAX}) and maximum ambient temperature
3. Required reduction of inrush current to determine R25 of NTC inrush current limiters
4. Maximum supply voltage

For further details, please see Epcos application note listed under Reference 9.

The Cantherm MF72 data sheet, *Power NTS Thermistor* of the selected NTC, MF72-22D11, already provides these data points. Important characteristics of the NTC are placed in Table 22.

TABLE 22: NTC KEY PARAMETERS

Part Number	R25	Stead State Current	Approx. R of Max. Current	Dissipation Coefficient	Load Capacitance	
					@ 120VAC	@ 240VAC
MF72-22D11	22Ω	2AΩ	0.563Ω	15 mW/ °C	880 uF	220uF

According to the MF72-22D11 data sheet, the maximum load capacitance at 220V is determined to be 880 uF, which is higher than the inverter board's load capacitors of 560 uF. Its ambient resistance at room temperature is 2 Ohms, which should limit the current to a 220V/22 = 10A. The designer should also check the diode bridge to ensure that the peak current is within the ratings. The steady-state current must be taken into consideration when driving larger motors or when modifying the V/f curve. Recall that large voltages at low frequencies will cause very large currents in the stator. If the motor is kept in this mode, the designer risks damaging the NTC.

The load capacitance is doubled from 280 uF (560/2) to 560 uF and the current is also doubled when using the voltage doubler at 120V. Please take this into consideration when choosing an NTC.

The manufacturer's maximum current derating curve must be looked at if the inverter board is to be placed into an application where the ambient temperature is not 25°Celsius. The resistance of the NTC is inversely proportional to the rise of the ambient temperature.

The NTC must be given sufficient time to bring itself back to room temperature after it has been consuming current, before the inverter board is switched back on. If the NTC has not properly reset its temperature to a safe point and the inverter is switched on too soon, the designer risks irreparable damage of the fuse. Since large capacitors are being charged in this application, the large time constant associated with these capacitors will usually cause the NTC to release thermal energy faster than the capacitors becoming fully discharged. The bleed-off resistors of R8 and R13 should be adjusted to tweak the RC time constant.

Lastly, it is not uncommon for the NTC to heat up during normal operation. According to Table 22, the temperature for the NTC is as seen in Equation 17.

EQUATION 17: NTC TEMPERATURE

$$P_{NTC} = I^2R = 2^2A \bullet 0.563\Omega = 2.252W$$

$$T_{NTC} = \frac{P_{NTC}}{C_{OEF} F_{NTC}} = \frac{2.252}{0.015} \approx 150°C$$

It is evident that the placement of the inrush limiter is critical; therefore, it should be placed so as not to touch or heat up any adjacent components.

Flyback Converter

The inverter uses a flyback converter to convert the rectified DC voltage into two separate and isolated power supplies. The LNK625 provides the regulation instead of the microcontroller. A lower cost solution should dedicate a PWM module plus other monitoring software to control the flyback power supply.

The feedback resistors, R16 and R17, are carefully chosen to bias the output voltage to around 14-15V. It is critical that these resistors are 1%. The 15V is used to supply power to the IGBT/FET driver chip. Its gate voltage is directly proportional to its supply voltage. The designer should verify that this gate voltage is sufficient to drive the switching elements.

The fast-acting diodes used in the input filter and output rectification should not be exchanged for general purpose ones. The output rectification capacitors are chosen to provide ample current to the low voltage electronics; however, their capacitance value may still be lowered and hence optimized after careful considerations of the load. Place these capacitors as close to the integrated circuits as possible.

The layout of the PCB should closely match that of the LNK625 data sheet. For more design considerations, please see the LNK623-626 LinkSwitch©-CV Family data sheet (Reference 14).

Linear Regulators

The MCP1703A provides the step-down voltage from 16V to 5V on both secondaries of the transformer. The MCP1703A is operating at its maximum input voltage of 16V. If the flyback regulation causes voltage spikes higher than the allowed maximum input voltage, designers may want to look at the MCP16301 switching regular for improved efficiency or at the MCP1804 as a replacement.

Another consideration is the package of the regulators. The optocouplers consume large currents, higher than 20 mA, while being biased in their active region. The two potentiometers and the dedicated isolated output have their associated optocoupler circuits biased this way. It is important that the designer correctly identifies the package for heat dissipation. The maximum power dissipation is shown in Equation 18.

EQUATION 18: PACKAGE SIZING

$$P_{MAX} = \frac{(T_{J-MAX} - T_A)}{\theta_{JA}}$$

Where:

Symbol	Description	Units
P_{max}	Maximum Power Dissipation	W
T_{J-max}	Maximum Junction Temperature	°C
T_A	Ambient Temperature	°C
θ_{JA}	Thermal Resistance from Junction to Ambient	°C/W

Solving for the MCP1703A in SOT-89 package:

$$P_{MAX} = \frac{(150°C - 25°C)}{153°C/W} = 817 \text{MW}$$

Therefore, to safely use the MCP1703A in an SOT-89 package, the maximum power must be limited to 817 mW. Power consumption higher than 817 mW would require reducing the ambient temperature or adding a heat sink.

The total allotted current for the SOT-89 regulator is as shown in Equation 19.

EQUATION 19: POWER CONSUMPTION IN SOT-89 PACKAGE

$$I_{MAX} = \frac{P_{MAX}}{(V_{IN} - V_{OUT})}$$

$$= \frac{817 \text{MW}}{(16V - 5V)} = 74 \text{MA}$$

If the above calculations were performed for an MCP1703A in an SOT223 package, the maximum current drawn from the 5V line can be up to 183 mA without having to add extra thermal dissipation. The current design uses the SOT223 package for flexibility.

Motor Feedback (Current Sense)

The current feedback system is a very simple and low-cost solution. In some motor applications, a high-side current reading circuit is employed due to its accuracy and non-invasiveness. The solution provided in Figure 44 presents a low-side current sense that consists of only a few discrete components.

FIGURE 44: MOTOR RC FEEDBACK FILTER

Symbol	Description
I_{motor}	Total current through the motor's stator.
$R_{Feedback}$	A power resistor. The value must be carefully calculated in proportion to the expected locked-rotor current of the motor.
D	A fast-acting diode that is used to eliminate negative transients.
R_{Filter} and C_{Filter}	Used to eliminate high-frequency noise by creating a low-pass filter. These are placed as close to the microcontroller pin as possible.

The feedback resistor must be carefully selected. The voltage drop across the resistor is used to determine if an overcurrent scenario has been entered. The resolution of the ADC is 4.88 mV per step (5V / 1023). A resistor with high-resistance will induce a larger voltage drop and hence a larger ADC resolution between the signal and the noise floor. However, the energy consumed by the resistor will be higher compared to a resistor of a lower value.
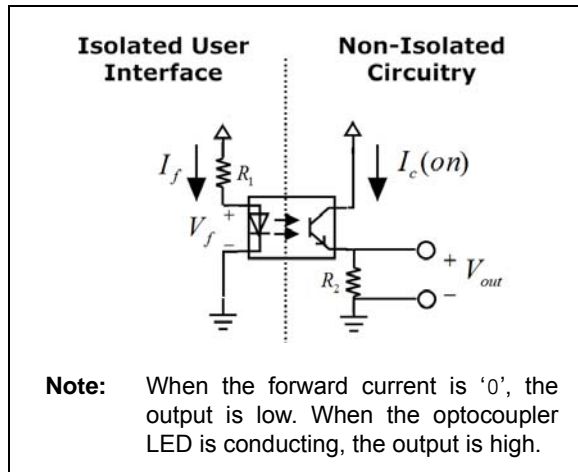
The inverter has a 5W 0.22 Ohm resistor as the feedback. With an expected maximum current of 4A, the total voltage drop across it will be 0.88V. The total power consumed is therefore 3.52W, which is below 5W. The designer has to avoid this voltage drop from rising high enough so as to cause the IGBTs to switch on. The minimum IGBT gate-to-emitter (V_{GS}) voltage for this inverter board is 10V. The IGBT driver supplies a driving voltage of 15V. If the voltage across the resistor rises to 5V, the designer risks the inverter malfunctioning and damaging the driver.

The designer may also want to include a hardware Fault-protection circuit to handle fast Fault type events.

Optocouplers

The isolation barrier between the microcontroller and the outside world is complete with optocouplers. The optocoupler can be biased in two modes of operation: Linear mode and Digital Logic mode. These two modes can easily be modified by the designer by changing only one resistor (R_2), as shown in Figure 45.

FIGURE 45: **THE COMMON-COLLECTOR CIRCUIT**

Note: When the forward current is '0', the output is low. When the optocoupler LED is conducting, the output is high.

The optocouplers are kept within their linear region for the potentiometer circuits so that every incremental swipe of the potentiometer can produce an amplified copied signal on the output. While the output is not a direct 1:1 relationship, it is a sufficient and cost-effective method in creating an isolated analog signal. A downside of this method is that large currents will be consumed by the optocoupler.

Digital Logic mode is used on the inverter board for all isolated digital I/O with the exception of the dedicated output. When the optocoupler LED is active, the output is high as indicated in Figure 45. Rise and fall times while operating in Digital Logic mode are much slower since the load resistor R_2 is increased. When R_2 is decreased, the rise (T_R) and fall times (T_F) decrease dramatically. This is why the dedicated output and input circuitries are biased in their active region.

The schematic seen in **Appendix B: "Complete Inverter Board Schematic"** shows that the multiplexed pins appear similar to Figure 45, with the exception of a voltage divider with a 10K pull-down resistor. The load resistors are carefully chosen to create offsets that are equidistant from one another so that the ADC on the microcontroller can easily differentiate between signals.

Note: The designer must take into consideration the 20-30 mA current consumption of the optocoupler LED circuitry and its effect on the maximum current capability of the linear regulator (MCP1703A).

LIMITATIONS

This low-cost board has two limitations that the designer should be aware of:

1. No power factor correction on the input stage
2. Decreased horsepower output compared to that of a traditional PSC setup with an identical motor

RECOMMENDATIONS

These tests that were conducted can be further expanded. The following lists some endeavors that should enhance this document further:

1. Characterize more than one split-phase motor
2. Test a three-phase motor
3. Rerun the existing tests at 115V input with the voltage doubler
4. Connect another measuring element to the three output PWM terminals. Between this measurement and the input power measurement, the designer can calculate the efficiency of the inverter and driving circuitry as separate entities
5. Power Factor Correction on the input stage of the inverter
6. Implement Space Vector PWM (SVPWM) instead of Sine PWM (SPWM) to compare total harmonic distortion and V_{DC} utilization (please see Reference 15).

ACCEPTANCE TEST

Introduction

This section provides a quantitative test bench and quick-start operation for the high-voltage and low-voltage properties of the inverter board, which are analyzed in this document.

This inverter was originally designed to drive a single-phase AC induction motor; however, it can be used to create any arbitrary phase difference between the three outputs.

General Safety Notice

This board consumes high currents and voltages with no isolation from the supplied input power. It is advised that extreme caution is taken while performing any measurements. The following are some general notes:

- If a scope is used, make sure that it is an isolated model since the GNDs are floating with respect to earth ground.
- It is safer to test the inverter using a DC power supply with current limiting for the initial test. 60VDC can be used to verify the low-voltage operation.
- The isolated section of the inverter has a separate return path from the non-isolated one.
- It is recommended to use an isolating transformer with the appropriate VA rating while testing and developing.

Power Supply

All measurements below (see Table 23 and Table 24) are in Volts DC (VDC) unless otherwise specified

TABLE 23: POWER SUPPLY MEASUREMENTS[1]

Description	Abbreviation	TP+	TP-	Min.	Max.	Expected	Actual[4]
Input Voltage[2]	V_{IN}	V_{IN}(P3)	V_{IN}(P3)	20VAC/ 30VDC	230VAC/ 325VDC	—	
5V Microcontroller Voltage	PIC_5V	6	PIC_GND	4.52	5.53	5.03	
15V Microcontroller Secondary Voltage	PIC_15V	7	PIC_GND	12.96	15.84	14.4	
15V Isolated Secondary Voltage	ISO_15V	8	ISO_GND	12.24	14.97	13.61	
5V Isolated Voltage	ISO_5V	9	ISO_GND	4.51	5.51	5.01	
V_{BUS} (representative of V_{IN})[3]	V_{BUS}	10	PIC_GND	$(V_{IN}*\sqrt{2})-1.4$	$(V_{IN}*\sqrt{2})+1.4$	$V_{IN}*\sqrt{2}$	
$V_{BOOTSTRAP}$ LNK	V_{BOOT}	11	PIC_GND	5.38	6.58	5.98	

Note 1: TP = Test Point

2: An applied AC voltage that is above 115V must not have the jumper placed in circuit. Doing so will cause the inverter to malfunction. There is no protection against this user error.

3: If V_{IN} is an AC signal, V_{BUS} = V_{IN} * $\sqrt{2}$. If V_{IN} is a DC signal, V_{BUS} = V_{IN} – 1.

4: To be filled in by the user.

Input / Output

TABLE 24: I/O MEASUREMENTS[1]

Setup	Abbreviation	TP+	TP-	Min.	Max.	Expected	Actual[2]	Notes
Isolated Auxiliary Inputs								
5V connected between C and D respectively	Aux0	1	PIC_GND	2.98	3.64	3.31		
5V connected between E and F respectively	Aux1	1	PIC_GND	2.25	2.75	2.50		
5V connected between G and H respectively	Aux2	1	PIC_GND	4.32	PIC_5V	4.80		
Isolated Auxiliary Outputs								
5V connected between A and B	Aux3	2	PIC_GND	4.48	PIC_5V	4.98		
Isolated Inverter Inputs (Switches)								
Press button S0	SW0	3	PIC_GND	4.29	PIC_5V	4.77		
Press button S1	SW1	3	PIC_GND	2.95	3.61	3.28		
Isolated Inverter Inputs (POTs)								
POT R36 turned fully clockwise	POT0	4	PIC_GND	0.00	0.00	0.00		
POT R36 at middle position	POT0	4	PIC_GND	0.99	1.24	1.10		
POT R36 turned fully counter-clockwise	POT0	4	PIC_GND	4.31	PIC_5V	4.79		
POT R37 turned fully clockwise	POT1	5	PIC_GND	0.00	0.00	0.00		
POT R37 at middle position	POT1	5	PIC_GND	1.07	1.39	1.19		
POT R37 turned fully counter-clockwise	POT1	5	PIC_GND	4.32	PIC_5V	4.80		

Note 1: TP = Test Point

2: To be filled in by the user.

Figure 46 shows how to test the isolated auxiliary inputs by applying a +5V DC supply on terminals A and B, C and D, E and F, G and H.   Please connect to the correct polarities on the terminals.

FIGURE 46: ISOLATED AUXILIARY INPUT TEST
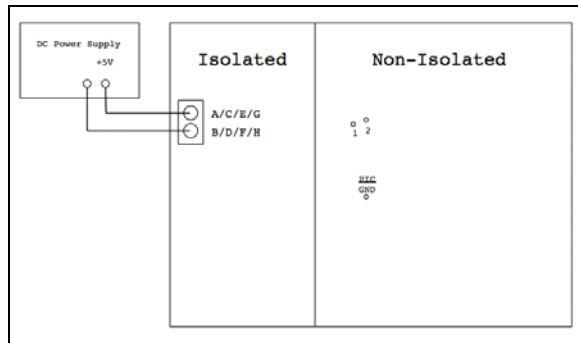
The resistors for the multiplexed resources were chosen to provide the largest voltage differential between states.

Isolated Output

Figure 4 shows the required setup to test the isolated digital output (Aux4). Terminal I should be connected to a +5V power source. Terminal J should be connected to ground through a 180Ω resistor. Isolated and non-isolated grounds need to be bridged and connected with the ground of the probe. Probe 1 should measure at test point J. Probe 2 should measure at test point 12. Figure 47 shows the expected output.

FIGURE 47:   ISOLATED OUTPUT TEST
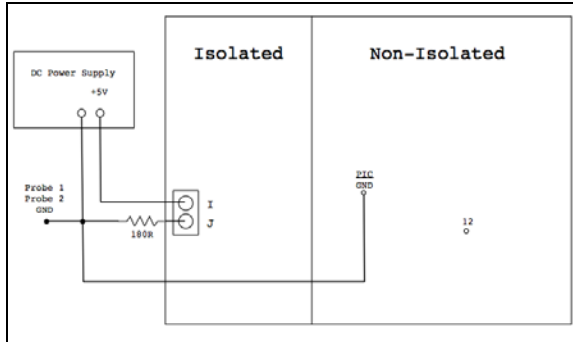
Upon power-up, the default code will present a 7.8 kHz PWM waveform on the digital output channel as seen in Figure 48.

FIGURE 48:   EXAMPLE OF PWM EXPECTED OUTPUT

Note 1: Scope 1 is the PWM output on P2.

2: Scope 2 is the PWM output on RC4.
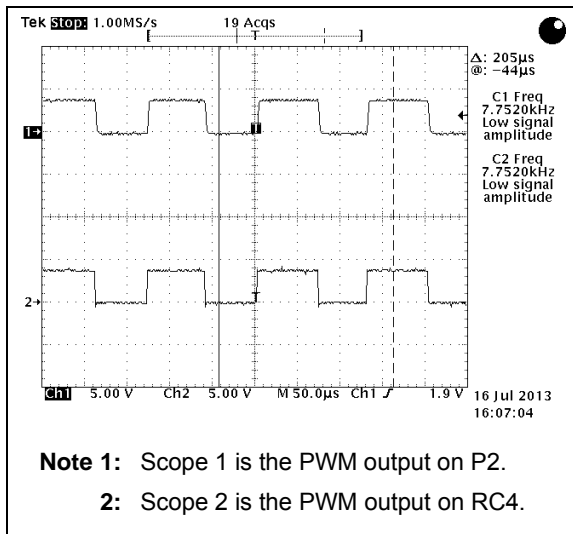
Inverter Board Operation

After the above measurements are validated, motor drive operation should be tested.

The software is capable of producing any output phase difference. The most common offsets are typically 90 or 120 degrees. The default firmware produces a 90-degree offset for driving single-phase AC induction motors. A three-phase ACIM may also be used with the inverter after the configuration file is modified by using the `ONE_TWENTY_DEG   #define` inside the `modulate.c` file.

Test procedure:

1. Connect the motors input wires to the U, V and W outputs of the inverter.
2. Apply 230V AC power to V$_{IN}$.
3. The PWR LED should light up, indicating power to the inverter.
4. Turn POT0 at the midpoint position, facing down. This is the *stop* position of the motor.
5. Press SW1 to start the motor.
6. Slowly turn POT0 fully clockwise. The motor should spin clockwise. The motor light on the inverter should blink at an increased rate, proportional to the speed of the motor.
7. Turn POT0 fully counter-clockwise. After the center-stop position (six o'clock) has been passed, the motor should start spinning in the opposite direction. The motor light should again blink accordingly.
8. Press SW1 again to turn the motor off.
9. POT1 adjusts the current pinch feature of the inverter. Press SW1 to start the board again. Lower the current limit and when the limit has been reached, the motor will shut off.
10. Apply 115V power to V$_{IN}$ with a jumper placed on W1. Placing a jumper on W1 will double the voltage going to the inverter.

Note: The voltage with the jumper W1 in-circuit must not exceed 115V, as there is no protection against this user error.

AN1660

APPENDIX A: BILL OF MATERIALS

TABLE 25: BILL OF MATERIALS

Quantity	Designator	Description	Part Number
2	C1, C7	CAP CER 470PF 100V 5% NP0 0805	CL21C471JCCNNNC
4	C2, C9, C24, C25	CAP ALUM 10UF 25V 20% RADIAL	UVZ1E100MDD
2	C3, C8	CAP ALUM 47UF 35V 20% RADIAL	ESH476M035AE3AA
4	C4, C5, C10, C18	Cap, Ceramic, 0.1uF, 50V X7R	08055C104MAT2A
10	C6, C14, C15, C16, C17, C19, C20, C21, C22, C23	CAP CER 1UF 50V 10% X5R 080	UMK212BJ105KG-T
1	C11	CAP CER 820PF 2KV 10% X7R 1210	1210GC821KAT1A
2	C12, C13	CAP ALUM 560UF 250V 20% SNAP	EET-UQ2E561CA
6	D1, D2, D4, D7, D8, D9	DIODE ULTRA FAST 600V 1A SMA	STTH1L06A
1	D3	Full Wave Diode Bridge	GBU10M-BP
1	D5	LED, SMD, YEL, 0805 package	APT2012YC
2	D6, D10	LED, SMD, GRN, 0805 package	APT2012CGCK
1	D11	DIODE_FAST_SOD123	CFRMT107-HF
1	F1	FUSEHOLDER 22.5MM PCB 5X20MM BK	0031.8201
1	NTC1	Current Limiter Inrush 100R 20%	NTC1MF72-010D11
1	P1	Header, PICkit™ 2, 1X6 0.1sp	TSW-106-07-F-S
1	P2	TERMINAL BLOCK 3.5MM 2POS PCB	ED555/2DS
1	P3	2PHDR-200	OSTTC022162
1	P4	TERMINAL BLOCK 5.08MM 3POS PCB	EDZ350/3
1	P5	Term_BLK_8pos 3.5mm	ED555/8DS
2	POT0, POT1	3386P-1-202TLF	3386P-1-202TLF
6	Q1, Q2, Q3, Q4, Q5, Q6	Insulated Gate Bipolar Transistor with Ultrafast Soft Recovery Diode	RG4BC20KDSTRLP
2	R1	RES 0.0 OHM 1/8W 0805 SMD	RMCF0805ZT0R00
5	R2, R3, R45, R47, R48, R49	RES 510 OHM 1/8W 0805 SMD	RRMCF0805FT510R
2	R4, R7	RES 47 OHM 1/8W 0805 SMD	RMCF0805FT47R0
2	R5, R6	RES 820 OHM 1/8W 0805 SMD	RMCF0805FT820R
2	R8, R13	RES 100K OHM 1/4W 5% CARBON FILM	CF14JT100K
1	R9	RES 270K OHM 1/4W 5% CARBON FILM	RNMF14FTC270K
2	R10, R11	RES 4.7K OHM 1/8W 1% 0805 SMD	RMCF0805FT4K70
1	R12	ES 330 OHM 1/4W 5% CARBON FILM	CF14JT330R
5	R14,R15, R23, R24, R36	RES 1K OHM 1/8W 1% 0805 SMD	RMCF0805FT1K00
1	R16	ES 30.9K OHM 1/8W 1% 0805 SMD	RMCF0805FT30K9
1	R17	RES 6.04K OHM 1/8W 1% 0805 SMD	RNCP0805FTD6K04
5	R18, R20, R25, R40, R42	RES 10K OHM 1/8W 1% 0805 SMD	RMCF0805FT10K0
1	R19	RES 160K OHM 1/8W 1% 0805 SMD	RMCF0805FT160K
6	R21, R27, R34, R35, R38, R43	RES 390 OHM 1/8W 0805 SMD	RMCF0805FT390R
2	R22, R44	RES 5.1K OHM 1/8W 1% 0805 SMD	RMCF0805FT5K10
1	R26	RES 0.22 OHM 5W 5% RADIAL	2-1623788-5
6	R28, R29, R30, R31, R32, R33	RES 20 OHM 1/8W 1% 0805 SMD	RMCF0805FT20R0

TABLE 25:   BILL OF MATERIALS (CONTINUED)

Quantity	Designator	Description	Part Number
1	R46	RES 6.8K OHM 1/8W 1% 0805 SMD	RMCF0805FT6K80
2	S0, S1	SWITCH TACTILE SPST-NO 0.05A 24V	B3S-1002
1	T1	Four-Winding Transformer (Non-Ideal)	750813144
1	U1	4-Pin Phototransistor Optocoupler	ACPL-217-500E
1	U2	8-Bit Micro	PIC16F1509-E/SO
1	U3	AC/DC Converter	LNK625DG
2	U4, U6	SOLATOR 3KVRMS 4CH TRANS 16SOI	ACPL-247-500E
1	U5	IC MOSFET DRIVER	IRS2334SPbF
2	VR1, VR2	Pos 5V 250mA, LDO Regulator SOT89	MCP1703T-5002E/MB
1	VR3	Resistor	MOV-07D471K

APPENDIX B: COMPLETE INVERTER BOARD SCHEMATIC

Non-Isolated

Isolated
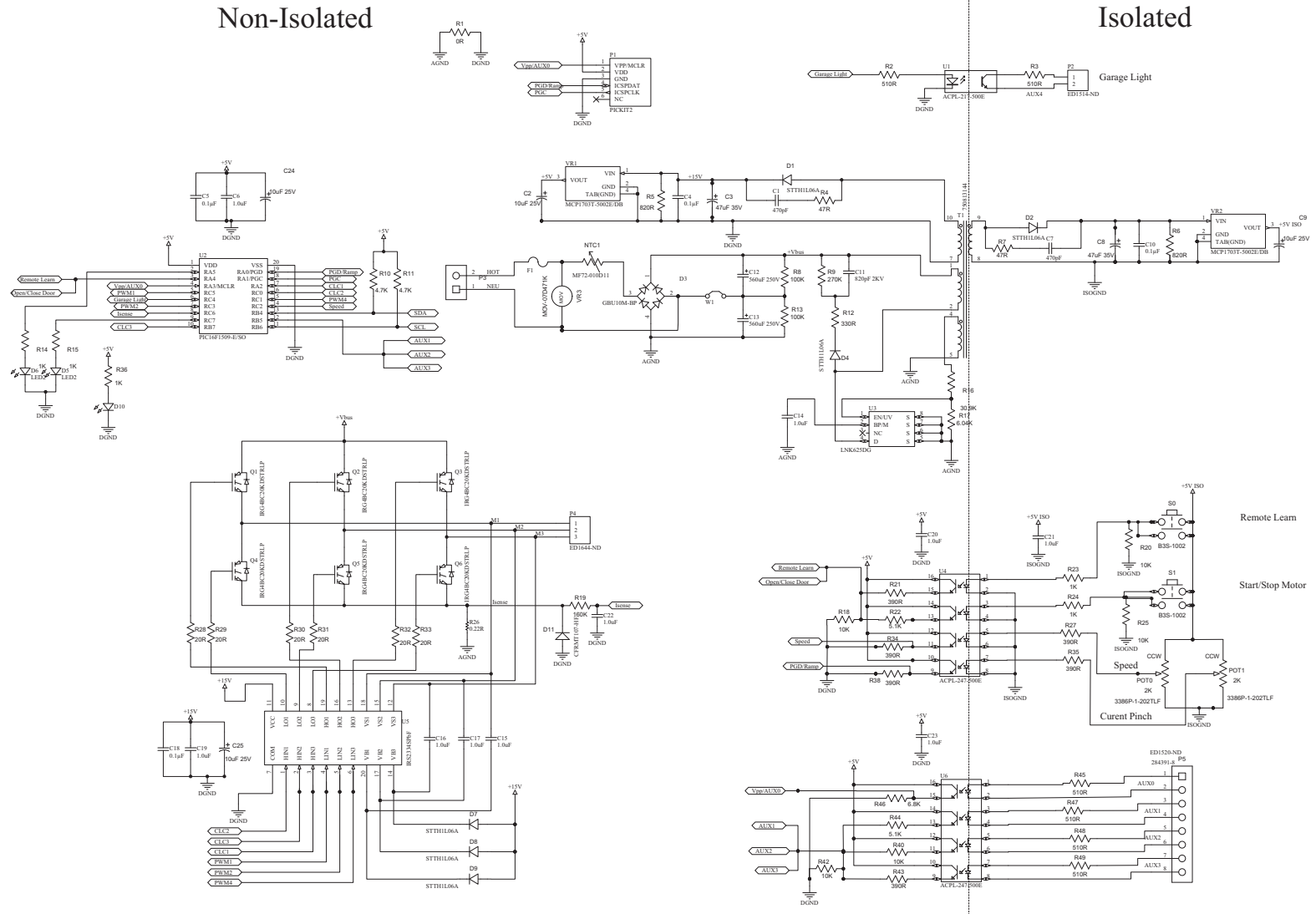
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