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ZIGBEE BASED WIRELESS ADJUSTABLE SPEED DRIVE SYSTEM

A Thesis

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by

Prajakta S. Moghe

In Partial Fulfillment of the

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ABSTRACT

Moghe, Prajakta S. M.S.E.C.E., Purdue University, May 2016. Zigbee Based Wireless Adjustable Speed Drive System. Major Professor: Euzeli dos Santos Jr.

This thesis proposes a remotely controlled motor drive system which is able to supply a regulated voltage for both DC and AC motors. The proposed system integrates two different technologies, each of which belongs to the field of wireless communications and semiconductor power electronics. The introduction highlights the literature review and technical contributions in these two electrical engineering fields. The pulse width modulated control algorithm for speed control is discussed in detail. Incorporating the zigbee wireless technology into the motor drive system, for the speed control of an AC and a DC motor, by implementing digital pulse width modulation technique is the aim of this thesis. The main characteristics of the proposed system are: 1) its universal feature since it can feed either DC or AC motor without changing the hardware, 2) remotely controlled, which allows the end-user to control the motor speed safely from a remote distance, 3) flexibility in installation of the motor drives in areas that are not easily accessible by end-users, and 4) uninterrupted speed control for distance of up to few 100 feet.

1. INTRODUCTION AND STATE OF ART

1.1 Introduction

Wireless communication is a self-defined term which means communication or transfer of data without the use of wires. As the cellular technology advances bringing the world closer, wireless communication is gaining in popularity. The ability to transmit data over larger distances with cheap devices and extreme low power losses has truly brought up the radio technology [1]. Some of the challenges that make this technology interesting include, but are not limited to, simultaneous use of multiple channels of communication [2–5], designing of a robust network [6–8], concatenating the use of several systems in one single network [9–16] to name a few.

Depending on the distance that a data can be wirelessly transferred, wireless communication is mainly divided into three categories: short range, medium range and long range wireless communication [17–21]. The short range wireless communication implies use of devices to transfer data over a short distance which ranges from few centimeters to several meters. As the wireless technologies evolved, different standards have been set up which enable the use of short range wireless technology in both industrial and domestic market. Bluetooth, Infra-red and the Zigbee are three of the many standards/devices that are comparable in terms of their application in short range wireless communication [22–25]. When it comes to general application, the short range wireless technology can be used in home-entertainment remote control [26], robot-control system, cordless microphones, remote control of environmental control system [27,28], energy monitoring, home security, monitoring residential wind turbines, etc. are to name a few. Fig. 1.1, 1.2 and 1.3 display a few applications of the Bluetooth, Infra-red and the Zigbee respectively.

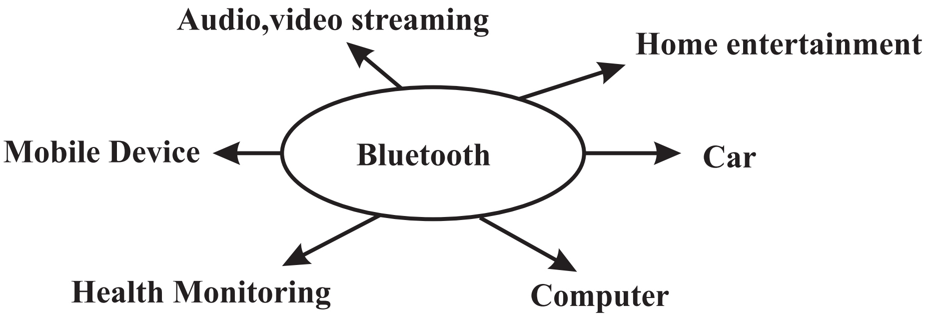


Fig. 1.1. Applications of a Bluetooth.

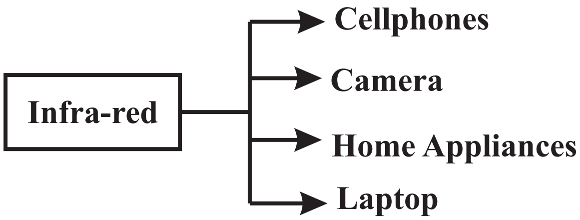


Fig. 1.2. Applications of an Infra-red.

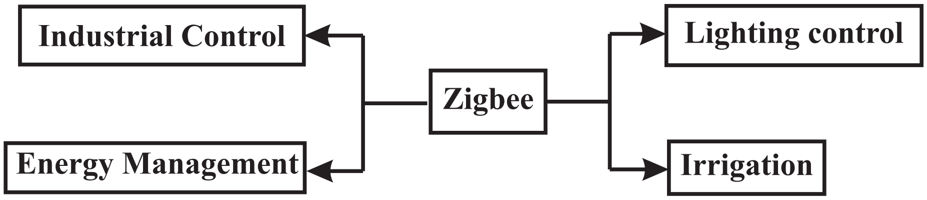


Fig. 1.3. Applications of a Zigbee.

One of the rapidly growing areas of research is the application of wireless technology to remotely control the real time operation of a motor [29–31]. The authors in [31] suggests the use of a wireless mode of data realization from a rotating rotor or shaft instead of connecting wires as the former is much simpler and cheaper solution as compared to the wired realization. Whether it is a DC motor or an AC motor, speed control of any motor is an important task from application point of view [32–34]. In [29], the authors discuss a novel approach to implement a real time control network based on zigbee to implement the control strategy for a DC motor. They also state the fact that the zigbee network helps in minimizing the delays in the control loop of the DC motor. [35] sheds light on the importance of wireless sensor networks in monitoring the real time parameters such as voltage, current, input power, power factor, torque and speed of a motor. The authors further conclude that real time monitoring of such parameters greatly helps in determining the condition of a motor.

The research interest for this thesis focuses on developing a remote control based on Zigbee protocol, as oppose to an Infra-red remote, to control the speed of a motor whether AC or DC. To achieve this, a wireless network is established by using XBEE Series-1 radio modules which operate on the Zigbee protocol. The value of the speed regulator is sent over the wireless communication. The receiver is then responsible to convert this value to a corresponding modulation index value which will in turn modulate the applied voltage of the motor. This voltage control is then further converted to obtain the desired speed control irrespective of the type of motor attached.

The chapters of this thesis are organized in the following manner. The second half of Chapter 1 describes the state of art for this thesis. Moving forward a detailed insight on the establishment of the wireless communication using a Zigbee protocol is presented in Chapter 2. Chapter 3 describes the general approach to implement speed control methodologies in both AC and DC motors. The experimental setup and an introduction to the hardware and software that are implemented are explained in detail in Chapter 4. Chapter 5 then presents detail results demonstrating the speed control of a universal motor. Chapter 6 finally concludes the thesis topic by highlighting the advantages of this design and its application.

1.2 State of Art

1.2.1 Wireless Communication Technology

When selecting a short range wireless communication technology for the application of this thesis, comparisons were made mainly based on the operating range, battery life and maximum range of uninterrupted transmission that can be achieved.

The Bluetooth and the Zigbee protocol both operate in the 2.4 GHz ISM Band, the Infra-red (IR) operation frequency range is 800 to 1000 m [22]. Infra-red has been used as the wireless technology for most of the remote control design for general household appliances [23]. However, it faces certain issues, one of the major one being the Line of Sight. Infra-red does not work well with walls or obstructions in between the transmitter and the receiver. This problem does not exist in a Zigbee radio which can be used even with walls in between. If required, to further boost up the transmission energy, a simple antenna can be attached to the zigbee radios which will help in increasing the overall range of transmission as well. That being said, an IR is focused on a point to point communication where a Zigbee radio can be used in a point to multi-point configuration where multiple devices can be controlled over a single remote. Speaking of the transmission range, in general, an IrDA infra-red wireless communication can last up to 1m in range [23] where as a zigbee radio under consideration can be implemented up to 100 feet (30 m) indoors and up to 90m outdoors [26] and [36]. Today, Zigbee radios up to 40 mile of range are also available. Another important aspect of the wireless technology selection is its battery life. In general a zigbee radio has an extended battery life due to its low power consumption.

Hence a radio based on Zigbee protocol will be an ideal choice for building up a remote to control the speed of a motor. The Xbee Series-1 radio module used in this thesis is based on the Zigbee Protocol. ZigBee (Alliance, 2006) is a wireless standard of ZigBee Alliance based on IEEE 802.15.4 standard [37].

1.2.2 Adjustable Speed Drive System

In the earlier days, a motor-generator set was used to control the speed of a motor. Gradually the motor-generator set was replaced by DC drives [38]. In the past few years, AC drives have steadily managed to replace their DC drive counterparts owing to the developments in reliable power electronics and robust controller algorithms

[39, 40]. As the name suggests, the DC motor drives are used to control the speed of a DC motor whereas the AC motor drives are used to control the speed of an AC induction motor and Synchronous motors. DC drives were exclusively used in offshore drilling rigs and production platforms. But recently, a combination of AC and DC drives are being used [41]. The applications of a DC drive were well known in the metal Industry [39]. In recent years, an AC drive, in the metal industry, has found its use in circulating fans on batch process furnaces, in fluid pumping, in conveyor applications, for crane hoist application and in tension changing and speed matching of rolls [42], thus replacing majority of the applications of the DC drives in the metal industry. Among the AC drives, speed control of the wound rotor induction motor has found its application in high power system with a narrow speed range [43]. The evolution of drives can be seen when we come across the comparative study of three types of AC drives: induction motor (IM) drives, permanent magnet brushless dc motor (BDCM) drives and the Switched reluctance motor (SRM) drives in [44], in order to elect the best suitable AC drive for electric vehicle propulsion application.

An adjustable speed drive is a controller which can be implemented to control the speed of both AC and DC motors [45]. Power quality is an important parameter when dealing with any system that involves motors. In commercial and industrial applications, the use of adjustable drive system has gained popularity as it helps in maintaining the energy efficiency and the power quality [46]. Use of such adjustable drive systems is rapidly increasing in the cement industry where speed controllable fans with adjustable speed drives are being implemented [47]. An important aspect of the motor drive system is the inverter. The NPC inverter are widely used in motor drive systems. [48] discusses one such model of a NPC inverter with motor drive system. The adjustable drive system are also known as variable speed motor drive system. Their applications can range from transportation, elevators to home appliances and air conditioners [49].

From research perspective, this thesis focuses on developing one such adjustable speed drive system which can be used for both AC and DC motors without changing the hardware. Such adjustable drives can be implemented in systems where DC motors are being replaced by AC motors or in systems where the exact identification of the motor attached is not known.

1.2.3 The Controller

The goal of the thesis is to control the speed of either a DC or AC motor by using the same hardware. This universal feature increases flexibility of the motor drive system. The speed control of a motor has been a topic of research interest for a very long time. The speed control is in general obtained with the help of a dsPIC or a microcontroller which acts as the central controlling unit. The output of these controllers will be connected to the driver units which then supply the required voltage to the motor thus controlling the speed [50, 51]. For a wireless control of the speed of a motor, presence of two controller units - one at the transmitter end and the other at the receiver end is necessary.

In [52], the authors state the volts/hertz (V/f) method and the vector control based speed controllers for induction motors. The paper also states that the stator voltage control method is suitable for fan type loads only. In [53] the use of dsPIC microcontroller as the controller for the AC drive system has been highlighted.

Tacho generators are used to convert the speed to voltage in a DC motor. The voltage is then fed back to control the speed of the DC motor [54]. Use of advanced speed control methods such as the Pulse-Width Modulation (PWM) is discussed in [55]. The author also states that this approach is flexible in terms of practical implementation with the use of a microcontroller.

Pulse width modulation has been a topic of extensive research when it comes to implementing of controls in power electronics [56]. Application of PWM in variable speed drives has gradually became the standard for present industry [57]. The output voltage of an inverter is controlled by controlling the pulse width modulation [58]. The PWM inverters have built in under voltage and current protection in case of abnormal operating conditions [57] and [59]. A vast literature on a variety of PWM techniques have been presented in [60–65] depending on the type of inverter, application of the drive and ongoing research in improving the PWM techniques. The vector space modulation technique becomes complex when the number of switches increase. Hence a PWM carrier based techniques for multi-level inverters, has been discussed in [66]. [60] enlightens the advantages of microcontroller generated PWM over analog generated PWM. [67] further develops a strategy to implement both analog and digital PWM, where the entire control is handled by the microprocessor.

The above thus leads us to the conclusion that the development of a PWM strategy using a dsPIC for implementing the speed control logic for a motor drive to operate a fan is acceptable.

2. ZIGBEE (XBEE) COMMUNICATION

2.1 Introduction

Keeping in mind the building of a low cost and a low power wireless network, Zigbee wireless technology was established. The zigbee standard operates on the IEEE 802.15.4 standard [68]. The IEEE 802.15.4 standard is maintained by the IEEE 802.15 working group. The standard specifies the physical layer and the media access control for low data wireless network. It assists in secure machine to machine communication and low data transfer rate [69]. The Zigbee standard, being a high level communication protocol, builds on IEEE 802.15.4 and further develops the higher layers which are not supported by IEEE 802.15.4. Fig. 2.1 shows the establishments of the Zigbee standard.

ZigBee Alliance is a group that maintains the Zigbee protocol. Some members of this group are companies that produce their own radio modules which operate under the Zigbee protocol/standard. Xbee Series-1 (Xbee S1) radio modules are one of the most basic and easy to implement radios operating under this protocol. The 802.15.4 firmware is by default present in the Xbee S1 radio modules. This makes them suitable for a point to point or a star topology of network. The Xbee S1 radio modules operate in the ISM 2.4 GHz band with interface data rate of up to 115.2 Kbps [19]. These modules use the IEEE 802.15.4 networking protocol for fast networking. For extending the transmission range, compatible antennas can be used. These antennas come in the form of U.FL, Reverse Polarity SMA (RPSMA), chip antenna or wired whip antenna [19].

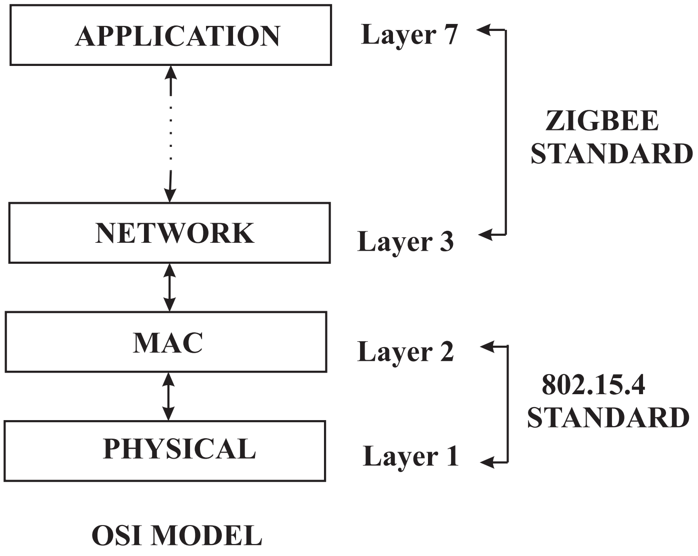
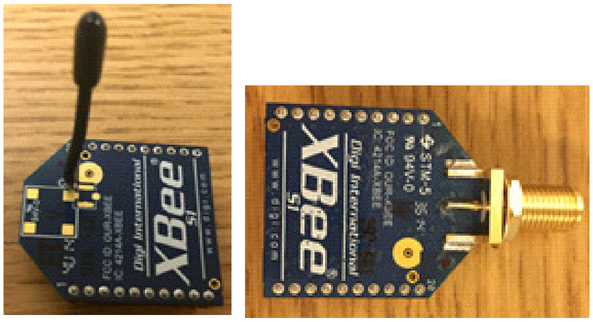


Fig. 2.1. OSI Model for Zigbee Standard.

2.2 Xbee Radios and Antenna

The S1 modules require a supply voltage of $3.3V$ typical to power up. For this thesis, two different modules were implemented for the wireless communication. Fig. 2.2(a) shows the Xbee S1 wire module and Fig. 2.2(b) shows the Xbee S1 RPSMA module.

The difference between these two modules is that the Xbee S1 wire module has



(a) (b)

Fig. 2.2. (a)Xbee Series 1 Wire Module (b)Xbee Series 1 RPSMA Module.

a wire antenna attached to it whereas the Xbee S1 RPSMA module has a connector where the user can connect an RPSMA antenna of his/her choice. The RPSMA antenna is as shown in Fig. 2.3. It is important to note that even when these modules are structurally different in terms of antenna mounted, both the modules belong to the same series S1. This is important for setting up the communication.

When considering the positioning of the antenna it should be noted that the antennas in general have a strong radiation and reception in the direction perpendicular to where they point. Hence to obtain a strong horizontal radiation, always keep the antenna in the vertical direction and vice-versa.

(a) (b)

Fig. 2.3. RPSMA Antenna.

2.3 Radio Configuration and Set up

2.3.1 Zigbee Network

A zigbee network in general consist of two or more modules. The module that is present at the center of the network is configured as the Coordinator which sends commands to all the other modules and is connected to them wirelessly. The module present at the end node is configured as the end device. All the remaining modules in between the coordinator and the end devices are configured as the routers which help in routing the information wirelessly. Fig. 2.4 below shows an example of the zigbee network.

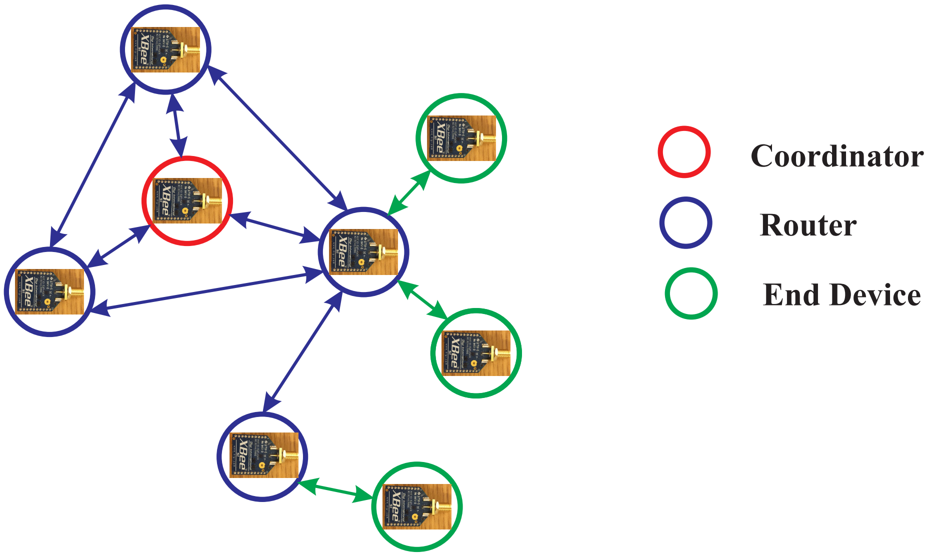


Fig. 2.4. Simple Zigbee Network.

The requirements of this thesis are limited to use of two radio modules the transmitter and the receiver. Hence we can either configure one of the modules as the coordinator and the other as the end device or we can keep both the modules as routers. Any of the above configurations works.

2.3.2 Initial Configuration and Mode of Operation

To set up a one-to-one communication link between the transmitter radio and the receiver radio module, certain parameters of both the modules need to be modified. A set of command called the AT command was developed which is the most widely used language to talk to the zigbee radios.

For communication to be established, each radio in the network should have the same PAN ID. This ID can be setup with the use of AT commands. Thus in this thesis experiments, the transmitter and the receiver radio modules are set up with the same PAN ID. Each Xbee radio module has a 64-bit address which is its unique identifier [28]. No other zigbee radio will have this address. When setting up the communication, it is important that the 64-bit address of the destination radio is fed into the source radio, so that the source radio knows where to send the given information.

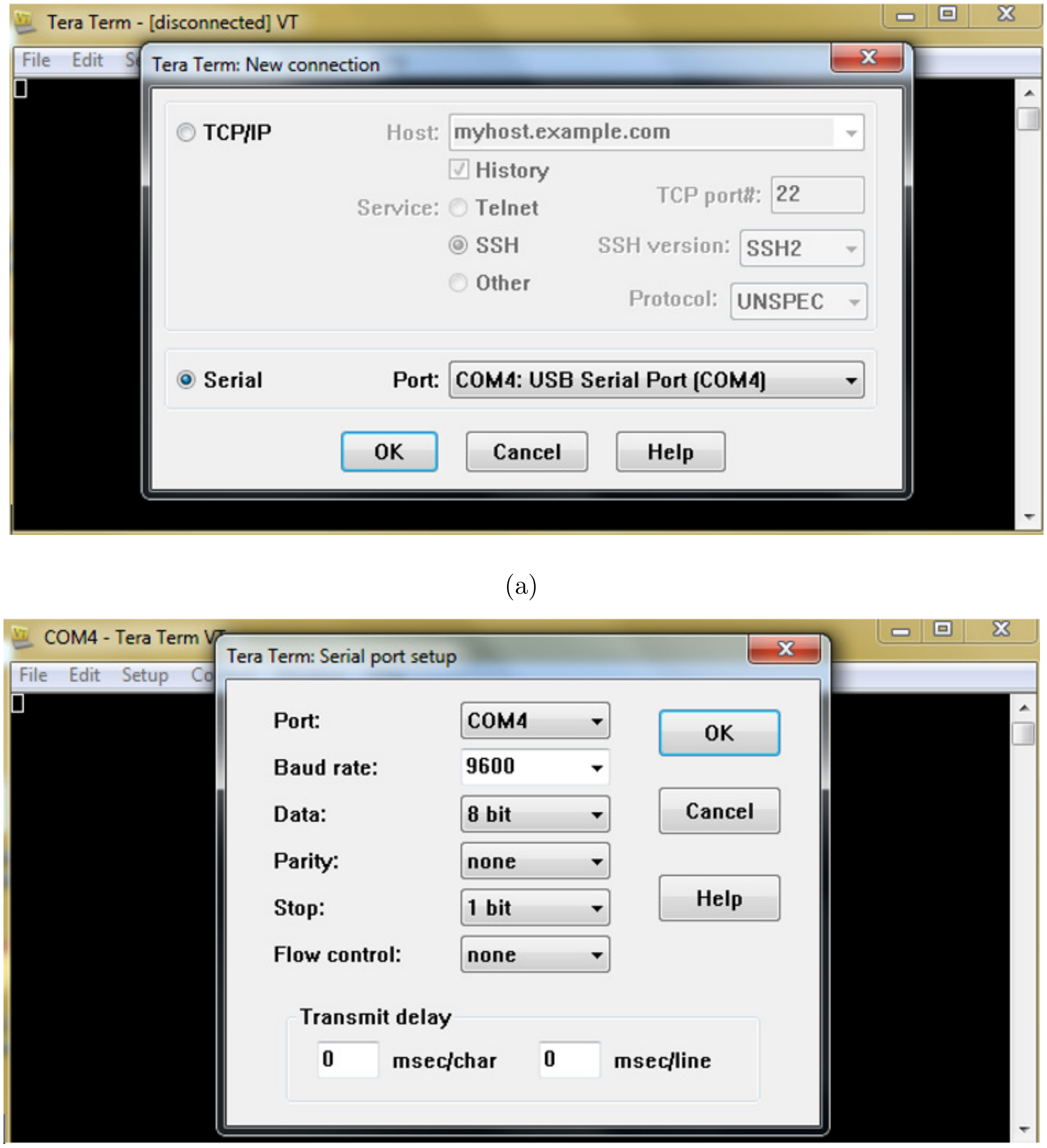
The data transfer operation for Xbee radios can be performed in two modes API Frame mode or the Transparent Mode. The API or the Application Programming Interface requires all communication with the module are to be done in a fixed frame format. The API mode specifies how a command is sent or received in the UART frame format. In this mode, the initial configuration of the PAN IDs and the destination address can be done by sending out the desired frame format. The transparent mode is the default mode of operation of Xbee radios. In this mode any data received via the DI pin is lined up for the RF transmission. To set the initial configuration of the PAN IDs and the destination address, one has to enter the AT command mode and complete the parameter setup. Another alternative is to make use of the X-CTU software which is a free software provided by the Xbee to update the radio firmware and set up the basic communication.

For this thesis, the transparent mode of operation was selected. The radio configurations were updated by using the AT commands and a free terminal software Tera Term.

2.3.3 Implementation

This thesis requires working with two radio modules. The first step is to note down the 64-bit address of both the radios. These address are written on the back side of each radio. This will then be used to set up the destination addresses on both the radios. The next step to configure the radio is to connect it to a computer via a USB. As mentioned in the earlier section, Tera Term is a free terminal software which is used to talk to the radios by making use of the AT command set via a serial port. Once the radio is connected to the computer, open Tera term. Select the port to which the radio is connected. Set the port baud rate to 9600 as it is the standard rate for the radios to communicate via a serial port. Set the number of data bits to 8 with no parity and 1 stop bit. Fig. 2.5 shows the initial windows for configuring the serial port. After setting up the port for communication, the terminal screen will be open. On the terminal screen send the special characters '+++' to the radio so as to enter into the command mode. The radio replies back with an 'OK' which is an indication that the radio module has entered the AT command mode. It is important to wait for the guard time before and after sending the '+++' command. The guard time by default is of 1 second but can be changed according to the user needs by making use of the AT command ATGT. The radio will be in the AT command mode for 10 sec. Once in the AT command mode, all Transparent mode operations will be halted. To move out of the AT command mode back to the transparent mode before the 10 sec mark, use the AT command ATCN.

In the AT command mode, the personal area network ID (PAN ID) can be easily accessed by the command ATID. To set a desired PAN ID write the command ATID XXXX where XXXX represent the ID number. For the thesis set up, the command ATID 3332 was sent which sets up the PAN ID to 3332 for this network. Perform this step by first connecting the transmitter radio and then by connecting the receiver radio so as to set the same PAN ID on both these radios. Next to read the source address (or the self-address), write the command ATSH to read the higher register of source address and ATSL to read the lower register of the source address. The source address will be same as the address that was earlier noted from the back side of the Xbee. The transmitter source address in this case is 0013A200 40C90BC5 and the receiver source address is 0013A200 40C31FF6. Now we will have to set the source address of the receiver as the destination address of the transmitter and vice versa. To set the destination address on the transmitter, use ATDH 0013A200 to set the higher register and ATDL 40C31FF6 to set the lower register of the destination address. To set the destination address on the receiver, use the command ATDH 0013A200 and ATDL 40C90BC5. To check if the destination address has been properly set, write the command ATDH and ATDL without any value. This should return the values



Tera Term - [disconnected] VT

Tera Term: New connection

○ TCP/IP Host: myhost.example.com

☑ History

Service: ○ Telnet TCP port#: 22

● SSH SSH version: SSH2

○ Other Protocol: UNSPEC

● Serial Port: COM4: USB Serial Port (COM4)

(a)

COM4 - Tera Term VT

Tera Term: Serial port setup

Port: COM4

Baud rate: 9600

Data: 8 bit

Parity: none

Stop: 1 bit

Flow control: none

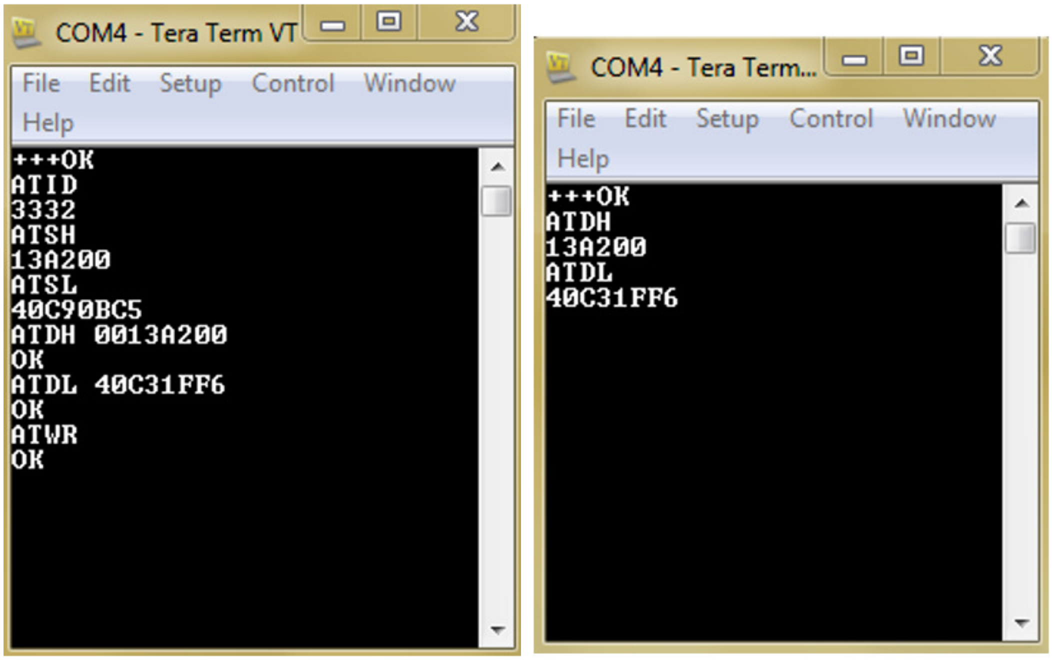
Transmit delay

0 msec/char 0 msec/line

(b)

Fig. 2.5. Serial Port Setting.

that had been set to the registers. After all the necessary changes have been made, use the command ATWR to write and save all the changes. The radios will reply back with an 'OK'. This finishes the basic configuration of the radios. Fig. 2.6 shows the set up commands for the transmitter side whereas Fig. 2.7 shows the command set on the receiver side.

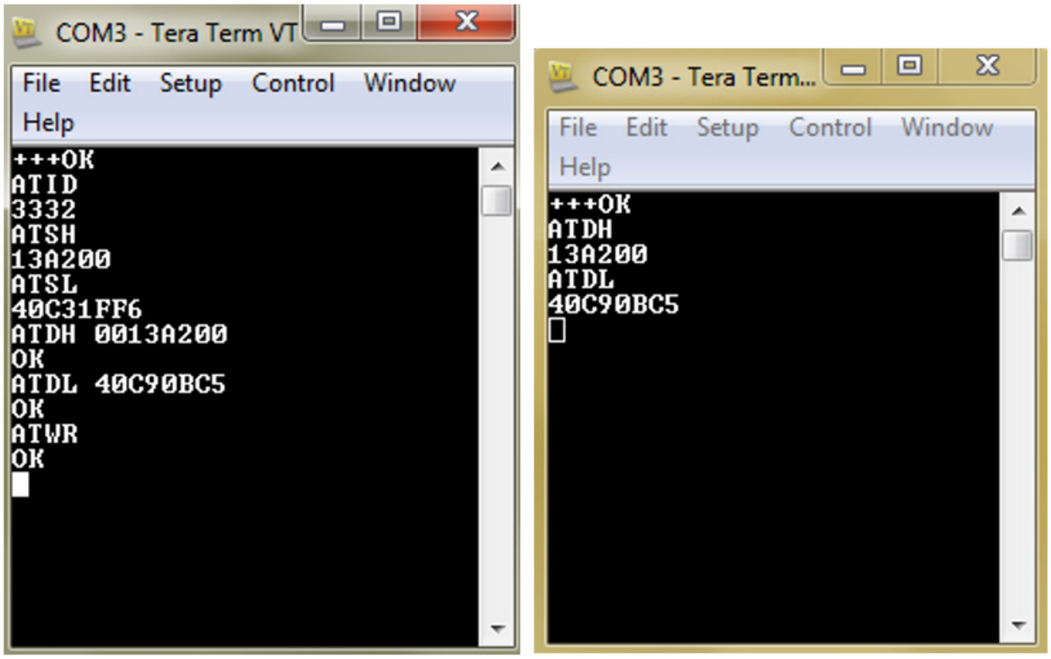


```
+++OK
ATID
3332
ATSH
13A200
ATSL
40C90BC5
ATDH 0013A200
OK
ATDL 40C31FF6
OK
ATWR
OK
```

```
+++OK
ATDH
13A200
ATDL
40C31FF6
```

(a) (b)

Fig. 2.6. (a)Transmitter Configuration - Setting the Destination Address
(b)Transmitter Configuration - Verifying the Set Destination Address.



```
+++OK
ATID
3332
ATSH
13A200
ATSL
40C31FF6
ATDH 0013A200
OK
ATDL 40C90BC5
OK
ATWR
OK
```

```
+++OK
ATDH
13A200
ATDL
40C90BC5
```

(a) (b)

Fig. 2.7. (a)Receiver Configuration - Setting the Destination Address (b)Receiver Configuration - Verifying the Set Destination Address.

3. ADJUSTABLE MOTOR DRIVE SYSTEM

3.1 Introduction

In any process which makes use of a motor, the best method of controlling that process can be obtained by controlling the speed of the motor [70]. Thus depending on various parameters like the horsepower rating, the motor application, a motor drive system can be divided into different categories. A motor drive system mainly consists of a converter/inverter which is used to control the speed of a particular motor within a range specified for it. The Pulse Width Modulated (PWM) DC to AC inverter is most widely used in motor drive system [71]. Due to excellent power quality and lower switching losses, multilevel inverters have found their applications in medium and high power areas [72]. A motor drive system connected to a multilevel inverter is expected to deliver high efficiency as the harmonic losses are reduced by the use of a multilevel inverter [73].

Renewable energy sources like wind and solar have seen an increase in their application when it comes to irrigation system [74–76]. With solar powered applications like water pumping system for irrigation which makes use of either AC or DC motor [74], an adjustable drive system presented in this thesis would be an ideal fit as the speed control strategies for this drive system work for both AC and DC motors. Also, the control of this drive system is based on a wireless network, which gives the user the extra flexibility needed to have a good control on the speed of the motor attached. Fig. 3.1 shows the block diagram of a general motor drive system.

This chapter describes in detail how a motor drive system works. The chapter highlights the inverter topology used and the Pulse Width Modulation technique for the motor drive system in this thesis. Two different control strategies for controlling the speed of a DC and an AC motor are described.

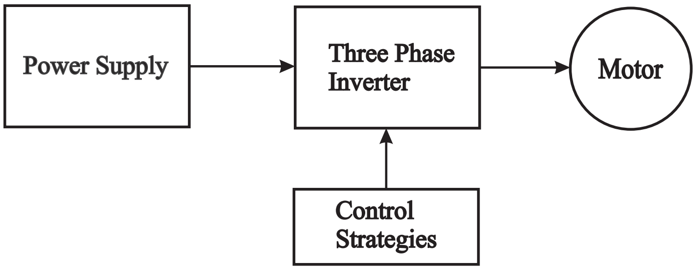


Fig. 3.1. Block Diagram - General Motor Drive System.

3.2 Motor Drive System

3.2.1 Power Electronics - The Inverter

The main device that constitutes a motor drive system is a DC to AC inverter. A three phase inverter is as shown in Fig. 3.2.

A power inverter is a device present in the system to convert DC-AC or convert

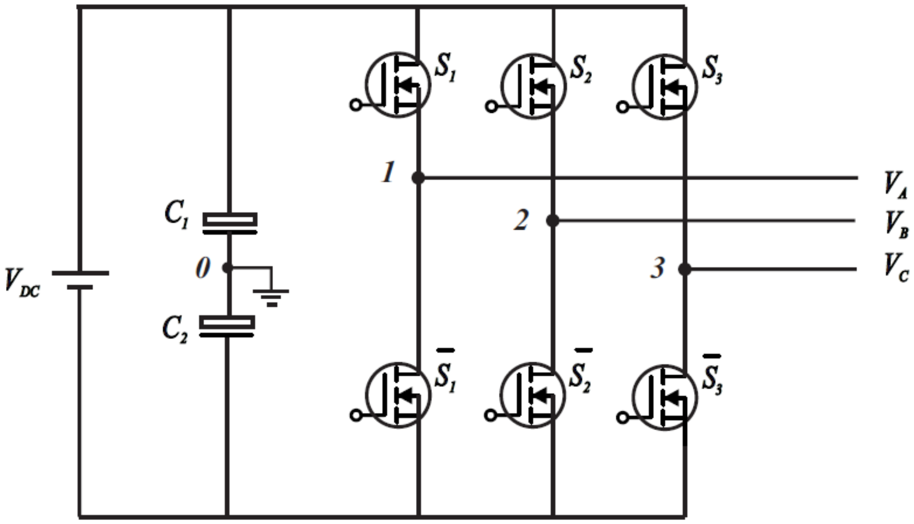


Fig. 3.2. DC-AC Inverter.

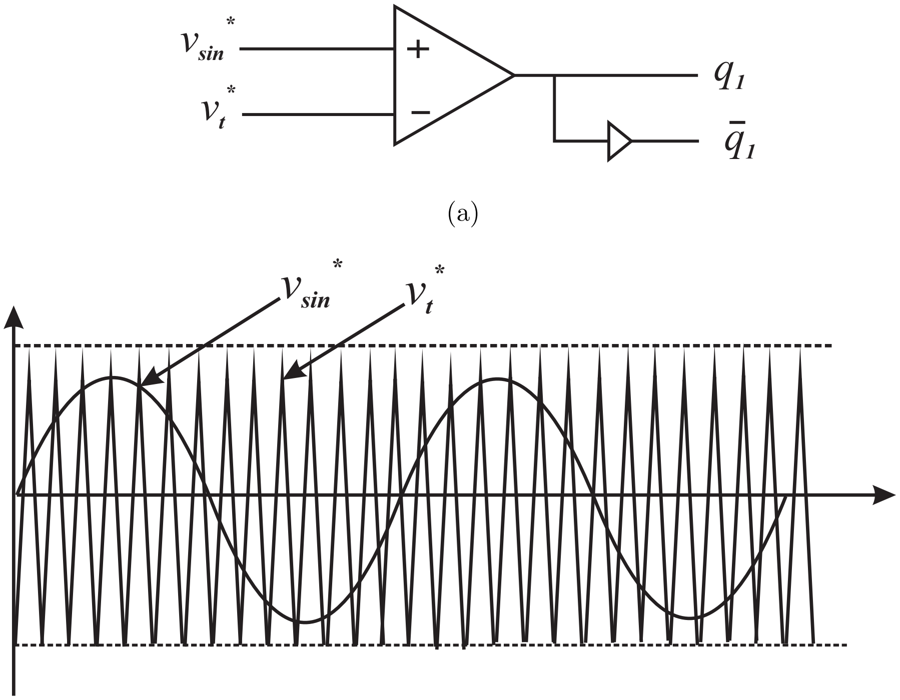
AC-DC-AC. The three phase inverter consists of three legs with two power switches (IGBTs) on each leg. The six switches S_1, $\overline{S}_1$, S_2, $\overline{S}_2$, S_3, $\overline{S}_3$ are as shown in Fig. 3.2. Each switch pair S_x and $\overline{S}_x$, where x= 1, 2 or 3 are complementary to each other. This implies if one switch is in the ON state, its complementary switch is in the OFF state. The switching of these power switches is controlled by application of PWM modulation control strategy. The modulation strategy can be performed in terms either frequency or amplitude to obtain a regulated voltage at the output [77]. The inverter apart from regulating the output voltage for the motor drive system has other applications like overvoltage protection, under voltage protection, over current protection.

For this thesis, a DC-AC inverter with six power switches is implemented to regulate the output voltage by applying the amplitude modulation strategy to control the power switches.

3.2.2 Pulse Width Modulation

Various PWM techniques have been studied to improve the quality of the regulated voltage at the output of the inverter [78]. [79] describes a technique where unipolar PWM is implemented with a triangular carrier wave. This technique helps in controlling the current and minimizing the ripples in the current. The three most common PWM techniques that can be applied to a multilevel inverter are Multilevel Sinusoidal PWM (SPWM), Space Vector PWM and Multilevel Selective Harmonic Elimination [80]. These techniques are implemented so as to obtain better quality of output voltage and current. PWM implementation can be either unipolar or bipolar. The advantages and disadvantages of both these implementations is discussed in [81] and a new technique which uses a combination of both unipolar and bipolar PWM is developed, which is found useful in reduction of total harmonic losses. Implementation of PWM helps in suppressing the ripples in the torque as the harmonic component due to PWM is relatively low [82].

The amplitude modulated PWM in this thesis is Sinusoidal Pulse Width Modulation where the modulating signal for the output voltage is a sinusoidal wave of low frequency, v^*_{sin} and the carrier signal is a triangular wave of high frequency, v^*_t. Fig. 3.3 demonstrates the sinusoidal PWM technique applied to a single leg of the inverter, using a comparator. The control outputs q_1 and its complementary $\overline{q}_1$=1-q_1 obtained as the PWM signal are then applied to the switches S_1 and $\overline{S}_1$ respectively.



(a)

(b)

Fig. 3.3. (a)PWM using Comparator (b)Sinusoidal Pulse Width Modulation.

The three phase inverter consists of three legs, each corresponding to the three phase voltages at the output, V_A, V_B, V_C as shown in the Fig. 3.2 above. The output voltages can be obtained as a function of the pole voltages V_{10}, V_{20}, V_{30} as seen in Fig. 3.2. Where, the pole voltages are obtained as a result of the application of the control signals q_1, $\overline{q}_1$, q_2, $\overline{q}_2$, q_3, $\overline{q}_3$ to the switches S_1, $\overline{S}_1$, S_2, $\overline{S}_2$, S_3, $\overline{S}_3$ respectively.

Another important factor in the PWM implementation is the modulation index. As mentioned above, this thesis implements amplitude modulated PWM and hence it is important to understand how the amplitude modulation index affects the PWM implementation. For a PWM implementation, the peak amplitude of the fundamental component of the pole voltage is given by 3.1.

$$v_{10(fundamental)} = (\frac{v^*_{sin}}{v^*_t})\frac{V_{dc}}{2} \tag{3.1}$$

Where, (v^*_{sin}/v^*_t)=ma, ma= modulation index

Thus lower the modulation index, lower is the amplitude for the pole voltage and hence reduction in the output voltage. And with higher modulation index, a higher output voltage can be obtained. Thus from the application point of view of this thesis, it can be seen that the speed of a motor which is a function of the output voltage of the inverter can be controlled by changing the modulation index.

Hence to prove the concept of wireless speed control of a motor, bipolar PWM with single carrier and multiple (three) modulation signal is selected for this thesis. The reason behind this selection is that this PWM approach is one of the simplest techniques that can be implemented in terms of both hardware and software.

3.2.3 AC Motor

For a three phase AC motor, the PWM implementation is similar to as shown in Fig. 3.3. A three phase motor is connected as shown in Fig. 3.4.

A three phase balanced AC system has three voltages of same magnitude but separated by an angle of 120 degrees. Thus to obtain the control signals for the six switches, we need three reference voltages separated by 120 degrees. The PWM signals are obtained by comparing the three reference voltages v^*_{10}, v^*_{20}, v^*_{30} as given in 3.2, 3.3 and 3.4 with a triangular carrier wave of high frequency. Fig. 3.5 illustrates the implementation of the PWM strategy.

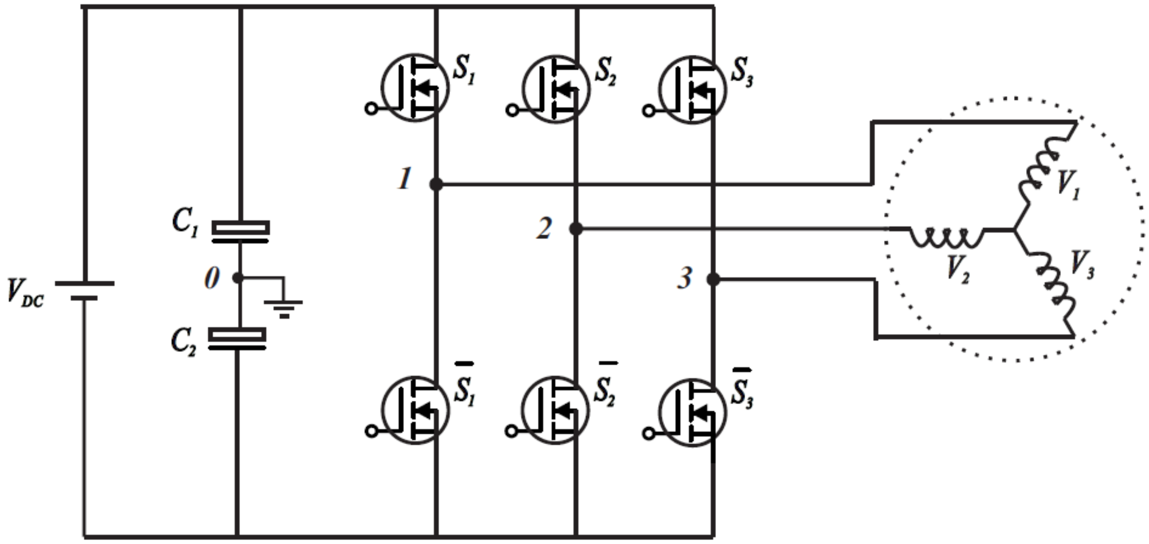


Fig. 3.4. Three Phase AC Motor Drive

$$v_{10}^{*} = ma \times \frac{V_{dc}}{2} \times sin(\theta) \tag{3.2}$$

$$v_{20}^{*} = ma \times \frac{V_{dc}}{2} \times sin(\theta - \frac{2\pi}{3}) \tag{3.3}$$

$$v_{30}^{*} = ma \times \frac{V_{dc}}{2} \times sin(\theta + \frac{2\pi}{3}) \tag{3.4}$$

The duty cycles τ_1,τ_2,τ_3 of the PWM waveform that is generated corresponding to the three phases are obtained by implementing 3.5, 3.6 and 3.7.

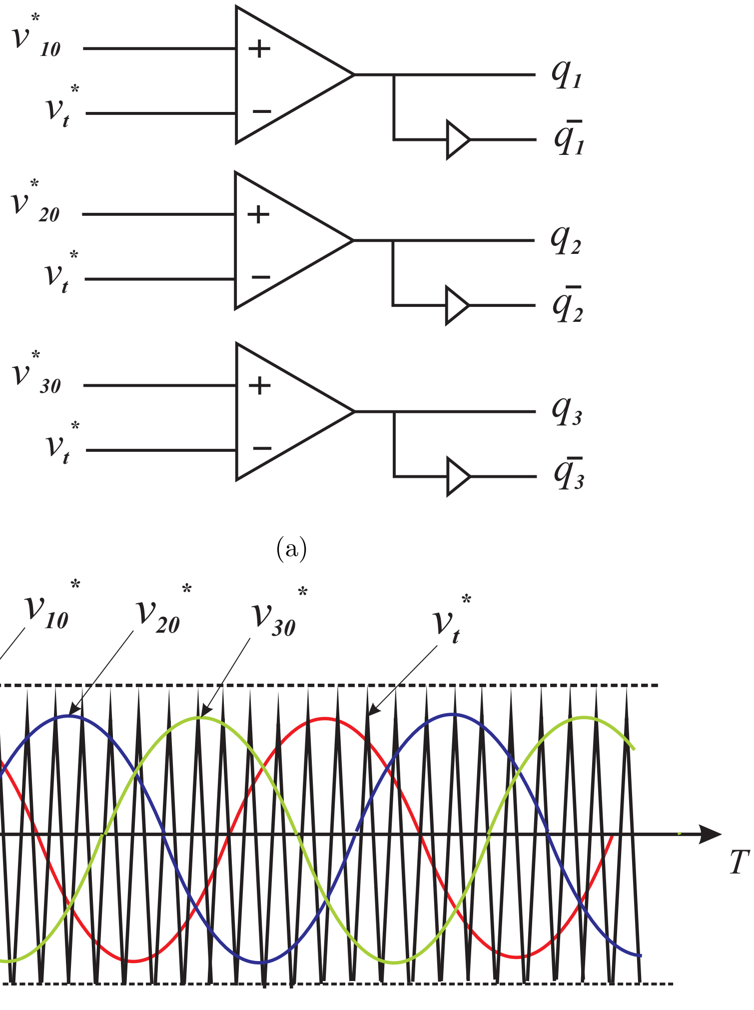
$$\tau_1 = (\frac{v_{10}^{*}}{V_{dc}} + \frac{1}{2}) \times T_s \tag{3.5}$$

$$\tau_2 = (\frac{v_{20}^{*}}{V_{dc}} + \frac{1}{2}) \times T_s \tag{3.6}$$

$$\tau_3 = (\frac{v_{30}^{*}}{V_{dc}} + \frac{1}{2}) \times T_s \tag{3.7}$$

Where, T_s is the total switching period of the generated PWM signal.

It can be observed from Fig. 3.5 , for a higher modulation index of 0.9, the duty cycle of the PWM is nearly 90% whereas for a modulation index of 0.1 the duty cycle is 10%. Thus we can conclude that for the given PWM strategy, the speed of a motor can be controlled from a maximum value to a minimum value.



(a)

(b)

Fig. 3.5. (a)PWM Control for Three Phase Inverter (b)PWM for 3-phase AC motor.

3.2.4 DC Motor

The inverter presented in Fig. 3.3 can as well be implemented in a DC motor drive system with a DC motor. Fig. 3.6 represents a DC motor load connected between the two legs of a three phase inverter.

Since the load is a DC motor, the PWM signals for the DC drive system are obtained by comparing a single DC reference voltage v_{ref} as given in 3.8, with a

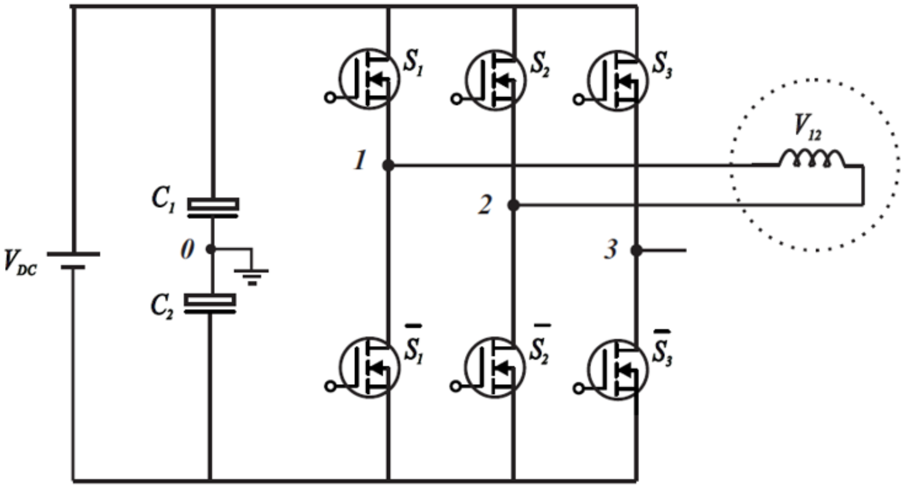


Fig. 3.6. DC Motor Drive System.

triangular carrier wave of high frequency. Thus it can be said that for a DC motor connected to a three phase inverter, $v_{10}^{*}=v_{20}^{*}=v_{30}^{*}=v_{ref}$. Fig. 3.7 illustrates the implementation of PWM strategy for a DC motor.

$$v_{ref} = ma \times \frac{V_{DC}}{2} \tag{3.8}$$

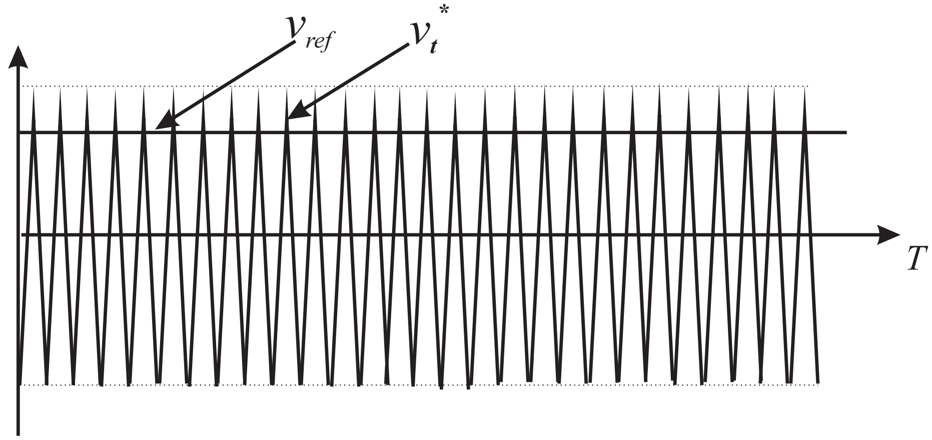


Fig. 3.7. PWM Implementation for a DC Motor Drive System.

The duty cycle of the PWM generated is calculated using 3.5, 3.6 and 3.7 by replacing v_{10}^*, v_{20}^*, v_{30}^* by v_{ref}. It can be observed from Fig. 3.5 that for a modulation index of 0.9, the duty cycle obtained is 90%, but for modulation index of nearly 0.1, the minimum duty cycle obtained is 50%. This implies that a DC motor with the given PWM strategy can be controlled from maximum speed to a speed which lies at the mid-range value.

The reason behind the difference in the duty cycle of a DC motor with respect to an AC motor for a modulation index of 0.1 is, that for an AC motor the reference signal being a sine wave can interact with the negative portion of the triangular wave, which corresponds to 50% of the time period of the triangular wave. But in a DC motor drive, as the reference signal is a DC, this interaction does not take place and hence the comparison with the remaining 50% of the period of the triangular waveform is not seen. The solution to this problem is implemented in the software by changing v_{ref}. This is further explained in Section 3.3.

3.3 Input to the Motor Drive System - Wireless technology

3.3.1 Transmitter

Being an implementation of the wireless technology, this thesis can be divided into two parts: the transmitter and the receiver. As mentioned before the aim of this thesis is to control the speed of a motor. One of the applications for this remote speed control can be in ceiling fans.

The speed of a motor varies with respect to its input voltage. This voltage is supplied by the inverter in the motor drive system. The inverter output voltage is a linear function of the modulation index used to implement the PWM control strategy. Hence higher the modulation index, higher is the inverter output voltage and thus the speed of the motor and lower the modulation index, lower is the speed of the motor.

The transmitter end of this motor drive system has a speed regulator with which the user can adjust the speed of a motor according to his needs. The modulation index parameter is obtained as an output of the speed regulator which is in control of the user. For this thesis, the output of the speed regulator is varied from 0 to $3V$. This voltage information is then transmitted using the wireless Xbee radios.

3.3.2 Receiver

At the receiver end, the Xbee radio receives the information of the output voltage of the speed regulator. This voltage is then converted to the corresponding modulation index. The relation between the speed regulator voltage and the modulation index is as shown in Fig. 3.8.

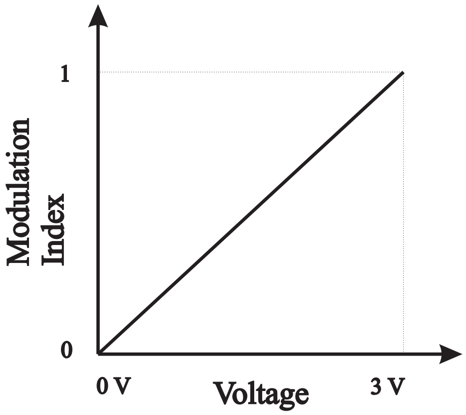


Fig. 3.8. Relation Between Speed Regulator Output Voltage - Modulation Index.

This modulation index is then applied to the PWM strategy as discussed in the previous sections. The comparator output is a PWM with the duty cycle that corresponds to the modulation index. The relation between the modulation index and the duty cycle is a linear one as shown in Fig. 3.9.

Thus as the user would change the regulator for different speeds, the information will be transferred to the receiver side with the use of wireless communication without significant delays and the speed of the motor can be controlled wirelessly.

For a DC motor, we did see that the PWM strategy can make a motor reach up to a minimum speed of 50% and not go below it. To compensate for this, the reference

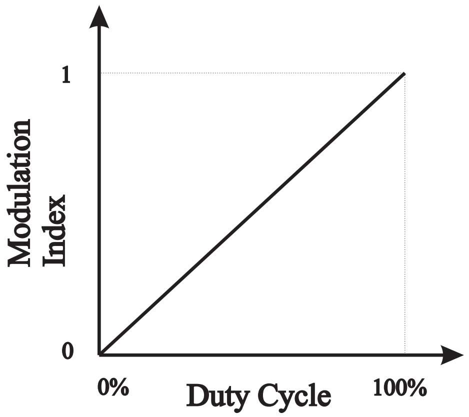


Fig. 3.9. Relation Between Modulation Index and PWM Duty Cycle .

voltage was derived from the following relationship between modulation index and reference voltage. This is shown in Fig. 3.10. The technique helps in compensating for the negative half cycle of the triangular wave and thus changes the speed range of 50-100% to go from 0 to 100%.

By application of this correction, the reference voltage for the PWM implementation for a DC motor drive is now re-defined as in 3.9.

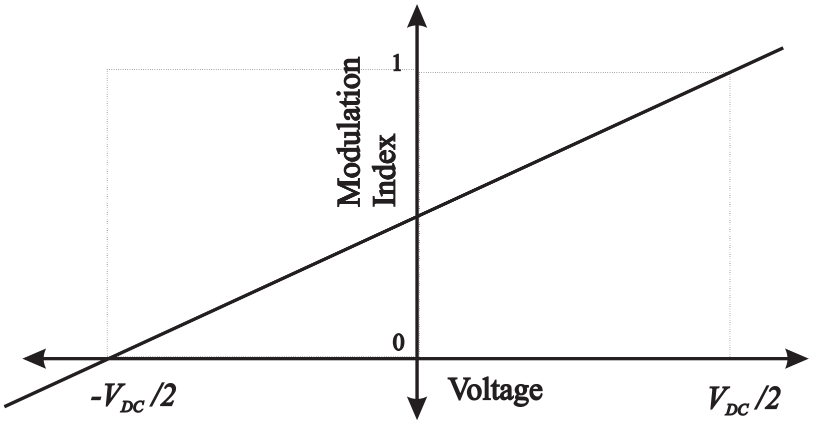


Fig. 3.10. DC Motor PWM Compensation Technique.

$$v_{ref} = (\frac{V_{DC}}{2})(2 \times ma - 1) \tag{3.9}$$

4. EXPERIMENTAL SETUP

4.1 Introduction

As described in earlier sections, the thesis is focused on implementing a wireless remote to control the speed of a motor. The experimental setup can be separated into two sections: the Transmitter section and the Receiver section. A general block diagram of the entire system is shown in Fig. 4.1.

The hardware was set up using the blocks presented in Fig. 4.1. Initially, the experiment was performed for a separation distance of 1 foot between the wireless link. This distance was then increased to 18 feet, to test the wireless communication with the motor drive system. The tests were performed for AC and DC motors and the results are as described in Chapter 5.

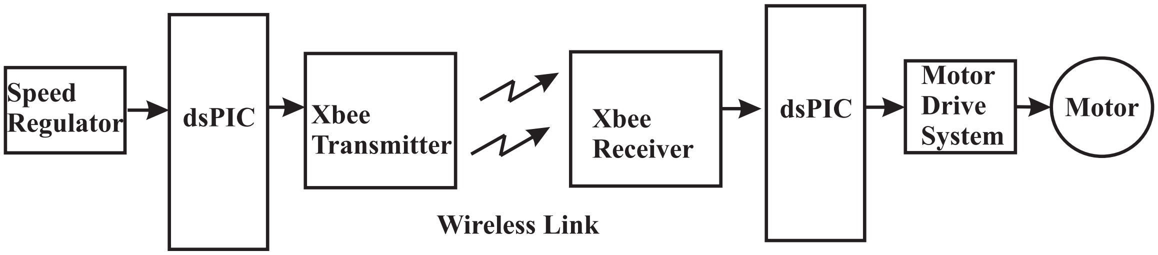


Fig. 4.1. Block Diagram of the Proposed Wireless Motor Speed Control System.

For the hardware to perform up to the mark, use of three important software programs was made. The X-CTU software was used for updating the radio firmware. The Tera Term terminal software was used to setup the required communication network by configuring the Xbee radios. For this thesis, all the control algorithms are programmed in the dsPIC. MPLAB-X was used to debug and program the dsPIC.

4.2 X-CTU

The X-CTU software is a free software that Digi International provides for its Xbee radio modules. The most important application of this software is to update the firmware library for the Xbee radio modules. If two radios in a network are updated to different firmware versions, the wireless communication between these radios is hampered. Hence it is important to update the firmware for both the radios using X-CTU to the exact same version.

4.3 Transmitter Setup

The transmitter section is basically a remote to control the speed of a motor. This remote consists of a speed regulator, a process controller and a wireless communication radio.

Fig. 4.2 is a schematic of the remote i.e. the transmitter section of this experiment.

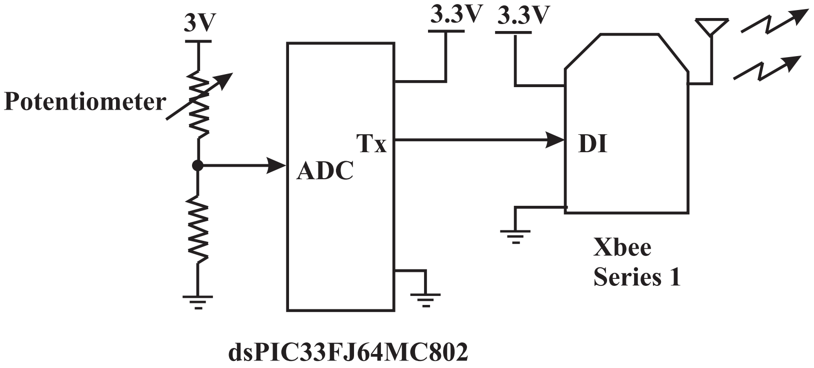


Fig. 4.2. Transmitter Schematic.

The speed regulator in this thesis is implemented with the use of a 1kΩ potentiometer connected to a 100Ω resistance in series. The Potentiometer is supplied with a voltage of $3V$. An output at the series connection of the potentiometer and the resistance is fed to the dsPIC. Thus the dsPIC receives voltage from $0.27V$ to $2.72V$. The lower voltage of $0.27V$ is translated to the low speed of a motor and the higher voltage of $2.72V$ gets translated to the high speed of the motor. This range for the voltages is thus used to define the range for the speed of the motor. In other words, the speed of the motor can be changed by changing the value on the potentiometer.

The process controller for this remote is the dsPIC. The dsPIC33FJ64MC802 was selected keeping in mind the PWM requirements for the motor drive system at the receiver end. The dsPIC is a 16-bit digital signal controller with 28 pins, which requires a typical power supply of $3.3V$. On the transmitter end, the function of the dsPIC is to sense the voltage coming from the potentiometer and transmit this value to the Xbee radio on the transmitter side using the UART Tx pin. The advanced analog feature of the dsPIC provides us with a 10/12 bit ADC. The 12 bit ADC is used to sense the input voltage from the potentiometer. The UART for the dsPIC is set for a 9600 baud rate, 8 data bits, no parity and 1 stop bit. These setting are selected as the Xbee radios operate at a 9600 baud rate and 8 data bit configuration. As the data is sensed at the ADC, it is continuously transmitted to the Xbee radios using the Tx pin on the dsPIC. The radio then further transmits the data over the wireless link. The program is implemented in MPLAB-X which uses C-30 compiler for coding.

For the wireless communication, Xbee series 1 radio are being implemented. These radios require an operating voltage of $3.3V$ typical. The Xbee radio on the transmitter end is configured to operate in the transparent mode as described in chapter 2. The Tx pin on the dsPIC is connected to the DI (Rx) pin on the radio module. The DI pin is ideally in the high state when no data is being received by the module. The radio module receives the data i.e. the voltage information from the UART on the DI pin as an asynchronous serial signal. As the radios are operating in the transparent mode, any data received on the DI pin is immediately lined up for the RF transmission. And thus the voltage information gets transferred to the receiver side.

4.4 Receiver Setup

The receiver section of the experimental setup acts as the decision maker unit to generate the required speed of the motor. This section consists of the wireless communication module, the process controller, the motor drive system and the load i.e. AC or DC motor. The schematic for the receiver section is as shown in Fig. 4.3.

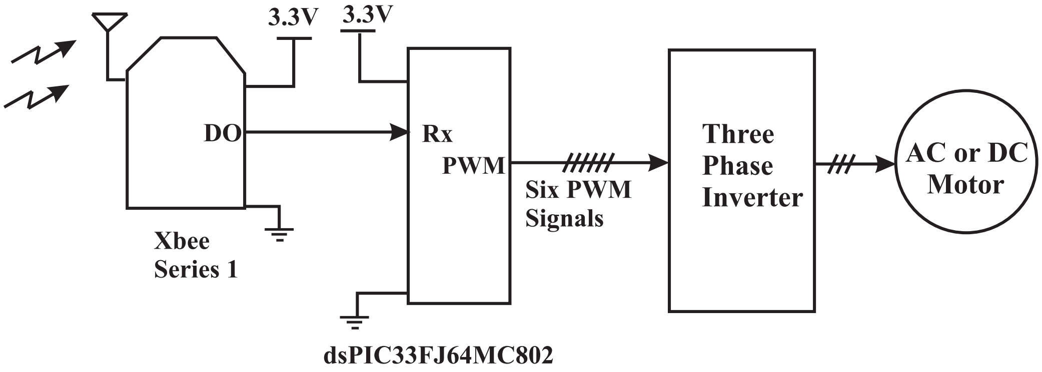


Fig. 4.3. Receiver Schematic.

The Xbee radio module at the receiver side receives the RF-packets that are sent by the transmitter radio. The module at the receiver is configured in the transparent mode. Hence any data received through the RF communication is immediately lined up in the data out buffer and transferred to the UART via the DO pin.

The process controller for the receiver side is the dsPIC33FJ64MC802. The main feature of the dsPIC is its motor control PWM signal which makes it an ideal choice. The speed regulator information in terms of the potentiometer voltage is transferred from the DO pin of the radio to the Rx pin of the dsPIC via UART. The dsPIC then processes this voltage information and converts it into the corresponding modulation index value by the relation explained in chapter 3. Using this modulation index value, and depending on the nature of the motor connected i.e. AC or DC, the reference voltages are calculated using (2), (3), (4) or (9) respectively as in chapter 3. Further, these reference voltages are then used to calculate the duty cycle by using the relation described in (5), (6) and (7) in chapter 3. A total of 6 PWM signals are generated using the three reference voltages. The six PWM signals from the dsPIC are obtained from the pins PWM1H1, PWM1H2, PWM1H3, PWM1L1, PWM1L2 and PWM1L3.These are then applied as the gating signals for the switching of the IGBT switches of the inverter.

The inverter is a three phase inverter which has a total of six IGBT switches. The three signals PWM1H1, PWM1H2 and PWM1H3 from the dsPIC are applied to the switches S_1, S_2, S_3 respectively, and their complement signals PWM1L1, PWM1L2 and PWM1L3 are applied to switches $\overline{S}_1$, $\overline{S}_2$, $\overline{S}_3$ respectively. For this experimental set up, International Rectifier's IRAM630-1562F is used as the inverter chip. It is a $15A$, $600V$ Inverter Intelligent Power Module (IPM). The PWM signals from the dsPIC are $3V$ in amplitude and can be directly applied to the pins of the inverter chip. The chip requires a power supply of $15V$. The $15V$ supply is obtained by using the regulator chip LM7815 from Texas Instrument. Thus the six PWM signals are used to generate the three phase voltage at the output of the inverter. This experiment was performed separately for AC motor and DC motor. The distance between the transmitter and the receiver was maintained at 18 feet in the laboratory environment. For a three phase AC motor, the tests were performed by connecting the AC motor to the three phases of the inverter. While for a DC motor, the tests were performed by connecting a resistance between two of the three phases and monitoring the applied voltages. All test results are presented in chapter 5.

5. EXPERIMENTAL RESULTS

5.1 Introduction

To implement the proposed system, the hardware is set up as described in chapter 4. Each experiment is performed for three different modulation index (ma) values of 0.9, 0.5 and 0.12 which translate to the high, medium and low speed of operation of the motor respectively.

The first set of experiments were performed without the motor drive system connected. This was to make sure that the signal at the receiver is exactly same as the signal sent by the transmitter. Next the motor drive system i.e. the inverter was connected to the receiver radio, and tests were performed by connecting the resistive load first to and then by connecting the AC motor. The last step was implementing the DC motor. Due to unavailability of this motor, experiments were performed by connecting a resistive load to the inverter and the applied signals were observed.

Fig. 5.1 shows the experimental setup of the transmitter and Fig. 5.2 shows the experimental set up of the receiver with an AC motor.

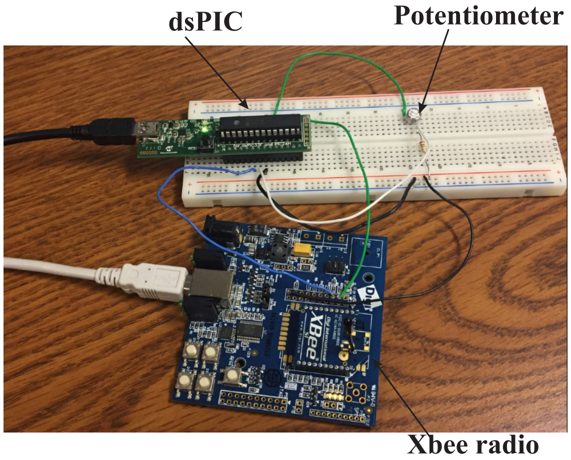


Fig. 5.1. Transmitter Setup.

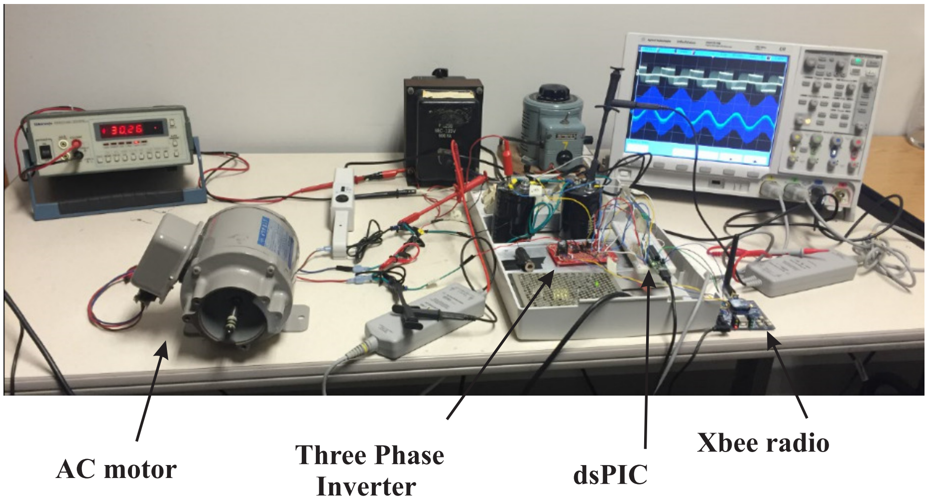


Fig. 5.2. Receiver Setup with AC Motor.

5.2 Wireless Link - 1 Foot Separation

For the initial part of the testing, the distance between the transmitter and the receiver was 1 foot. Both the transmitter emitted signal and the receiver emitted signal were monitored by continuously changing the modulation index. To perform this, the transmitter signal was monitored by using a PWM output pin on the transmitter dsPIC. The signal received on the ADC of the transmitter dsPIC was converted to a PWM signal at the transmitter so as to verify the signal being transmitted and received was the same. This was done only for validating the results and will not be applied in the actual system. For this experimental setup, the wireless transmission worked perfectly without connecting the antennas to the radio.

For a modulation index of 0.12, 0.5 and 0.9, the results were as observed in Fig. 5.3, 5.4 and 5.5 respectively. The channel 1 represented by the yellow signal is corresponding to the transmitter signal whereas the channel 2 represented by the green signal corresponds to the receiver side.

It is observed for all the three cases, the frequency of the transmitter and the receiver is set to 20 kHz. This is due to the frequency of the triangular wave used in the PWM modulation which is 20 kHz. It can also be noted that the receiver waveform is not synchronous to the transmitter waveform. This is due to the fact that the wireless transmission makes use of asynchronous transmission. The main aim of this thesis is to control the duty cycle of the PWM waveform in order to control the speed of a motor. It can be observed from Fig. 5.3 that for a ma= 0.12, the duty cycle at the receiver is 12%. For a ma =0.5, the duty cycle increases to 50.2% as in Fig. 5.4. Finally for a ma=0.9, the duty cycle reaches the maximum value of 90% as in Fig. 5.5. Thus a change in the duty cycle is observed with a change in the modulation index.

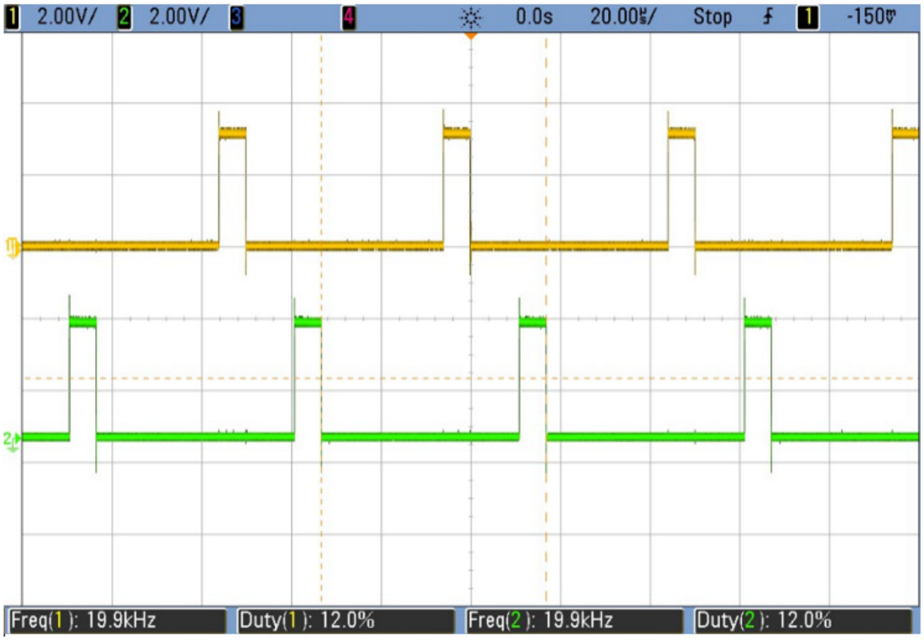
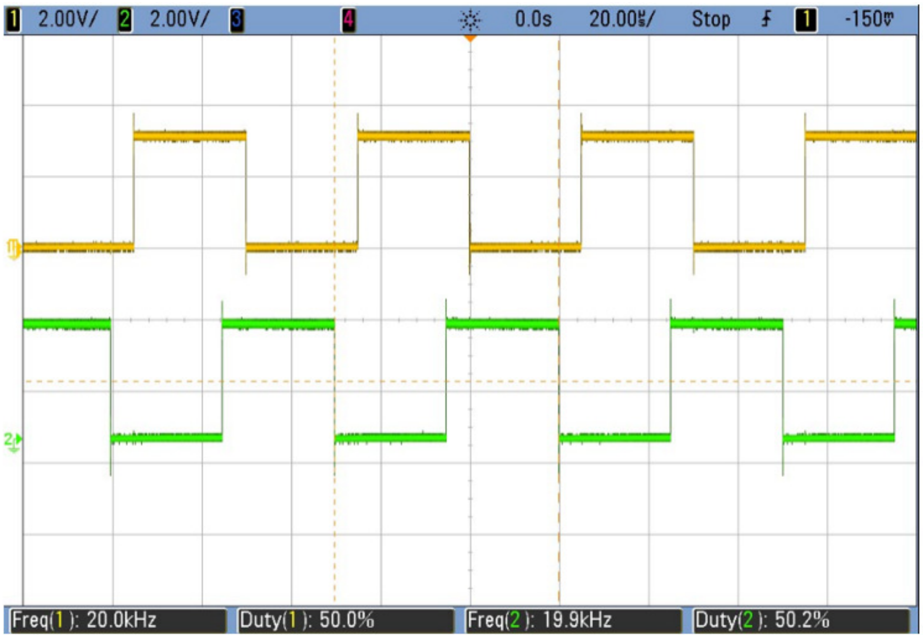
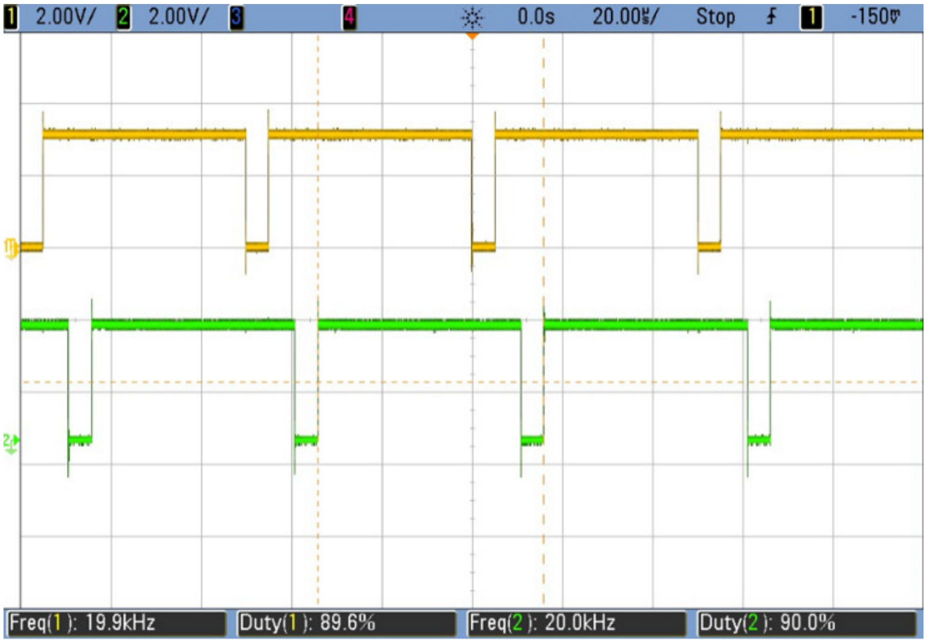


Fig. 5.3. Wireless Link Distance of 1 foot, ma = 0.12.



Freq(1): 20.0kHz Duty(1): 50.0% Freq(2): 19.9kHz Duty(2): 50.2%

Fig. 5.4. Wireless Link Distance of 1 foot, ma = 0.5.



Freq(1): 19.9kHz Duty(1): 89.6% Freq(2): 20.0kHz Duty(2): 90.0%

Fig. 5.5. Wireless Link Distance of 1 foot, ma = 0.9.

5.3 Wireless Link - 18 Feet Separation

The next step was to test the wireless link for a distance of 18 feet. As it was observed from the previous results that the receiver did receive the exact duty cycle as of the transmitter, it was considered safe to connect the receiver to the inverter. Since the distance was increased to 18 feet, connecting the antenna to the radio module was mandatory for a clear communication.

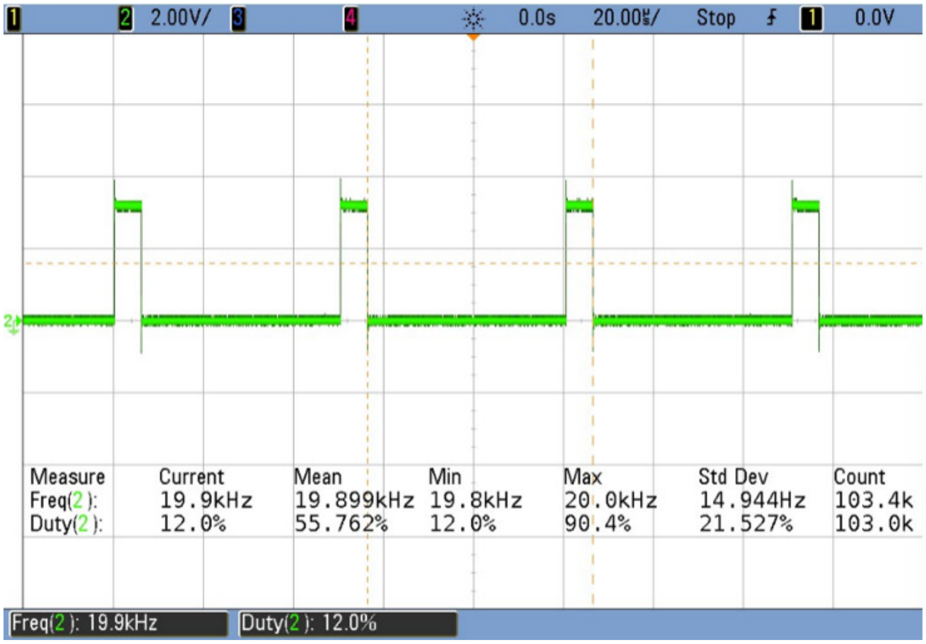
This part of the experiment was performed in the order of the following sections.

5.3.1 Resistive Load

As the radio module was connected to the three phase inverter, to make sure that the six PWM signals worked as desired and the output voltage of the inverter was appropriate, a resistive load was connected at the output of the inverter. Each phase of the inverter was connected to a 100 Ω resistance as load. The DC link voltage for the inverter was at a constant value of $20V$ and the frequency of the reference voltages was set at $60Hz$ in the software. The receiver dsPIC was programmed with the PWM algorithm of the AC motor. The duty cycle at the receiver end for ma = 0.12, 0.5 and 0.9 was monitored and three phase voltage at the inverter output was observed. Fig. 5.6, 5.7 and 5.8 represent the duty cycle at the receiver for a modulation index of 0.12, 0.5 and 0.9.

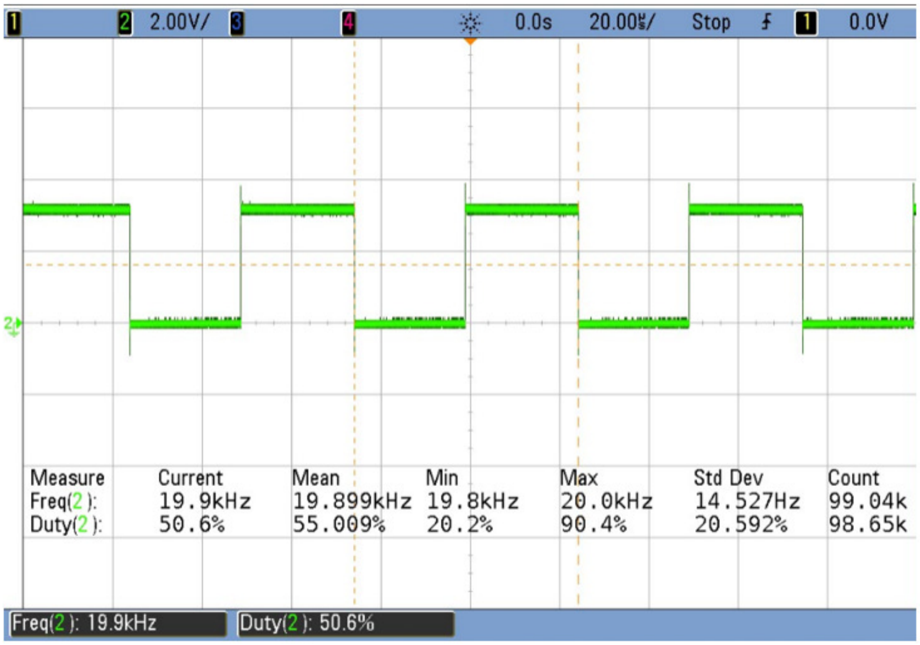
It is observed from Fig. 5.6 that for a ma = 0.12, the duty cycle was at 12%. On increasing the ma value to 0.5, the duty cycle changed to 50.6% as in Fig. 5.7. For a higher ma = 0.9, the duty cycle switched to 90% as shown in Fig. 5.8.

Fig. 5.9 represents the line-to-line voltage of the inverter. The line-to-line voltage for this inverter is a three level signal. The line-to-neutral voltage of the inverter is as shown in Fig. 5.10. The line-to-neutral voltage is a five level signal. These voltages remain fixed even when the modulation index is changed.



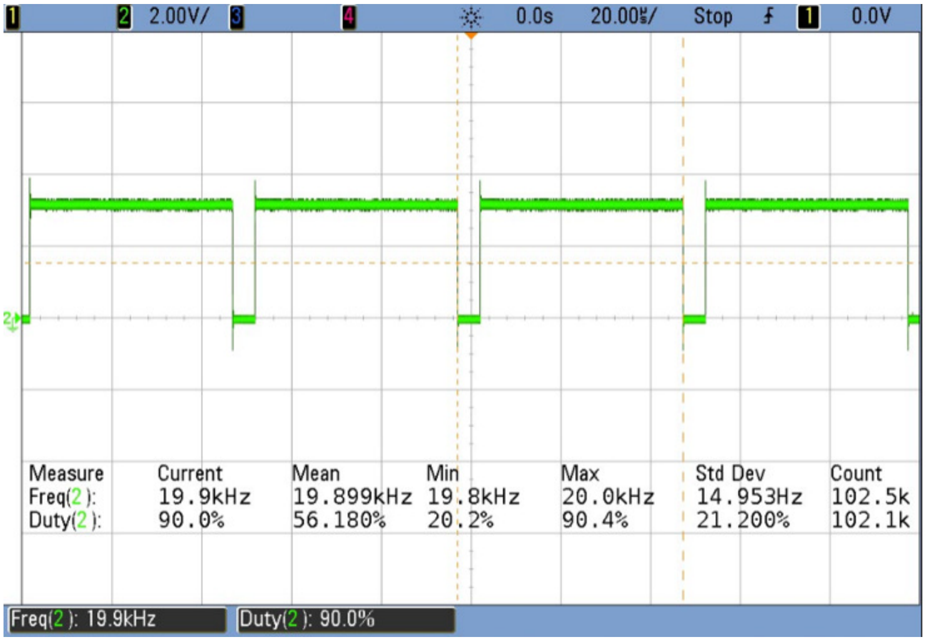
Measure	Current	Mean	Min	Max	Std Dev	Count
Freq(2):	19.9kHz	19.899kHz	19.8kHz	20.0kHz	14.944Hz	103.4k
Duty(2):	12.0%	55.762%	12.0%	90.4%	21.527%	103.0k

Fig. 5.6. Wireless Link Distance of 18 feet, ma = 0.12.



Measure	Current	Mean	Min	Max	Std Dev	Count
Freq(2):	19.9kHz	19.899kHz	19.8kHz	20.0kHz	14.527Hz	99.04k
Duty(2):	50.6%	55.009%	20.2%	90.4%	20.592%	98.65k

Fig. 5.7. Wireless Link Distance of 1 foot, ma = 0.5.



Measure	Current	Mean	Min	Max	Std Dev	Count
Freq(2):	19.9kHz	19.899kHz	19.8kHz	20.0kHz	14.953Hz	102.5k
Duty(2):	90.0%	56.180%	20.2%	90.4%	21.200%	102.1k

Fig. 5.8. Wireless Link Distance of 18 feet, ma = 0.9.

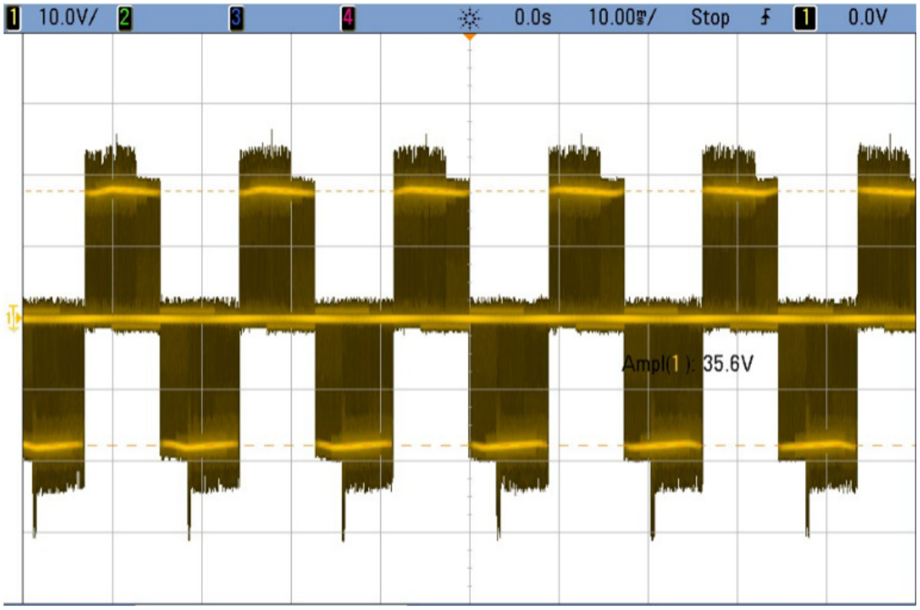


Fig. 5.9. Line-to-Line Voltage at Inverter Output.

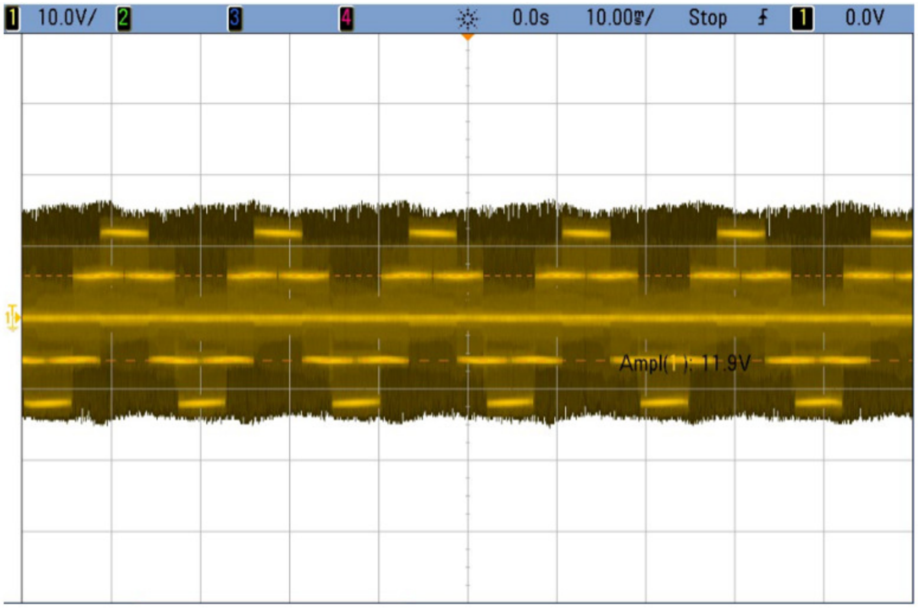


Fig. 5.10. Line-to-Neutral Voltage at Inverter Output.

5.3.2 AC Motor

After performing the experiments in section 5.3.1, the inverter output voltages and the receiver duty cycle for a wireless communication distance of 18 feet were validated. Hence, the next step was to connect the AC motor at the output of the inverter. The AC motor is a heavily inductive load. The three phase output of the inverter were connected to the three phases of the AC motor. The program in the receiver dsPIC was kept same as the previous test i.e. PWM algorithm for AC motors. The frequency of the reference voltage was reduced to $10Hz$ and the DC link voltage was kept at $30V$ constant. The potentiometer at the transmitter end was set to 0.12 modulation index. The motor was then switched ON. For a modulation index of 0.12, the motor did not start rotating. As the modulation index was gradually increased, the motor started rotating and its speed was observed to be changing with a change in the modulation index. The maximum speed of rotation for this case was observed at ma = 0.9.

The motor current was observed for modulation index of 0.12, 0.5 and 0.9. Fig. 5.11, 5.12 and 5.13 represent the motor current for ma = 0.12, 0.5 and 0.9 respectively. The line-to-line voltage was observed to be same as that for the resistive load. This voltage is as shown in Fig. 5.14.

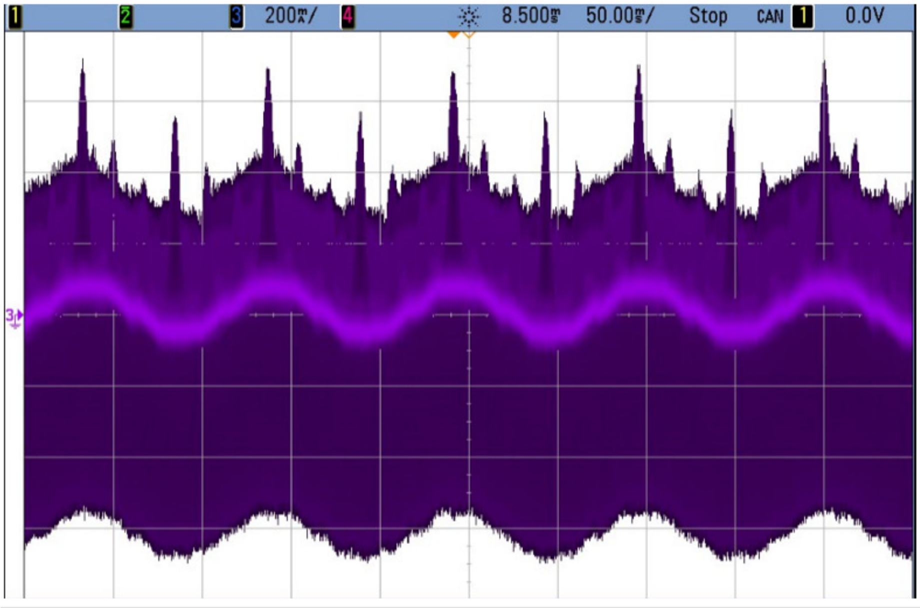


Fig. 5.11. AC Motor Current for ma = 0.12.

The scale for all the three plots for the motor current has been kept constant at 200 mA/div. Hence just by observation, it can be concluded that an increase in the motor current is observed as the modulation index is changed from 0.12 to 0.9. This increase in current corresponds to a increase in the speed of the motor.

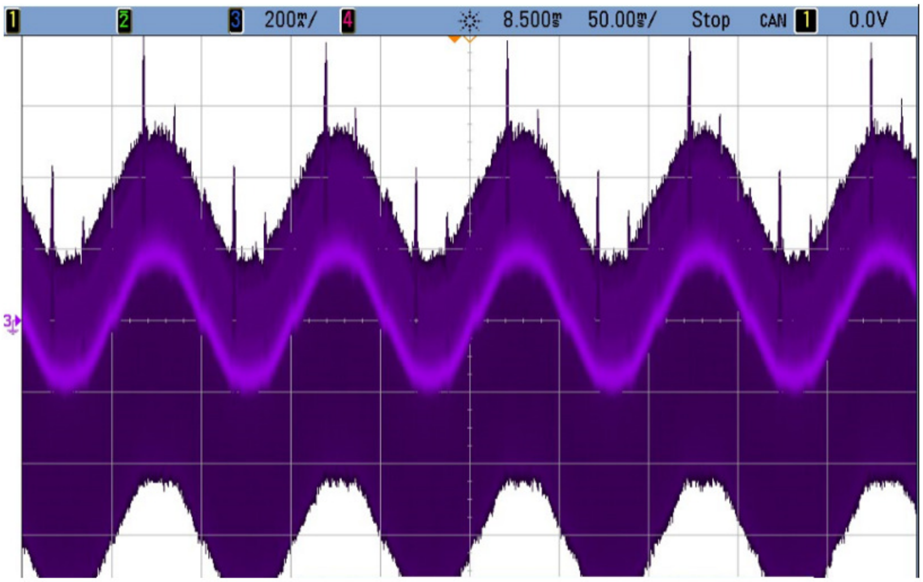


Fig. 5.12. AC Motor Current for ma = 0.5.

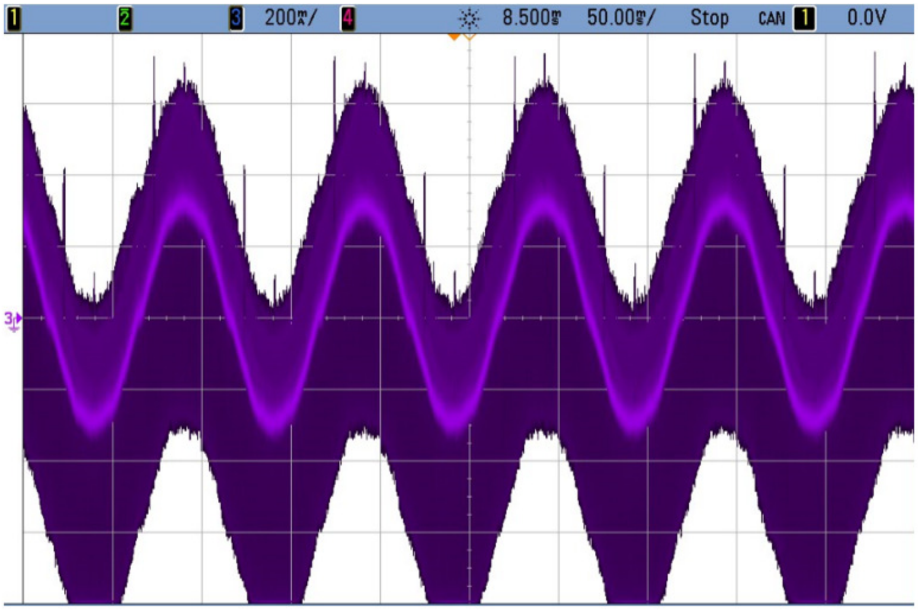


Fig. 5.13. AC Motor Current for ma = 0.9.

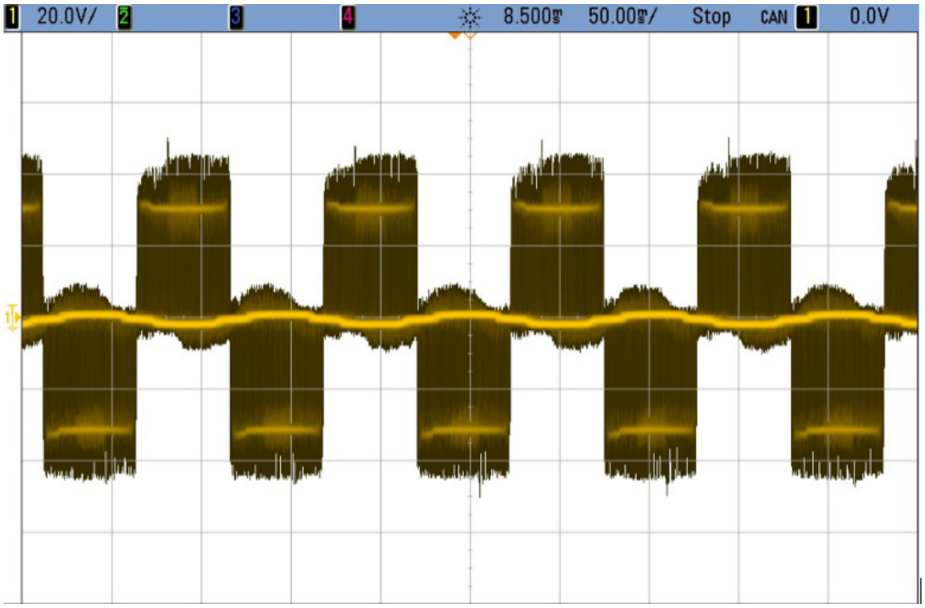


Fig. 5.14. Line-to-Line Inverter Voltage with AC motor Connected.

5.3.3 DC Motor

After the experiment involving AC motor, the next step is to check for DC motor. One of the applications that the proposed system focuses on is the implementation of this drive in ceiling fans. Thus the motor under consideration will be a DC motor. Due to unavailability of a DC motor, this tests was performed by connecting a resistive load between two of the three phases of the inverter output. The dsPIC at the receiver was programmed with the PWM algorithm for DC motors. The DC link voltage was set to $17V$. Fig. 5.15 shows the experimental set up at the receiver end for the DC motor. The PWM signals at the receiver were observed for ma = 0.12, 0.5 and 0.9. Fig. 5.16, 5.17 and 5.18 represent the PWM signal for ma = 0.12, 0.5 and 0.9 respectively.

From Fig. 5.16, 5.17 and 5.18 it can be observed that for a load connected between the two phases of the inverter, on implementation of the DC motor PWM algorithm, the duty cycle corresponding to the modulation indices can be obtained. From Fig. 5.16 for a ma = 0.12, a duty cycle of 12% is obtained. A 50% duty cycle

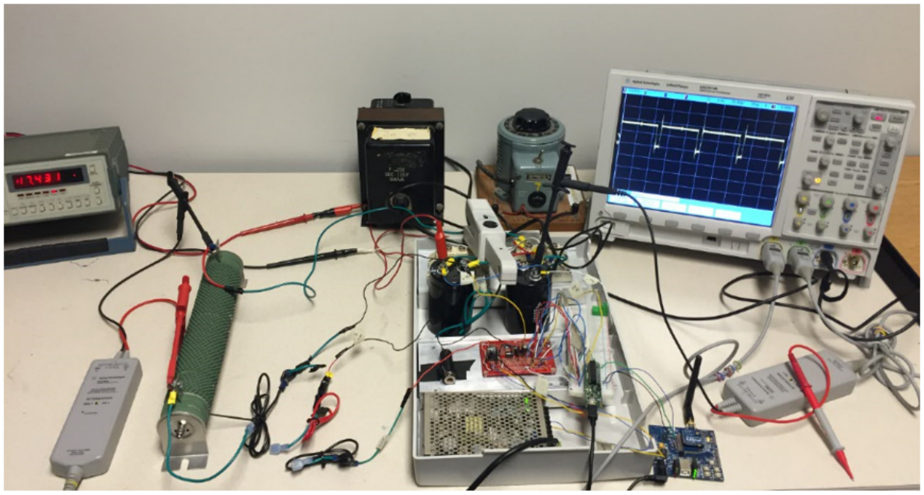


Fig. 5.15. Experimental Set up for DC Motor.

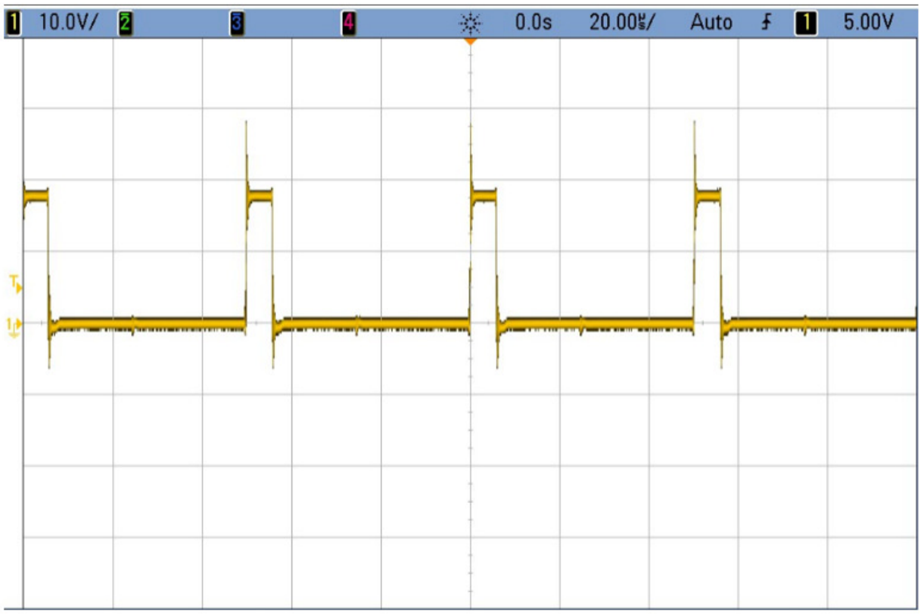


Fig. 5.16. PWM for ma = 0.12, DC Motor Application.

is obtained when the modulation index is increased to 0.5 as shown in Fig. 5.17. While it can be seen from Fig. 5.18 that 90% duty cycle is obtained on setting up the modulation index to 0.9. Thus for a DC motor application, increasing the modulation index increases the duty cycle of the PWM and hence the speed of the motor.

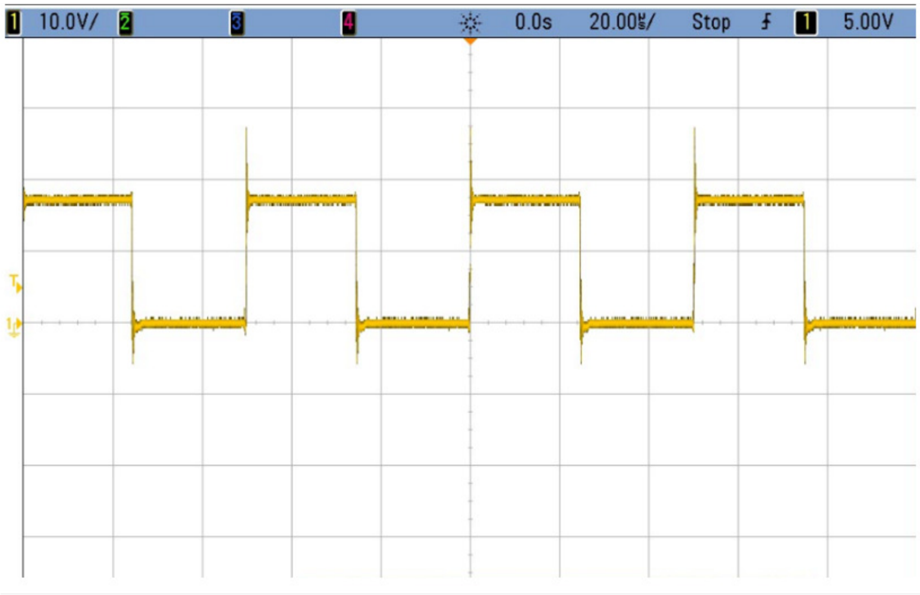


Fig. 5.17. PWM for ma = 0.5, DC Motor Application.

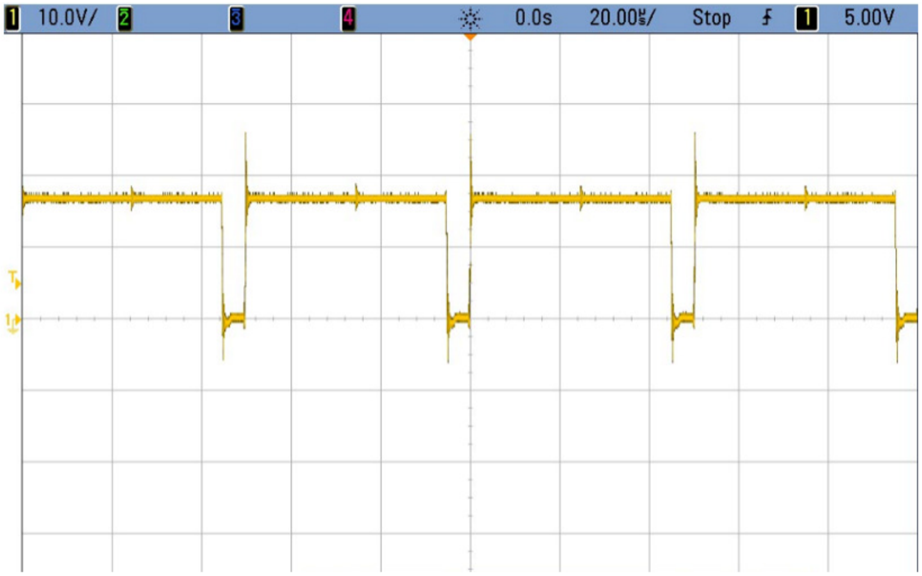


Fig. 5.18. PWM for ma = 0.9, DC Motor Application.

6. CONCLUSION

The proposed system with integration of zigbee to the motor drive system was successfully implemented and tested. The speed of rotation of an AC motor and the duty cycle for the DC motor application were observed as a function of the modulation index, thus validating the PWM strategy for both AC and DC motors. The modulation index was continuously changed using the potentiometer from 0.12 to 0.9 and back to 0.12, and the corresponding change in the speed of the motor was observed.

The Xbee modules which operate on the zigbee protocol were set to a baud rate of 9600. The fast RF- transmission due to its operation in the transparent mode helps in immediate transfer of the data from the transmitter to the receiver end. The ease of configuration of the radio modules by using AT commands and simplicity in the network set up makes Xbee radios one of the best choice for this application. With the transmission range of nearly few 100 feet makes this application user friendly for remote access.

As discussed in the chapters above, the system is implemented for both AC and DC motors. The hardware is kept same for both the motor operation. By changing the reference voltages, the PWM algorithm for AC motors was converted into the PWM algorithm for the DC motor. Hence ease of implementation became a major advantage. By keeping the same hardware for the drives of AC and DC motor, overall cost saving can be achieved in processes where one motor replaces other. Also in applications such as irrigation, the speed control from a remote distance can be of great use.

The Sinusoidal PWM technique is one of the most basic PWM algorithms that can be developed and tested. By making use of dsPIC33F, digital PWM signals were obtained which have better accuracy as compared to their analog counterparts. Since the chosen dsPIC had PWM pins devoted to motor control application, implementation of six PWM signals was done with minimal hardware.

The inverter was a conventional three phase inverter with a 3 level line to line voltage. The three phase AC motor was connected to the three phases of the inverter and the experiments were successfully performed. For the DC motor application, a resistive load was connected between two of the three phases and the experiments were successfully performed.

The future extension of this system can comprise of developing an algorithm to find the type of motor connected and setting up the PWM algorithm with respect to that. Secondly various PWM techniques can be implemented to improve the quality of output voltage which will ensure better operation of the motor. A higher version of Xbee module can be implemented to further increase the range and expand this two point system to a multipoint network.

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