Chapter 5

EXPERIMENTAL VERIFICATION

5.1 Introduction

The objective of the conducted experiment is to assess the versatility of IDH technology, which provides heat up of conducting and non-conducting materials.

In this chapter, first the proposed IDH system has been described and the considered the experimental parameter has been defined and follows the experimental results.

5.2 Experimental System

Induction Dielectric Heating takes power from the mains, converts it into frequencies suitable for specific applications, and then uses this power to create controllable heat in any conducting material or non-conducting material.

Power is applied to the work-piece by 3 phase induction coils. An alternating current flowing through a coil; (i) Generates a magnetic field, (ii) Places a work-piece, (iii) Induces eddy current or displacement current within the magnetic field. Heat is produced only after the eddy current or displacement current is induced.

The heating pattern of an object mainly depends on the design of winding or induction coil pattern. However the power and frequency can be obtained by taking suitable converter rating. The depth of heat penetration into the work-piece depends on the frequency; the lower the frequency, the deeper the penetration.

Figure 5.1 demonstrates structure of the 1 phase to 3 phase IDH coil control which can be divided into seven parts as follows:

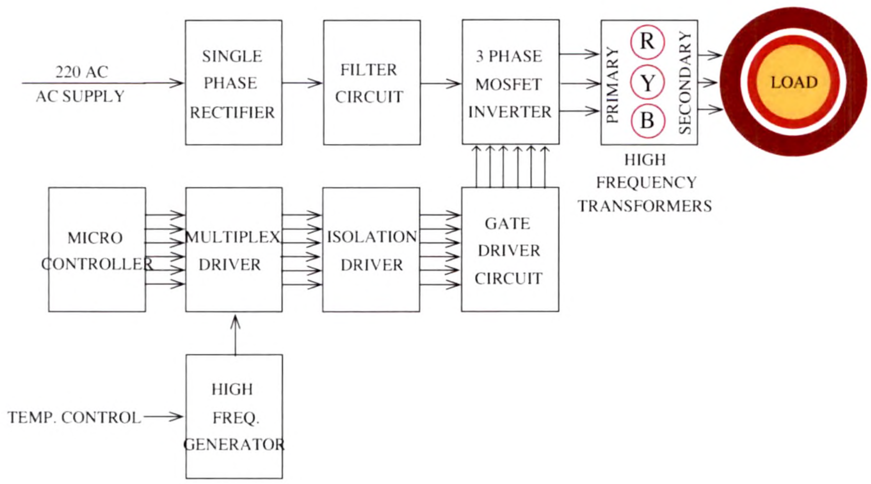

Figure 5.1: The Experimental System of IDH System Control

A. Main control unit

Main control unit consists of micro controller and multiplex driver as shown in Figure 5.1. In the experimental system the main control unit has to do the following tasks:

(i) To determine the SVM signal patterns and the main frequency control values for the SVM signal generator has been described in chapter 2.

(ii) To read in the three phase signals from the encoder.

(iii) To implement the digital control system.

(iv) To calculate the switching actions for the three inverter-legs.

(v) To control all the six timings individually of the SVM signal for firing circuit of the MOSFET devices.

(vi) To send the switching actions to the MOSFET driver card through multiplex driver.

B. High frequency generator unit

To generate the high frequency signal for desired patterns using 4093 IC. The unit has protection circuit for false phase fixing which may damage the MOSFET's three phase inverter.

Figure 5.2: High Frequency Transformer

C. MOSFET gate driver unit

Adjusts the signal derived from the multiplex driver to suitable for the MOSFET gate in the MOSFET inverter unit.

D. Rectifier unit

1 phase or 3 phase AC to DC converter using bridge rectifier unit.

E. MOSFET inverter unit

Frequency value and patterns have been developed by the micro controller and supplying power to primary side of high frequency transformers. The switches used are MOSFETs with a rated current of 25 A. The dead-time is 6 micro second. The maximum switching frequency of the MOSFETs is 20 kHz.

F. High frequency transformer unit

Suppling driving power from the three phase MOSFET inverter to the 3 phase

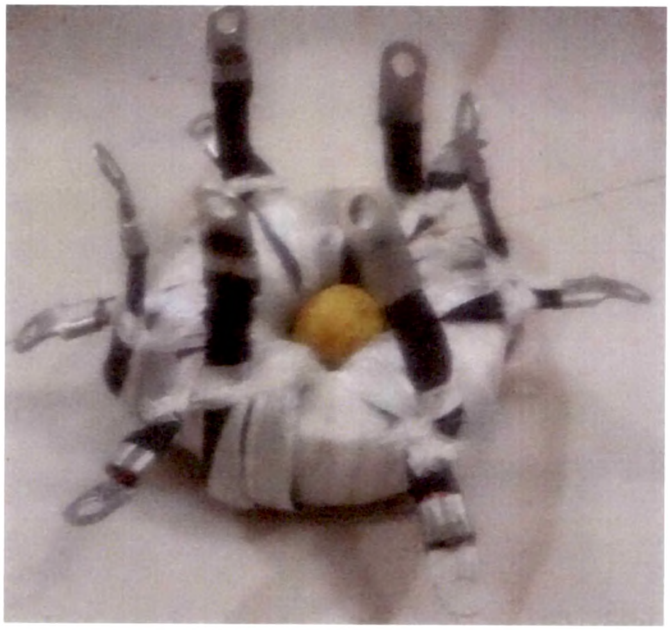

Figure 5.3: Three Phase Induction Coils

induction coil. High frequency transformer consisting of three, 1 phase transformers designed for specific needs as shown in Figure 5.2.

G. Heating coil unit

Generating high frequency magnetic field at resonance position for distributing heat to the material. Three phase induction coils are shown in Figure 5.3.

The hardware circuit layout for IDH control system is shown in Figure 5.4

5.2.1 Determination of control frequency

The control frequency which is required for heating the work-piece and can be determined by either main control unit or high frequency generating unit depending on type i.e. conducting or non-conducting material.

The main control unit frequency generated by the micro controller [108], [115] can be

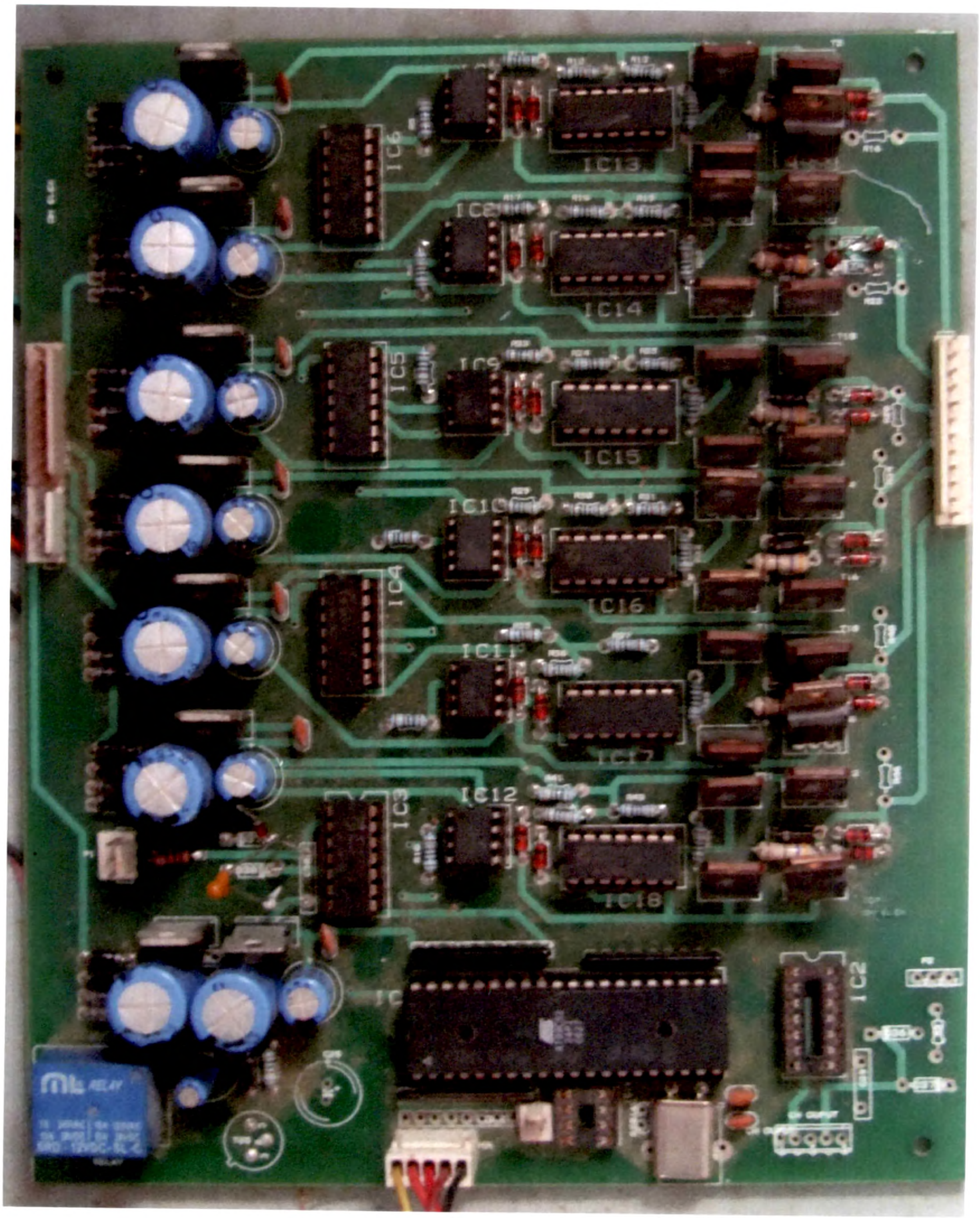

Figure 5.4: Hardware Structure of IDH System Control

Table 5.1: Limits of f_{PWM} and f_H

Range	f_{PWM}	f_H							
		8	7	6	5	4	3	2	1
Max (kHz)	15.69	2007.84	1003.92	501.96	250.98	125.49	62.75	31.37	15.69
Min (kHz)	0.03	3.94	1.97	0.98	0.49	0.25	0.12	0.06	0.03

derived from the following equations:

$$f_{CPU} = \frac{f_{OSC}}{2 \times D_{OCR}} \tag{5.1}$$

Where

f_{CPU} = Main control frequency generated by the micro controller in Hz
f_{OSC} = Micro controller clock signal in Hz
D_{OCR} = Divided frequency value in the micro controller in Hz

PWM frequency is given as follows:

$$f_{PWM} = \frac{f_{CPU}}{256 \times 2} \tag{5.2}$$

Where

f_{PWM} = PWM frequency in the induction coil in Hz
f_{CPU} = Main control frequency generated by the micro controller in Hz

The high frequency generated unit by the IC 4093 can be derived from the following equations:

$$f_H = \frac{1}{1.1RC} \tag{5.3}$$

Where

f_H = High frequency in the IDH coil in Hz

So that, equations of induction coil PWM frequency is obtained as follows:

$$f_{PWM} = \frac{f_{OSC}}{1024 \times D_{OCR}} \tag{5.4}$$

And equations for calculating the divided frequency value in the micro controller is

$$D_{OCR} = \frac{125}{16 \times f_{PWM}} \tag{5.5}$$

Where

f_{OSC} = $11.0592MHz$

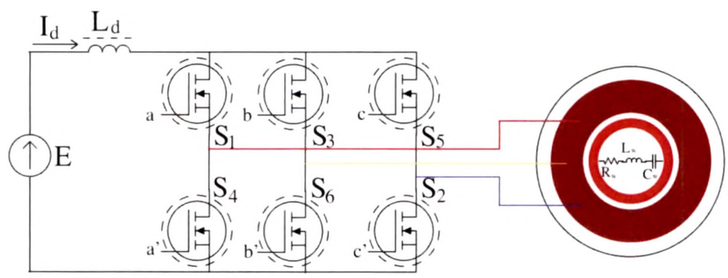

Figure 5.5: Three Phase MOSFET Base Inverter

According to the equation 5.3 and equation 5.4 the frequency generated from f_H and f_{PWM} are shown in Table 5.1. Results from Table shows that by using the PWM principle the frequency has been determined between $0.03 - 15.69$ kHz by main control unit. The high frequency generator unit generates the frequency in the range of 0.03 to 2007.84 kHz.

5.3 Protection Considerations

Three phase MOSFET base inverter as shown in Figure 5.5. Protection against over voltages across the power devices is shorting out devices S_1 & S_4 and concurrently forcing the DC current to zero. Over voltages could arise as a result of too large a capacitor voltage. This in turn could take place if the load coil were to become open circuited. The current source inverter has the additional attribute of tolerating fault currents since DC current source is controllable. Consequently the applied current source can be phased back upon detection of a fault current. A fault current would occur if either the coil or a device were to become shorted or if a device had failed to commutate. Additional necessary protection includes the capability of maintaining sufficient turn off time margin for the load commutated devices. This can be accomplished by monitoring the tank voltage and calculating the turn off time available until the succeeding voltage zero crossing. Consequently transient changes in the systems could result in a commutation failure. Hence additional turn off time margin has been typically provided in order to take into account the likelihood of such an event. This type of event mainly occurs for ferrous metal melting where the resonance frequency increases during the melt cycle.

5.4 Component Ratings

The ratings of the components are established by using Fourier analysis techniques. Initially an equivalent circuit model is developed. This model is based on the following simplifying assumptions:

1. The input current of the inverter is constant.
2. The semiconductor switches are ideal.
3. The output transformer is ideal and has a unity turns ratio.
4. The inverter operates in the continuous mode.
5. The effect of the overlap period is neglected.

It is also convenient to define base values for voltages, currents and times for adopting a comparative reference base from which other inverter schemes are to be judged. From a users point of view, it is appropriate to consider the effective coil resistance as a base impedance. Furthermore, it is useful to establish the driving source as base value. This happens to be the current for the case of a current source.

5.5 Advantages

The technical features of induction dielectric heating deliver three key benefits: improved throughput, better and consistent quality and reduced costs.

5.5.1 Throughput

Using induction dielectric heating into the production line improves production efficiency. It can cut lead times and speed up throughput. The IDH heating process itself is faster than open-flame and oven alternatives.

5.5.2 Quality

Quality improves because it can apply pre-set temperatures to pre-set parts of individual work-pieces and because induction coils are special-made for specific work-pieces, in advance, the delivered heat pattern. Also, precise heat delivery means any adjoining components and/or materials remain unharmed during the heating process.

5.5.3 Costs

Costs go down because of shorter lead times and increased throughput. Integrated in-line induction dielectric heating means lower pre-processing and logistics costs. Swift heat cycles, precise delivery and accurate repeatability minimize waste and scrap. IDH frequency converters are particularly effective at lowering energy costs, as it has a proven higher efficiency and power factor than competing converters.

5.6 Experimental Results

Experimental circuit parameters are given in Table 5.2. The switching frequency generated from encoder is $279H_Z$. Figure 5.6, Figure 5.7 and Figure 5.8 show waveform of encoder, respectively. Figure 5.9, Figure 5.10, Figure 5.11, Figure 5.12, Figure 5.13 and Figure 5.14 show waveform of gate pulse applied to power devices using main control unit, respectively. High frequency transformer input and output voltages are shown in Figure 5.15, Figure 5.16, Figure 5.17, Figure 5.18, Figure 5.19 and Figure 5.20, respectively for conducting material. Figure 5.21, Figure 5.22 and Figure 5.23 show FFT of three phase inverter output voltage waveform, respectively. FFT of three phase IDH (Load) waveforms are shown in Figure 5.24, Figure 5.25 and Figure 5.26, respectively for conducting material.

Figure 5.27 shows high frequency generator unit waveform. Figure 5.28, Figure 5.29, Figure 5.30, Figure 5.31, Figure 5.32 and Figure 5.33 show waveform of gate pulse applied to power devices using high frequency generator unit, respectively. High frequency transformer input voltages are shown in Figure 5.34, Figure 5.35, Figure 5.36, respectively for non-conducting material. Figure 5.37, Figure 5.38 and Figure 5.39 show FFT of three phase inverter output voltage waveform, respectively for lemon. Experimental verification summaries are given in Table 5.3. Experimental sample results are shown in Figure 5.40 and Figure 5.41 respectively.

Table 5.2: Circuit Parameters

Parameter	**Value**	**Parameter**	**Value**
Utility	220V/50H$_Z$	N$_1$/N$_2$	50
V$_{ref}$	300V	L$_F$	200μH
L$_P$	10μH	C$_P$	26.96μF
R$_o$	50mΩ	L$_M$	20mH

Table 5.3: Experimental Verification Summaries

Parameter	**Value**	**Parameter**	**Value**
V$_{ab}$	1.272 V	I1	122 A
V$_{bc}$	1.285 V	I2	132 A
V$_{ca}$	1.269 V	I3	118 A
PF	0.9999	THD(V_O)	0.7%
F$_s$	279H$_Z$	Pout	100.61W

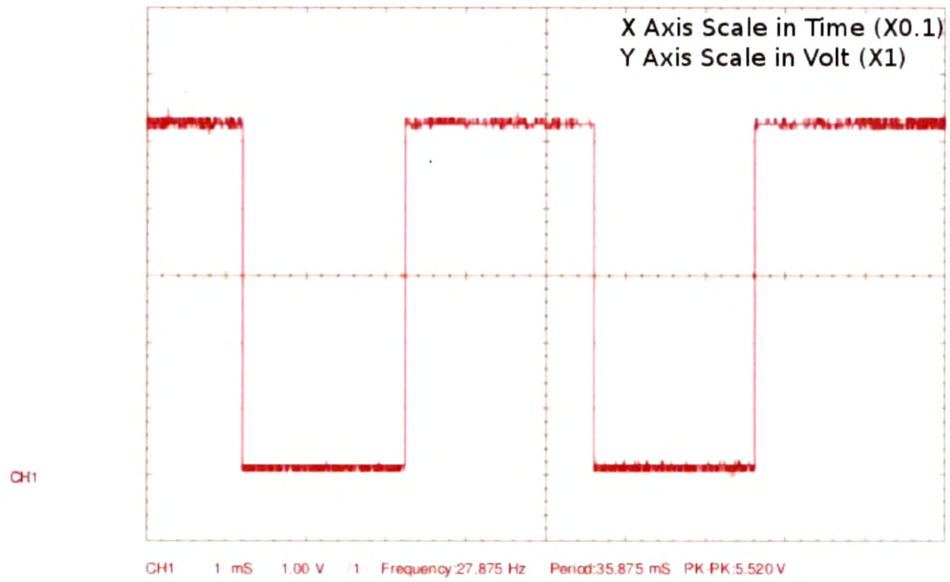

Figure 5.6: Encoder 1

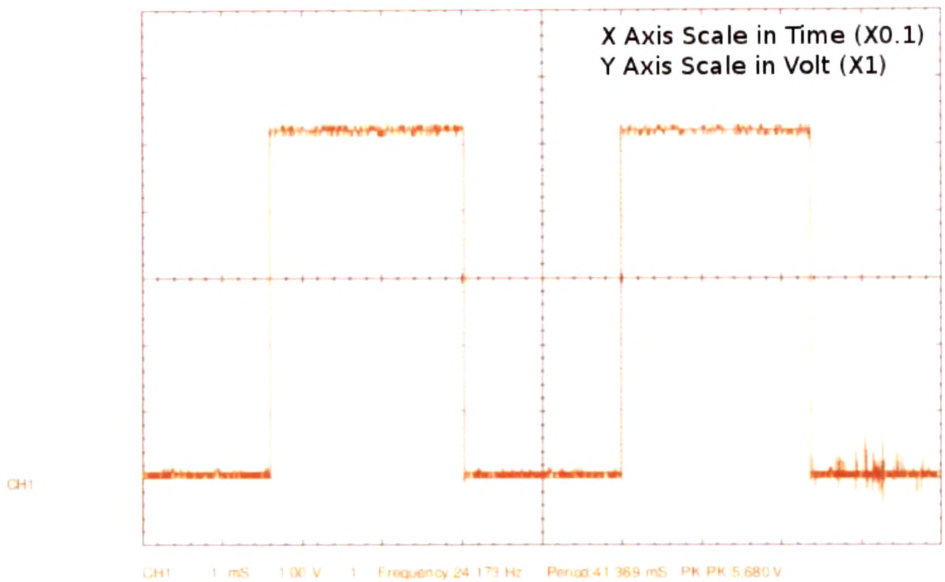

Figure 5.7: Encoder 2

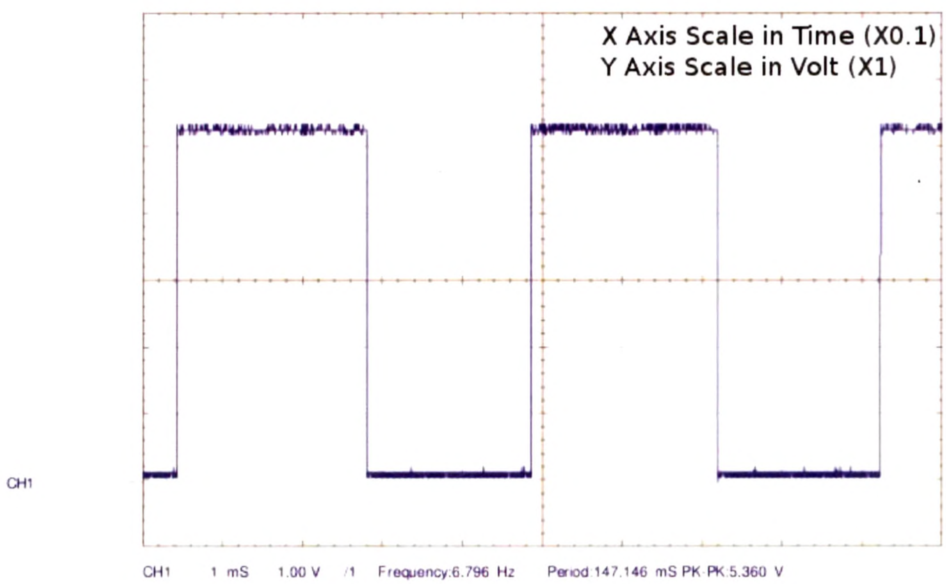

Figure 5.8: Encoder 3

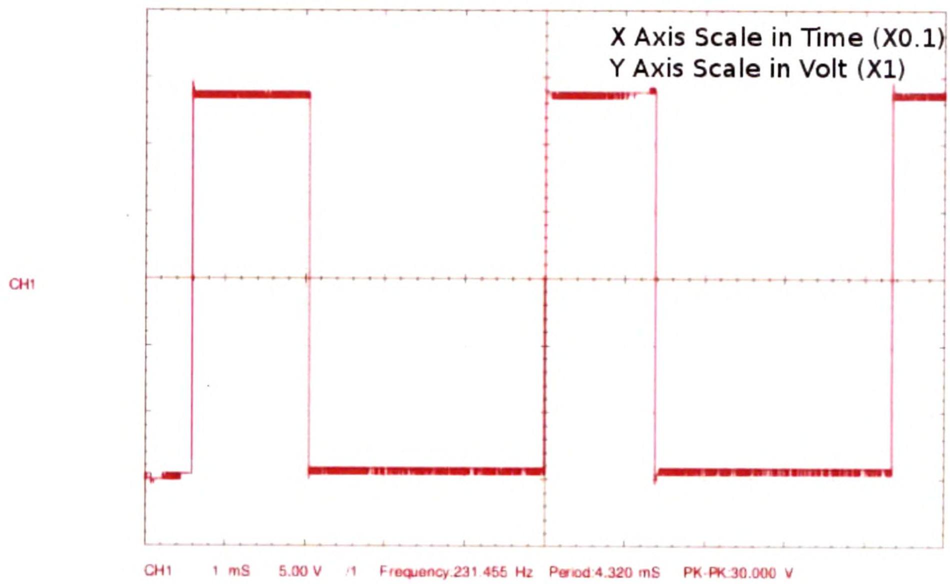

Figure 5.9: Gate Pulse for S_1 Using Main Control Unit

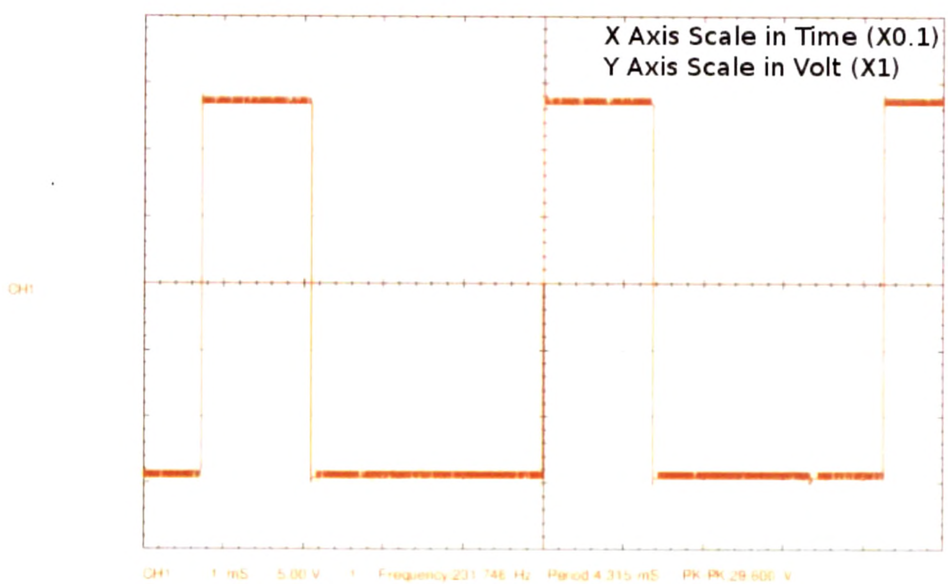

Figure 5.10: Gate Pulse for S_3 Using Main Control Unit

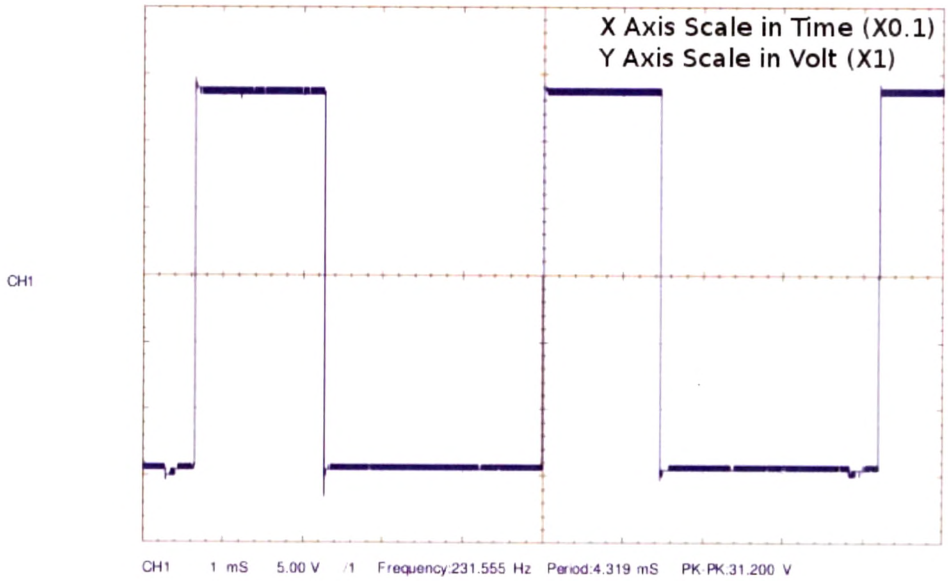

Figure 5.11: Gate Pulse for S_5 Using Main Control Unit

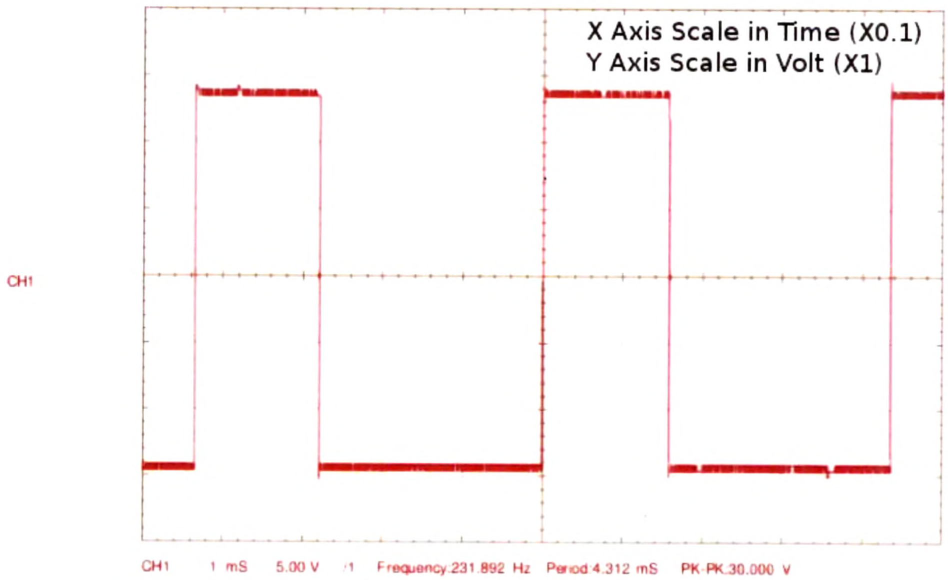

Figure 5.12: Gate Pulse for S_4 Using Main Control Unit

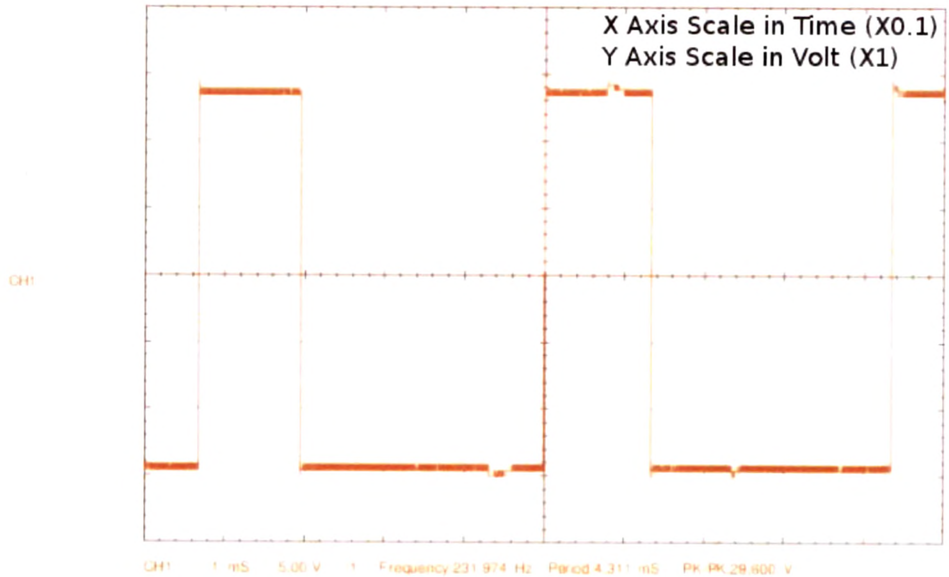

Figure 5.13: Gate Pulse for S_6 Using Main Control Unit

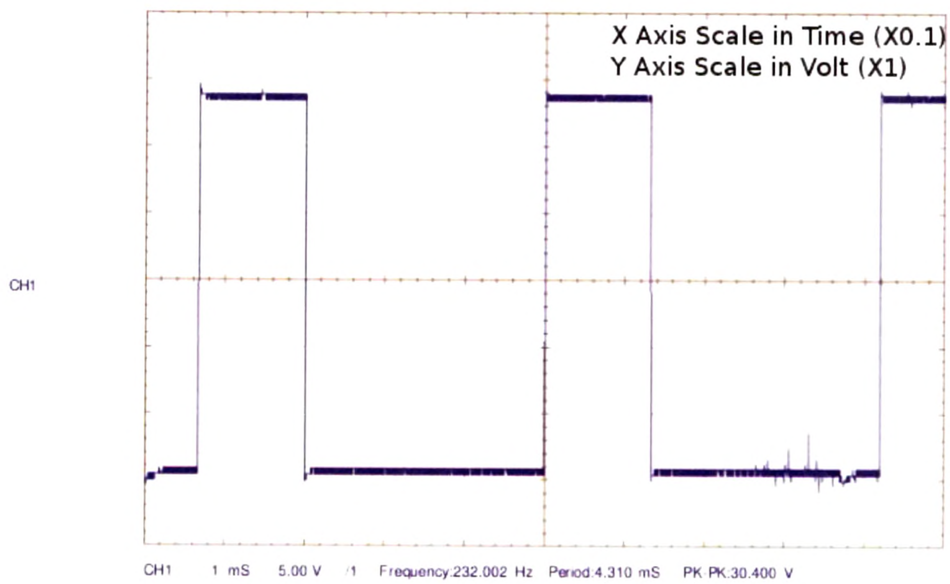

Figure 5.14: Gate Pulse for S_2 Using Main Control Unit

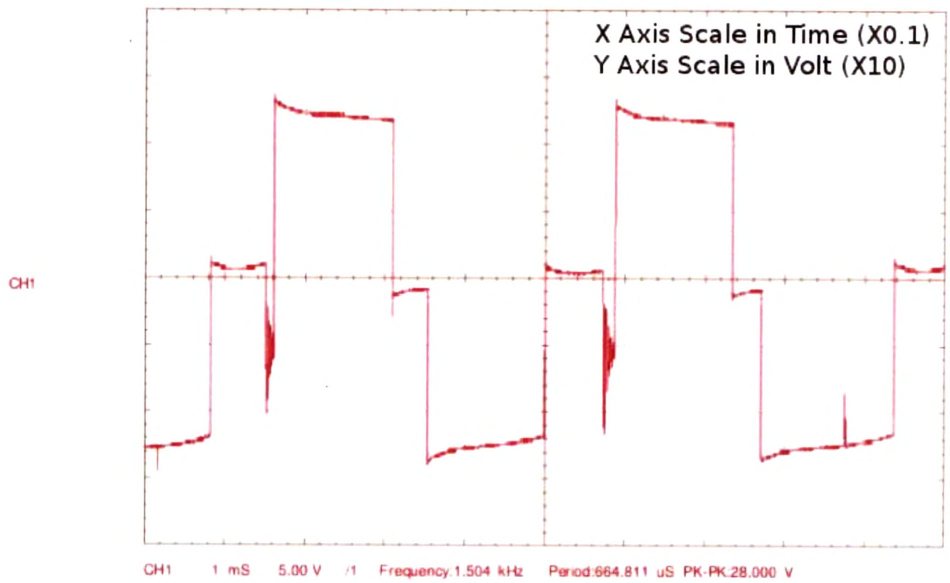

Figure 5.15: High Frequency Transformer Input Voltage Waveform (V_{iRY})

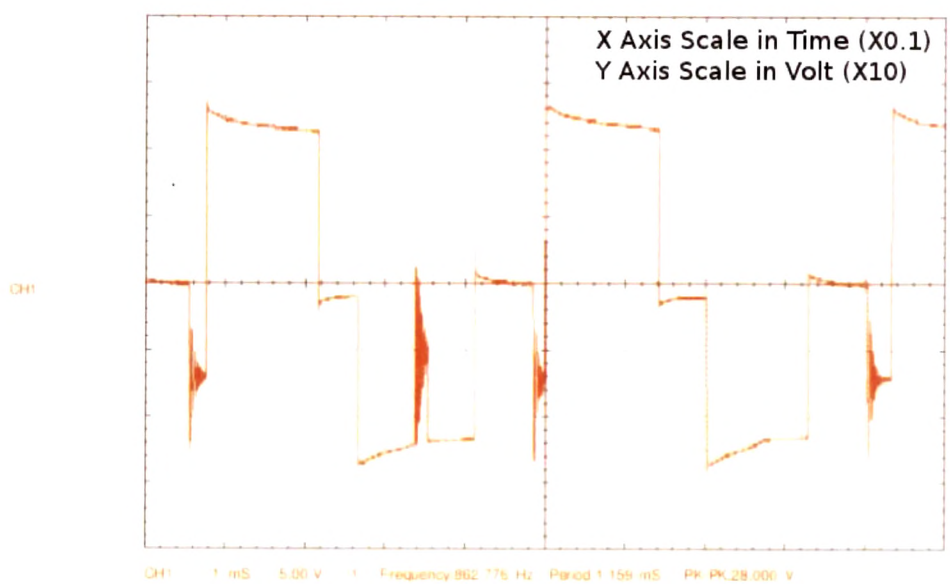

Figure 5.16: High Frequency Transformer Input Voltage Waveform (V_{iYB})

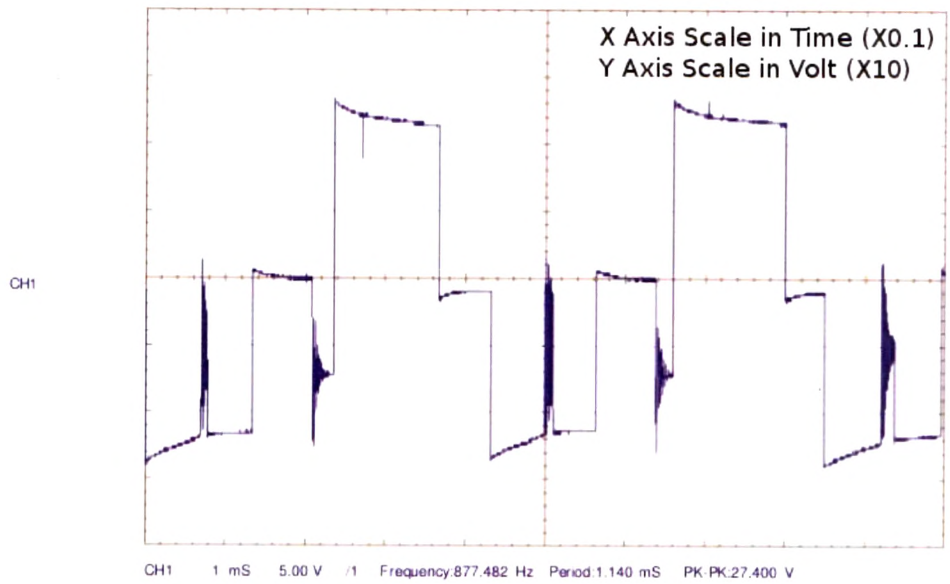

Figure 5.17: High Frequency Transformer Input Voltage Waveform (V_{iBR})

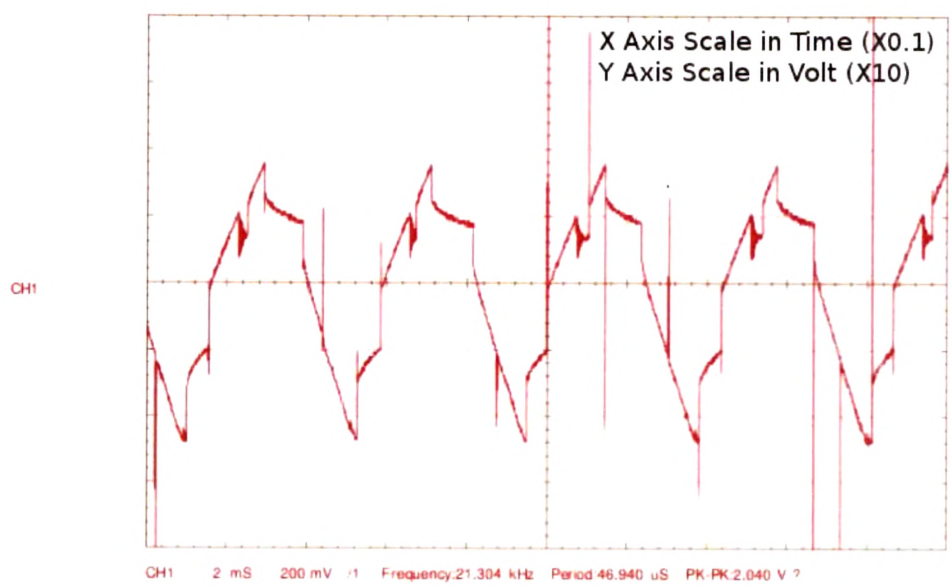

Figure 5.18: High Frequency Transformer Output Voltage Waveform (V_{oRY})

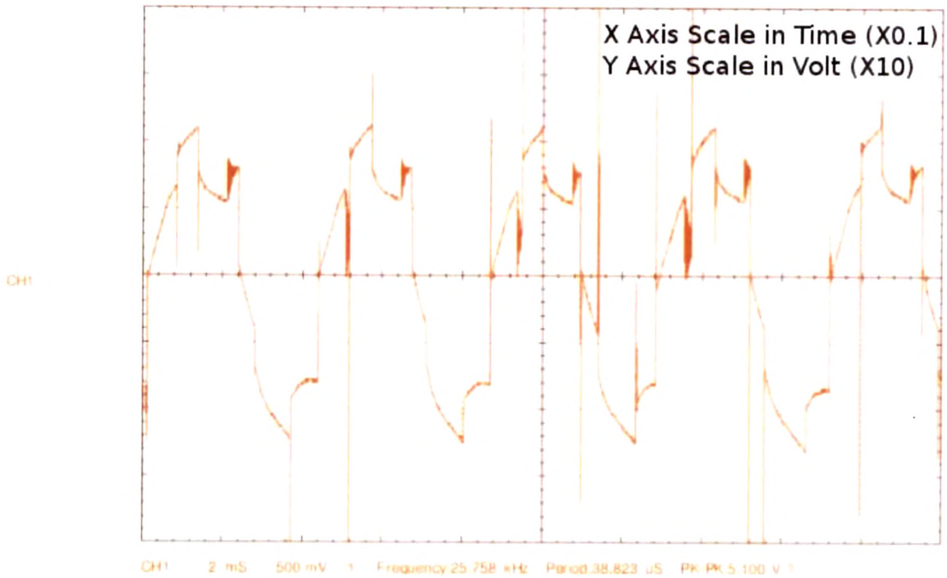

Figure 5.19: High Frequency Transformer Output Voltage Waveform (V_{oYB})

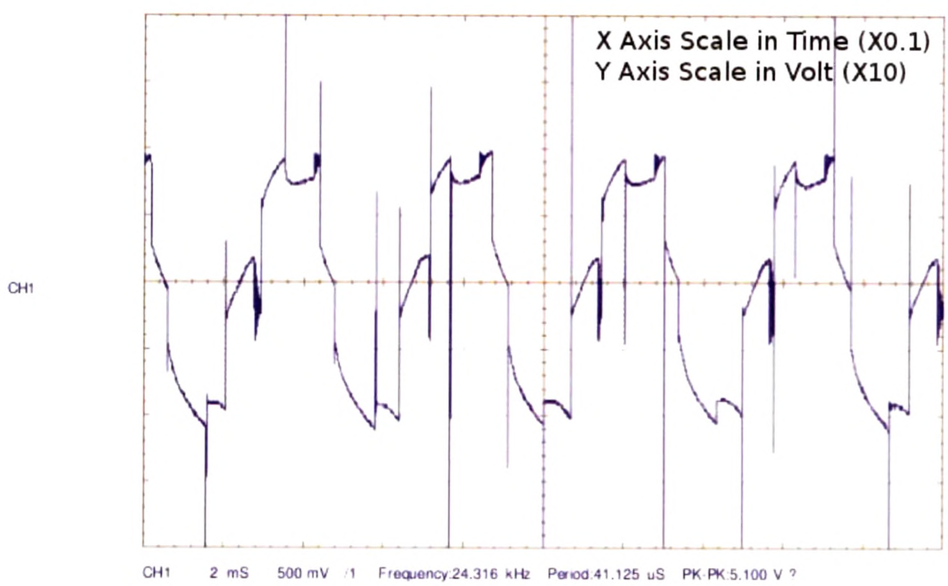

Figure 5.20: High Frequency Transformer Output Voltage Waveform (V_{oBR})

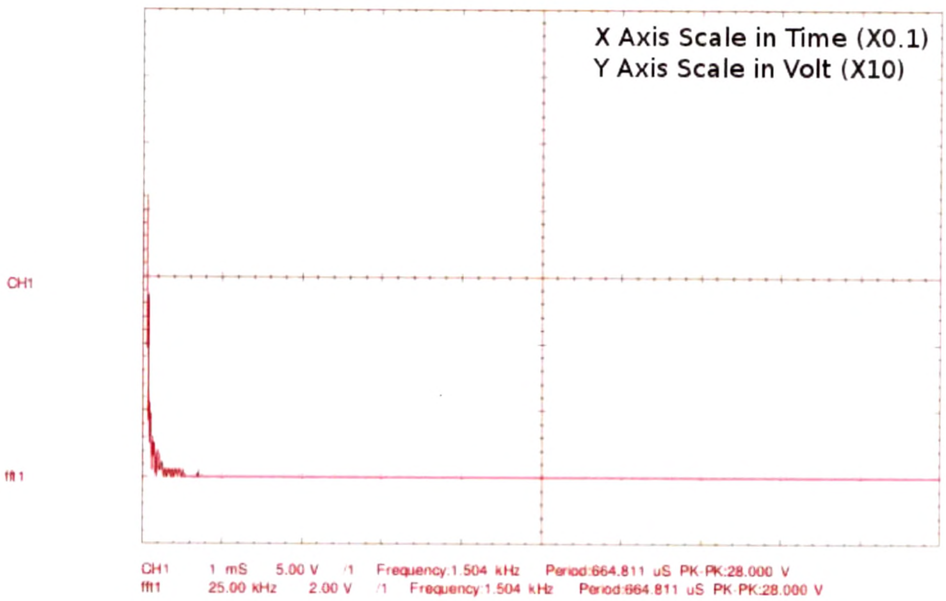

Figure 5.21: FFT of Three Phase Inverter Output Voltage Waveform (V_{iRY})

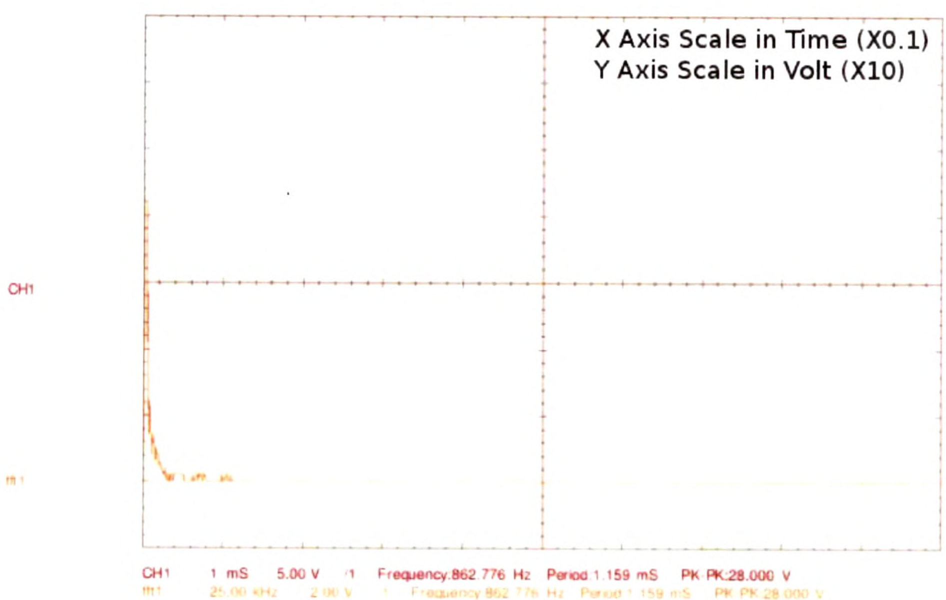

Figure 5.22: FFT of Three Phase Inverter Output Voltage Waveform (V_{iYB})

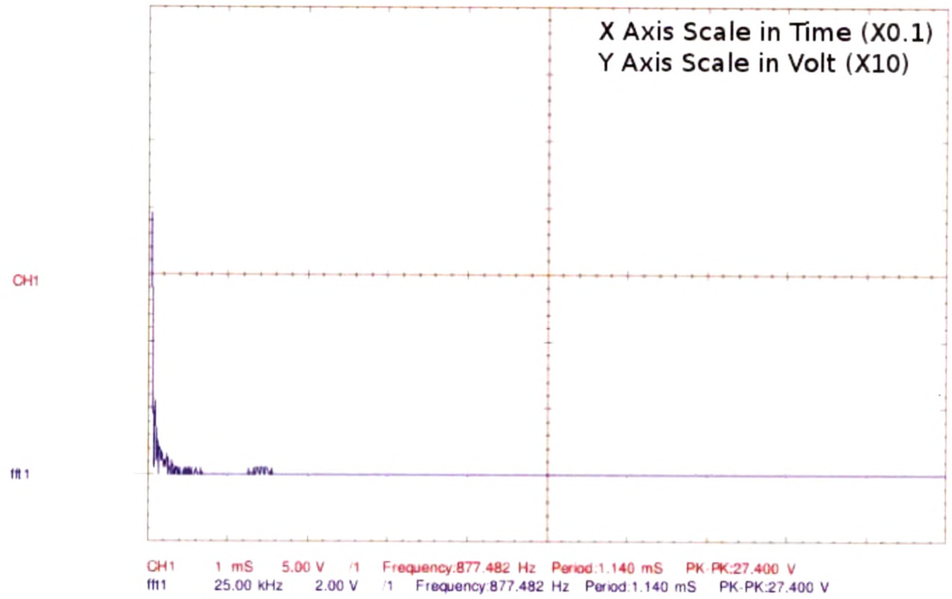

Figure 5.23: FFT of Three Phase Inverter Output Voltage Waveform (V_{iBR})

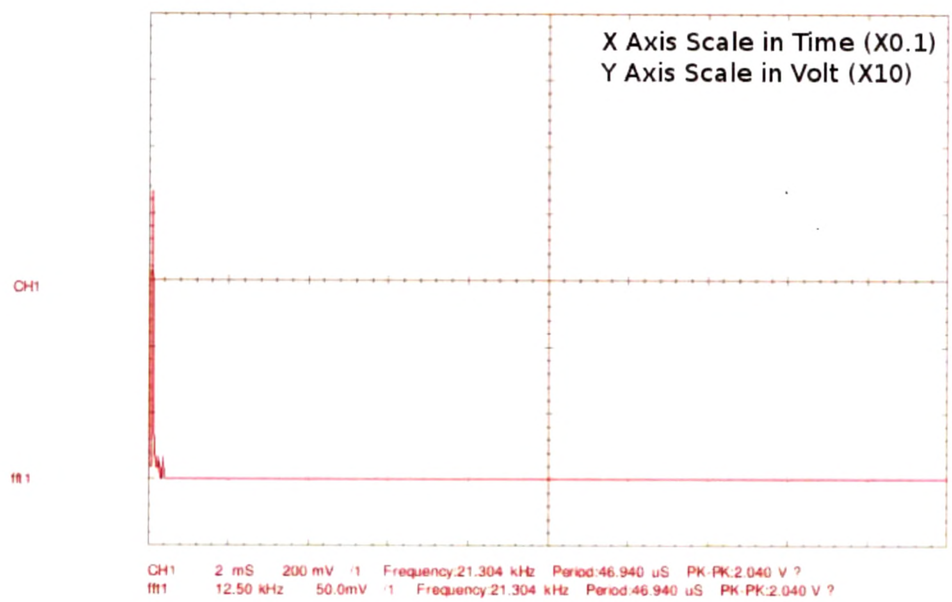

Figure 5.24: FFT of Three Phase IDH (V_{oRY})

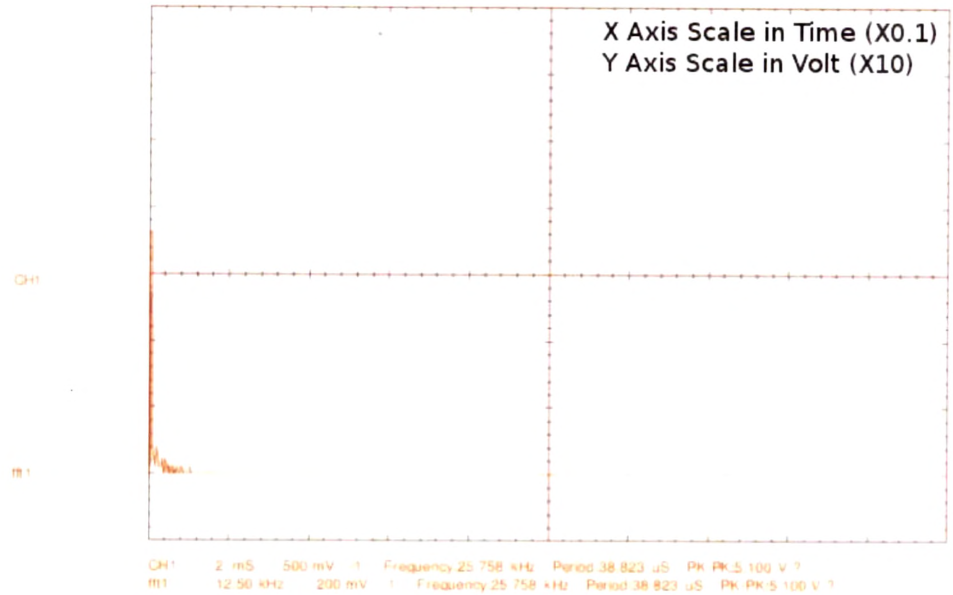

Figure 5.25: FFT of Three Phase IDH (V_{oYB})

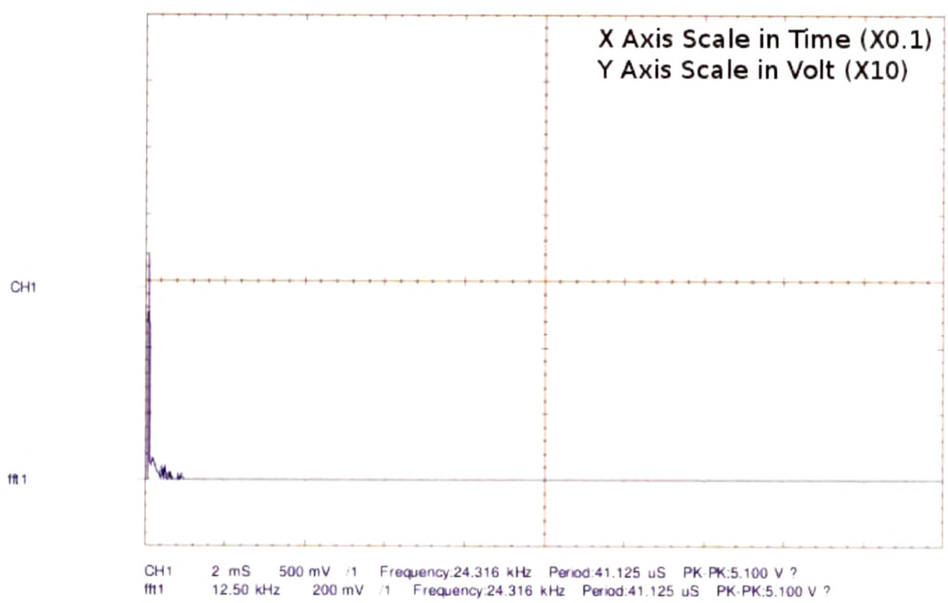

Figure 5.26: FFT of Three Phase IDH (V_{oBR})

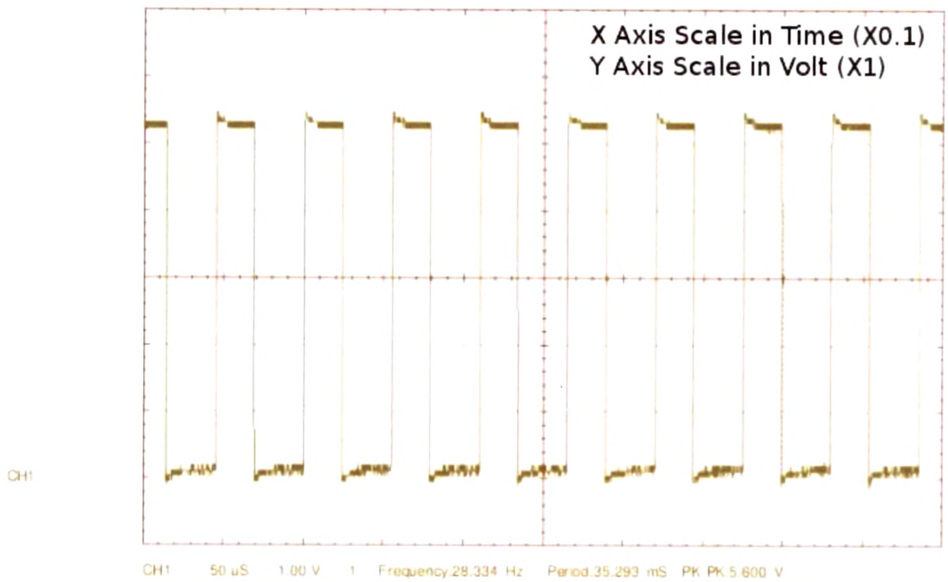

Figure 5.27: High Frequency Generator Unit

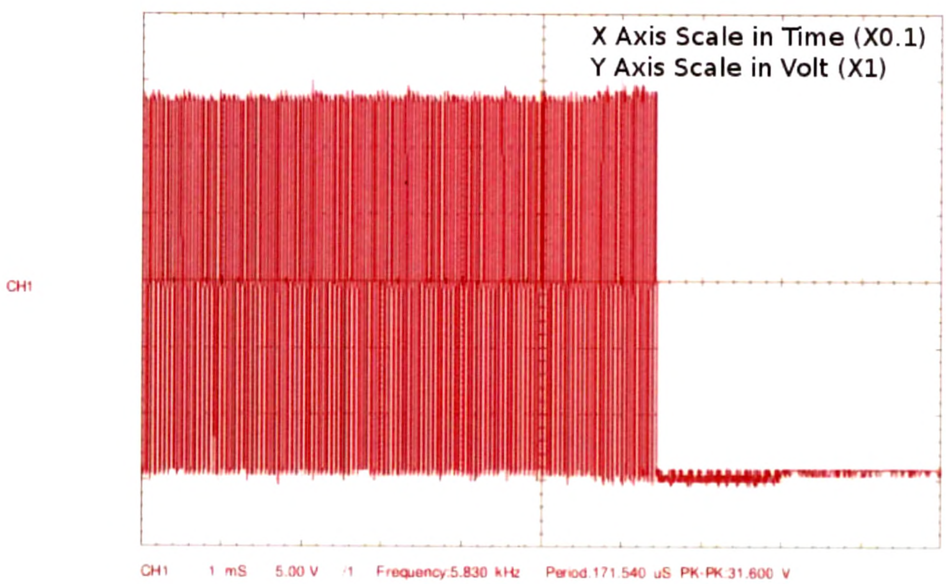

Figure 5.28: Gate Pulse for S_1 Using High Frequency Generator Unit

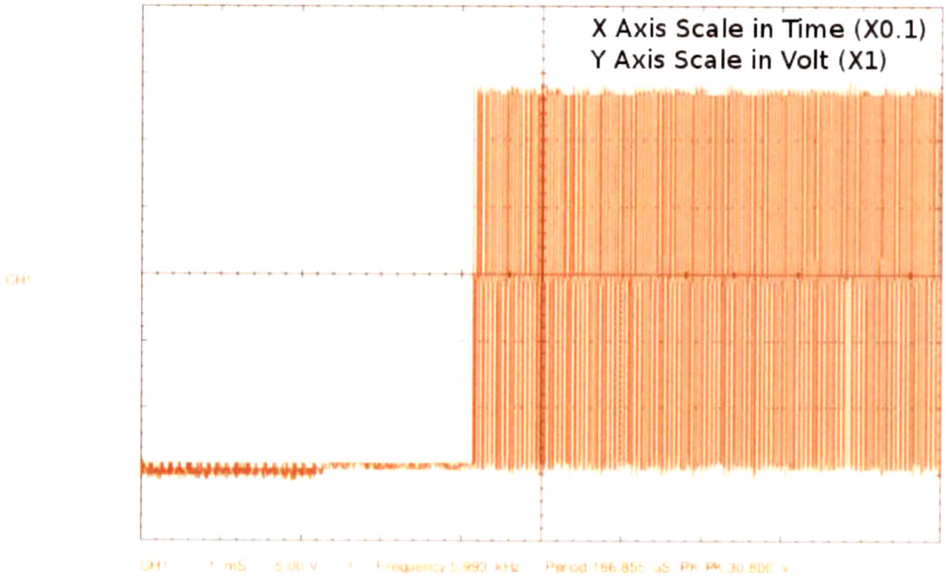

Figure 5.29: Gate Pulse for S_3 Using High Frequency Generator Unit

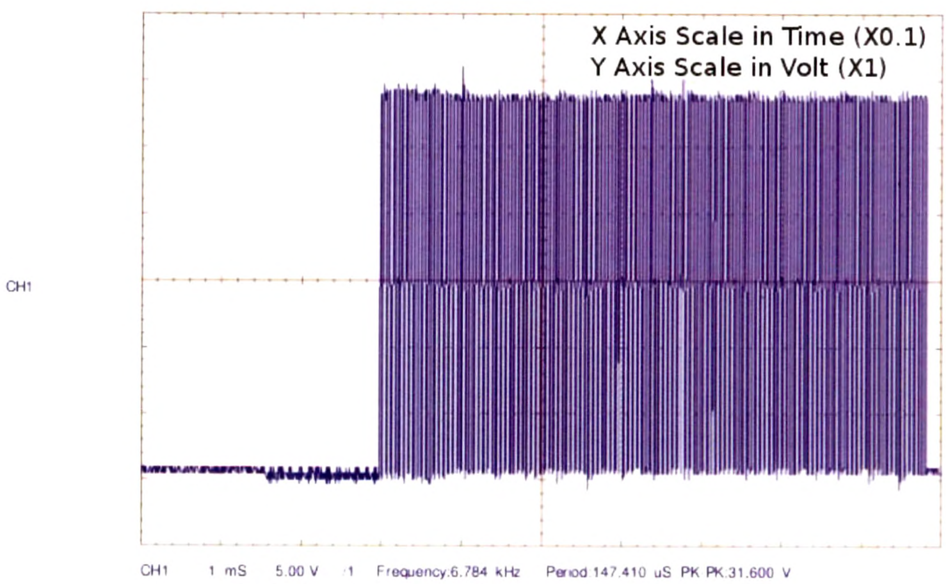

Figure 5.30: Gate Pulse for S_5 Using High Frequency Generator Unit

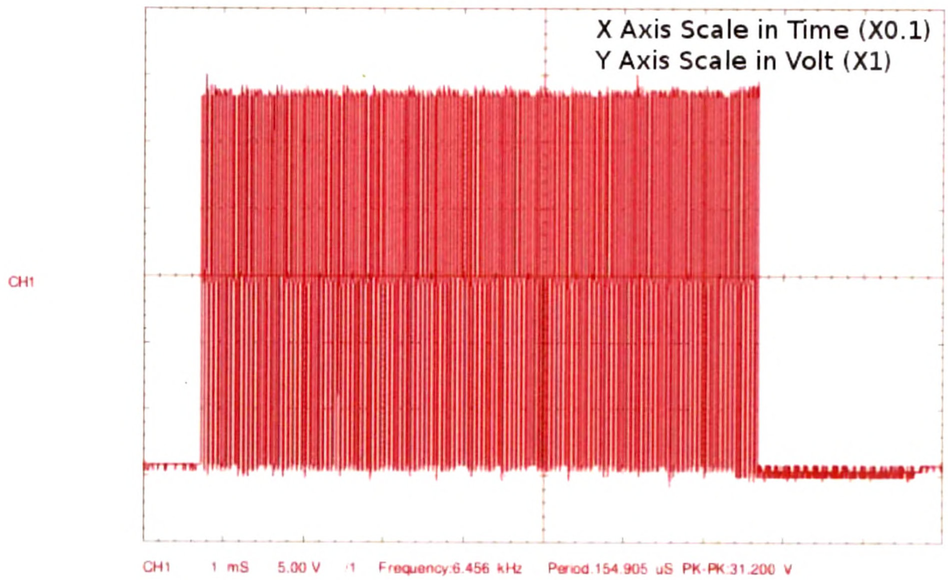

Figure 5.31: Gate Pulse for S_4 Using High Frequency Generator Unit

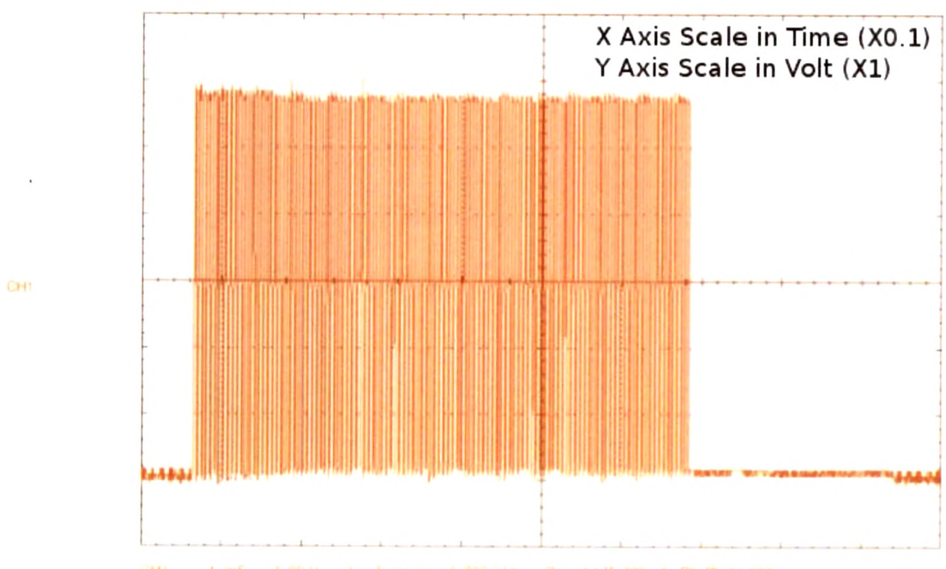

Figure 5.32: Gate Pulse for S_6 Using High Frequency Generator Unit

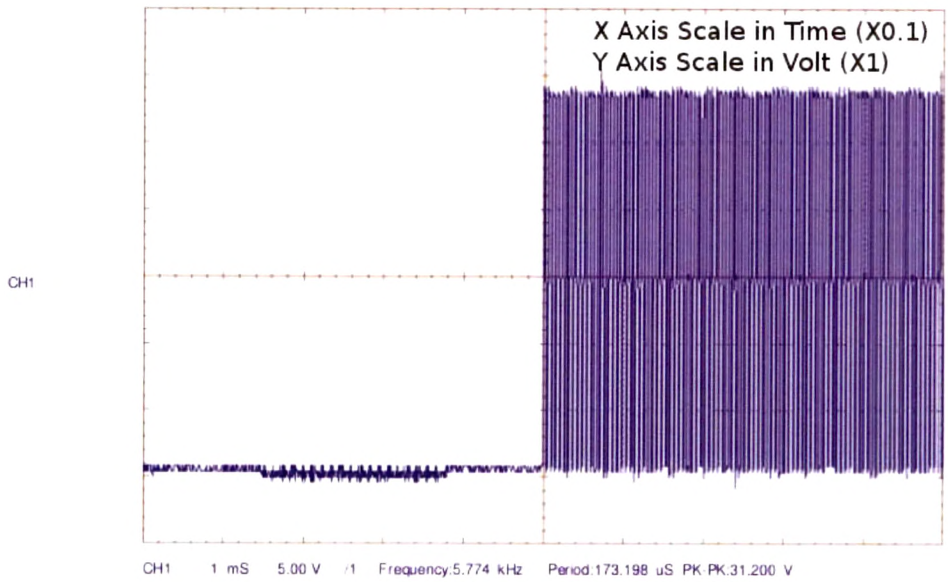

Figure 5.33: Gate Pulse for S_2 Using High Frequency Generator Unit

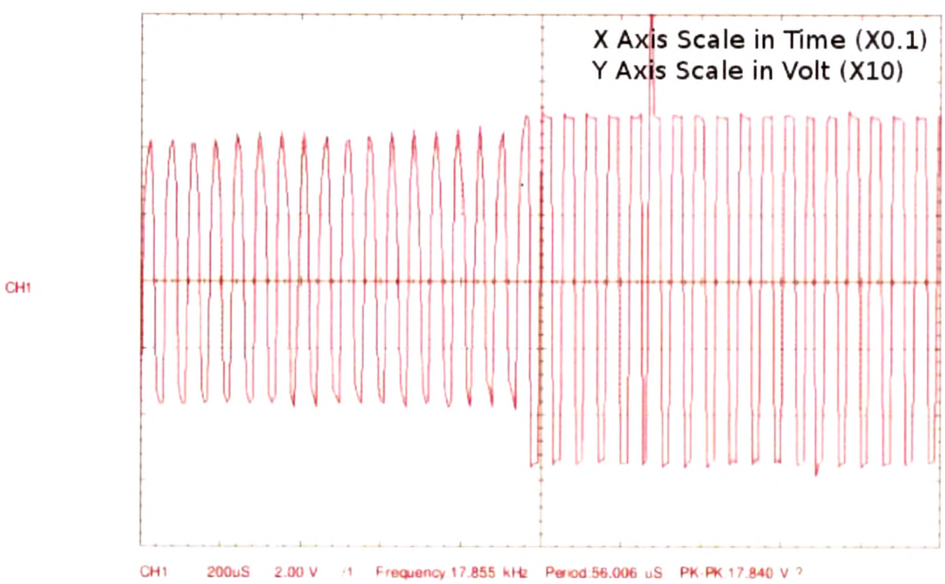

Figure 5.34: High Frequency Transformer Input Voltage Waveform (V_{iRY})

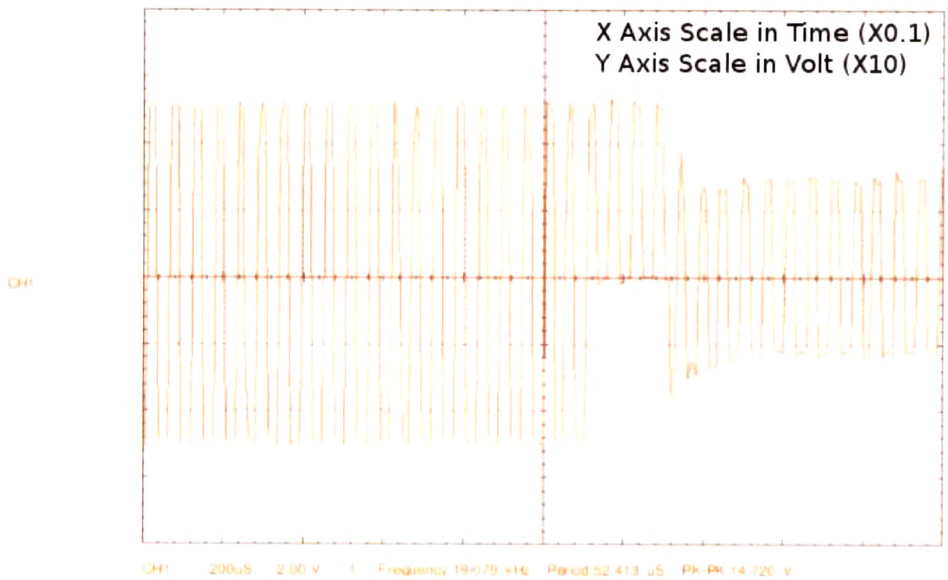

Figure 5.35: High Frequency Transformer Input Voltage Waveform (V_{iYB})

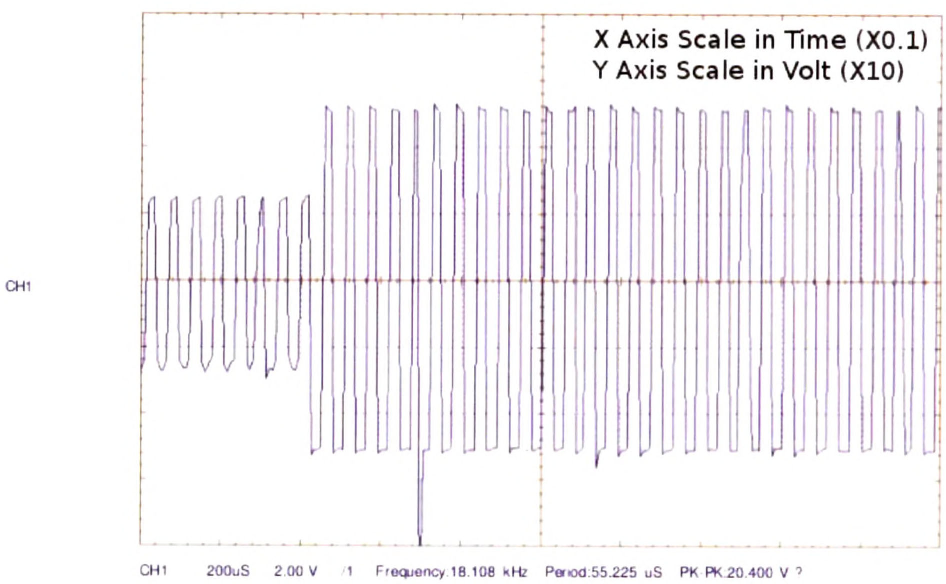

Figure 5.36: High Frequency Transformer Input Voltage Waveform (V_{iBR})

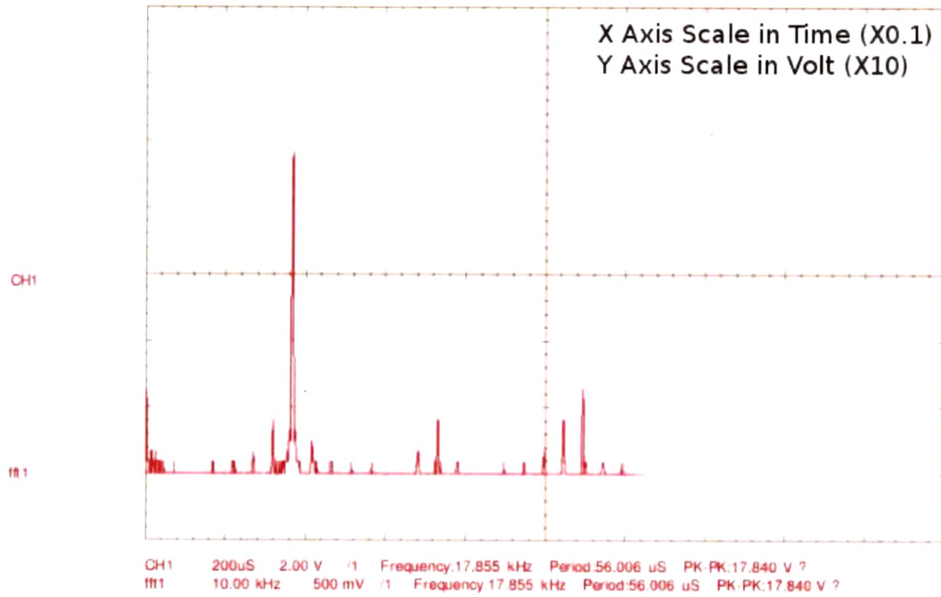

Figure 5.37: FFT of Three Phase Inverter Output Voltage Waveform (V_{iRY})

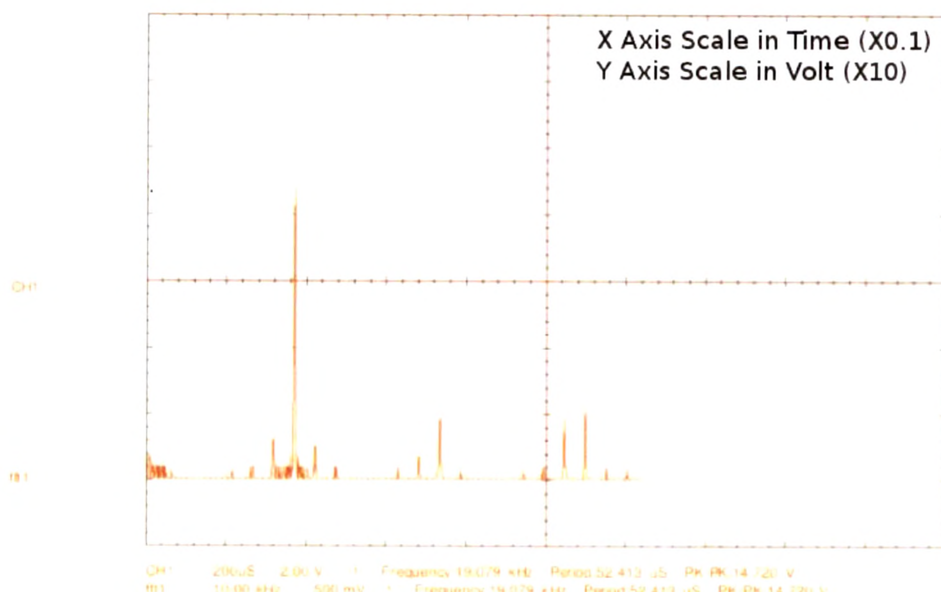

Figure 5.38: FFT of Three Phase Inverter Output Voltage Waveform (V_{iYB})

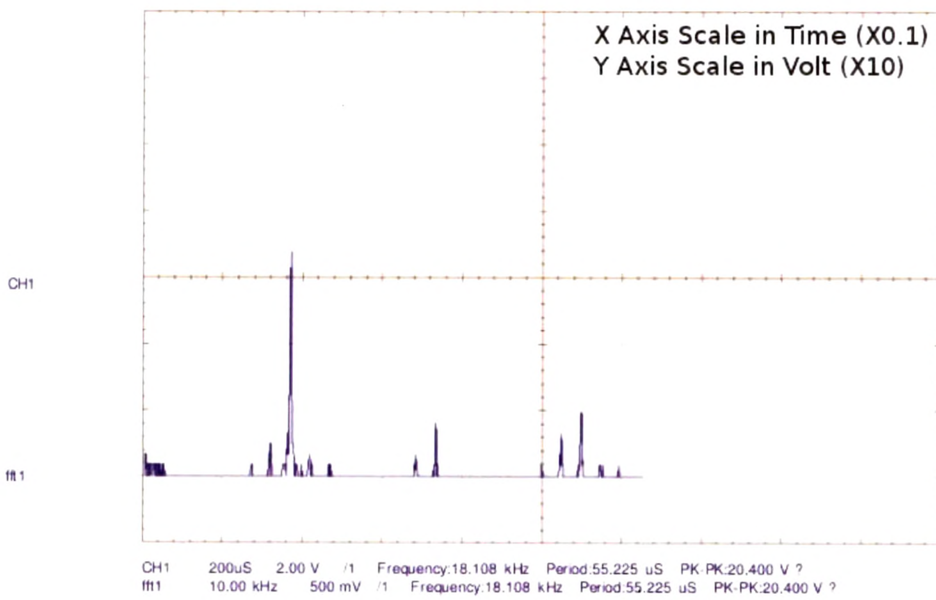

Figure 5.39: FFT of Three Phase Inverter Output Voltage Waveform (V_{iBR})

Figure 5.40: Sample Result 1

Figure 5.41: Sample Result 2

5.7 Conclusions

This chapter has described an induction dielectric heating experimental control structure and reveals the following findings:

1. This experiment demonstrated the ability of voltage level conversion ability, which leads to desired power even at low input voltage levels.

2. As frequency increases, the current becomes concentrated along the outer surface of the object.

3. The frequency of load can be varied by encoder.

4. The proposed algorithm is flexible and suitable for advanced vector control.

5. The strategy of the switching minimizes the distortion of load current as well as loss due to minimization commutations in the inverter.

6. Experimental technique of Induction Dielectric Heating (IDH) has been developed using micro controller.

7. The effectiveness of the SVM in the contribution in the switching power losses reduction has been demonstrated by performing an experiment.

8. SVM is one of the best solutions to achieve good voltage transfer.

9. It also provides excellent output performance optimized efficiency and high reliability compared to similar three phase inverter with conventional pulse width modulations.

10. Flexibility aspects of switching transformer leads to several advantages such as nearly unity power factor without using any reactive elements, symmetric loading from utility point of view, isolation of working coil, compact dimensions and almost uniform output voltage and temperature. It is proved by experimental setup.