T.R.
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCE

RESEARCH OF INVERTER SWITCHING DEVICES IN SERIES ARRANGEMENT

BEKİR EROĞLU

MASTER THESIS
ELECTRICAL ENGINEERING DEPARTMENT
ELECTRICAL MACHINES AND POWER ELECTRONICS PROGRAMME

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Bekir Eroğlu, a M.Sc. student of Yıldız Technical University Graduate School of Natural and Applied Science, successfully defended his thesis work on 12.01.2012 which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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At the end of my graduate study I want to thank my supervisor Prof. Dr. Asım Kasapoğlu of being great help during the development of this thesis and also my family who never give up supporting me through all my life.

January, 2012

Bekir EROĞLU

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LIST OF ABBREVIATONS

AC	Alternating Current
DC	Direct Current
HVDC	High Voltage Direct Current
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
PWM	Pulse Width Modulation
AC – PWM	Sinusoidal Pulse Width Modulation
V_{DSS}	Drain – Source Surrender Voltage
I_D	Drain Current
$R_{DS(on)}$	Drain – Source ON Resistance
TD	Delay Time
TR	Rise Time
TF	Fall Time
PW	Pulse Width
PER	Period
VOFF	Offset Voltage
VAMPL	Voltage Amplitude
FREQ	Frequency

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ABSTRACT

RESEARCH OF INVERTER INVERTER SWITCHING DEVICES IN SERIES ARRANGEMENT

Bekir Eroğlu

Department of Electrical Engineering

MSc. Thesis

Advisor: Prof. Dr. Asım Kasapoğlu

Today, power electronic converters have an extensive area of usage. As the one of these power electronic converters, DC – AC converters (also known as inverters) are also used for a wide variety of applications.

Using serially connected switching devices for inverter circuits is an important issue and provides several advantages such as low - cost and better switching characteristics.

In this paper, availability of using switching devices in series for inverter circuits is examined. Consequently, half - bridge inverter circuits (2 MOSFETs in series and 3 MOSFETs in series) are simulated. Then half – bridge inverter circuit with 2 MOSFETs in series is built and tested in laboratory. For all simulations and laboratory works; IRFS4410 (100V) model numbered MOSFETs are used as main switching devices. In brief; compatibleness, adaptability and power sharing capability of MOSFETs are tested and test results bring to a successful conclusion.

Key words: DC – AC converter, inverter, switching devices in series, switching devices in series arrangement

ÖZET

İNVERTERLERDE SERİ BAĞLI ANAHTARLAMA ELEMANLARI KULLANIMI

Bekir Eroğlu

Elektrik Mühendisliği Anabilim Dalı

Yüksek Lisans Tezi

Tez Danışmanı: Prof. Dr. Asım Kasapoğlu

Günümüzde, güç elektroniği dönüştürücüleri geniş bir kullanım alanına sahiptir. Bu güç elektroniği dönüştürücülerinden biri olan DC – AC dönüştürücüler (inverterler) ayrıca çok çeşitli uygulamalarda kullanılmaktadır.

İnverterlerde seri bağlı anahtarlama elemanlarının kullanımı; düşük maliyet ve daha iyi anahtarlama karakteristiği gibi bir takım avantajlar sağlayan önemli bir konu olarak görülmektedir.

Bu tez çalışmasında, inverter devrelerinde seri bağlı anahtarlama elemanlarının kullanımı incelenmiştir. Dolayısıyla, yarım köprü inverter devreleri (sırasıyla, seri bağlı 2 MOSFET ve seri bağlı 3 MOSFET kullanılarak kurulmuş) simüle edilmiştir. Ardından her kolda seri bağlı 2 MOSFET ile yarım köprü inverter devresi kurulmuş ve laboratuvarda test edilmiştir. Bütün simülasyon ve laboratuvar çalışmalarında ana anahtarlama elemanı olarak; IRFS4410 (100V) model numaralı MOSFETler kullanılmıştır.

Özet olarak; MOSFETlerin, bağdaşabilirlik, uyumluluk ve güç paylaşımı kabiliyetleri test edilmiş ve başarılı bir sonuca ulaşılmıştır.

Key words: DC – AC dönüştürücü, inverter, seri bağlı anahtarlama elemanları

CHAPTER 1

INTRODUCTION

1.1 Literature Review

Power electronics is very important and became wide-spread in every part of life today; such as controlling electrical machines, heat and light systems. Electrical energy is modified by power electronic converters. These converters are classified as [1]:

- Diode Rectifiers (Uncontrolled Rectifiers)

- AC – DC Converters (Rectifiers)

- DC – AC Converters (Inverters)

- DC – DC Converters (DC Choppers)

- AC – AC Converters (AC Choppers)

- Static Switches (Thyristorised contactors)

The most standard electrical devices are designed to be supplied by only alternating current. Because, electricity is supplied from the grid with the form of alternating current and to supply an electronic device from a direct current source, direct current is needed to transform into alternating current [2]. DC – AC converters are also called as Inverters convert direct current (DC) to alternating current (AC) and are used for a variety of applications such as; uninterruptable power supplies (UPS), emergency lighting systems, providing AC power by DC power source, HVDC power transmission, induction heating and AC variable speed drives.

Half - Bridge inverter (Figure 1.1) is also known as the “inverter leg”. Because half - bridge inverter is used as a block to build other advanced inverter types. Full bridge (single phase) inverter (Figure 1.2) is built from two half - bridge inverter legs and there is 180 degrees of delay between two legs [3]. In this thesis work, all circuits are built on half - bridge inverter circuit.

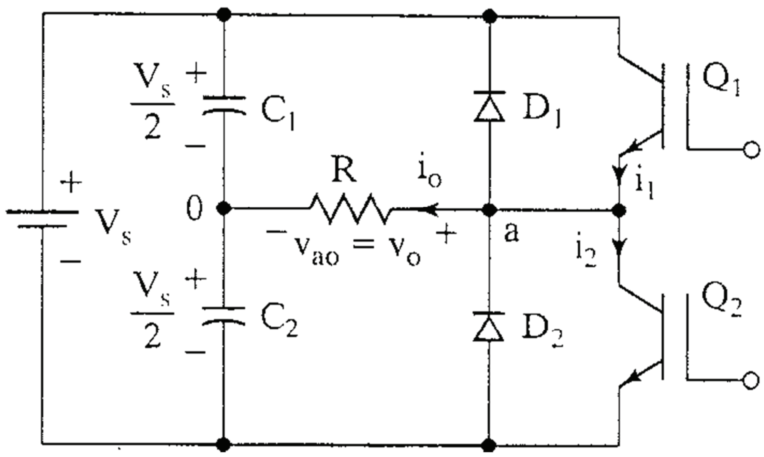


Figure 1.1 Single - phase, half - bridge inverter

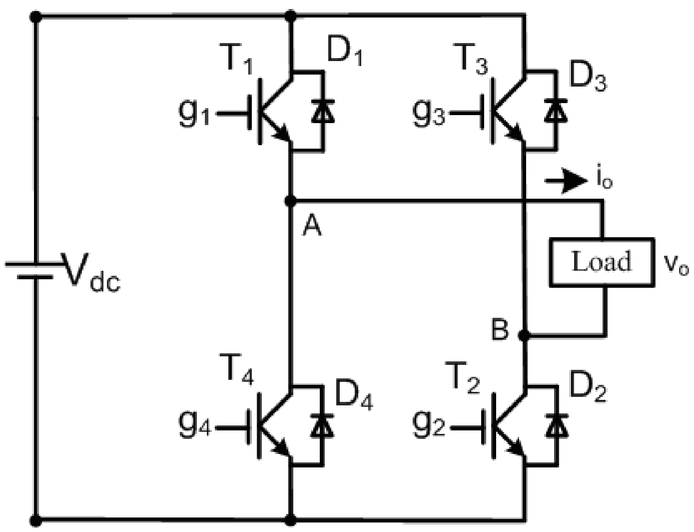


Figure 1.2 Single - phase, full - bridge inverter

1.2 Purpose of Thesis

Using devices in series for a power inverter brings several advantages which are objectives of this thesis work:

- First of all, realizing high - power inverter applications will be possible by shared power density between switching components.

- Besides there is an exponential relation between the switching device power values and prices. In other words using switching devices in series allows building cheaper inverters for same power.

- Also another important point is that the characteristics of low power transistor and MOSFET components are better than high power ones such as fast switching, short reverse - recovery time and poor parasitic capacitor.

1.3 Hypothesis

Multilevel power inverters are also used for high power applications and become popular in recent years because of low switching losses, higher voltage capability, higher power quality and better electromagnetic compatibility. But using devices in series has several advantages against multilevel inverters such as;

- For generating switching signals; standard PWM techniques can be used. By this way there is no need to generate special control signals.

- The use of serial devices reduces the total cost of the inverter circuit. Thereby number of power circuit components of inverters with devices in series is less than multi - level inverter circuits.

- Redundancy can be incorporated to improve reliability by using more series devices than actually required. The circuit can still work if one component fails (if the component fails to short circuit).

CHAPTER 2

PROPERTIES OF POWER MOSFET – IRFS4410

IRFS4410 Power MOSFET is used in all test circuits for simulations and also realized circuits. Some applications of IRFS 4410 are high efficiency synchronous rectification in SMPS, uninterruptible power supplies, high speed power switching, hard switched and high frequency circuits. IRFS4410 also have following benefits like improved gate, avalanche and dynamic dV/dt ruggedness, fully characterized capacitance, avalanche safe operating area, enhanced body diode dV/dt.

V_{DSS} of MOSFET is specified as 100 Volts and I_D is 96 Amps. Typical value of $R_{DS(on)}$ is given as 8 mΩ and maximum value of $R_{DS(on)}$ is 10 mΩ. Additionally MOSFET`s absolute maximum ratings, thermal resistance and reverse recovery diode characteristics are as follows (Table 2.1, Table 2.2 and Table 2.3).

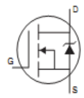
Table 2.1 Absolute maximum ratings of MOSFET (IRFS4410)

Symbol	Parameter	Max.	Units
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V	96①	A
I_D @ T_C = 100°C	Continuous Drain Current, V_{GS} @ 10V	68①	
I_{DM}	Pulsed Drain Current ②	380	
P_D @T_C = 25°C	Maximum Power Dissipation	250	W
	Linear Derating Factor	1.6	W/°C
V_{GS}	Gate-to-Source Voltage	± 20	V
dv/dt	Peak Diode Recovery ④	19	V/ns
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to + 175	°C
	Soldering Temperature, for 10 seconds (1.6mm from case)	300	
	Mounting torque, 6-32 or M3 screw	10lb·in (1.1N·m)	

Table 2.2 Thermal resistance of MOSFET (IRFS4410)

Symbol	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case ⑨	---	0.61	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat Greased Surface , TO-220	0.50	---	
$R_{\theta JA}$	Junction-to-Ambient, TO-220 ⑨	---	62	
$R_{\theta JA}$	Junction-to-Ambient (PCB Mount) , D^2Pak ⑧⑨	---	40	

Table 2.3 Reverse recovery diode characteristics of MOSFET (IRFS4410)

Symbol	Parameter	Min.	Typ.	Max.	Units	Conditions
I_S	Continuous Source Current (Body Diode)	---	---	96①	A	MOSFET symbol showing the integral reverse p-n junction diode. 
I_{SM}	Pulsed Source Current (Body Diode) ②	---	---	380	A	
V_{SD}	Diode Forward Voltage	---	---	1.3	V	T_J = 25°C, I_S = 58A, V_{GS} = 0V ⑤
t_{rr}	Reverse Recovery Time	---	38	56	ns	T_J = 25°C V_R = 85V,
		---	51	77		T_J = 125°C I_F = 58A
Q_{rr}	Reverse Recovery Charge	---	61	92	nC	T_J = 25°C di/dt = 100A/μs ⑤
		---	110	170		T_J = 125°C
I_{RRM}	Reverse Recovery Current	---	2.8	---	A	T_J = 25°C
t_{on}	Forward Turn-On Time	Intrinsic turn-on time is negligible (turn-on is dominated by LS+LD)				

“Typical output characteristics (while junction temperature – 25˚C and 175˚C)” and “Typical transfer characteristics” of The MOSFET (IRFS4410) which is used all circuit in thesis works are shown below (Figure 2.1, Figure 2.2 and Figure 2.3).

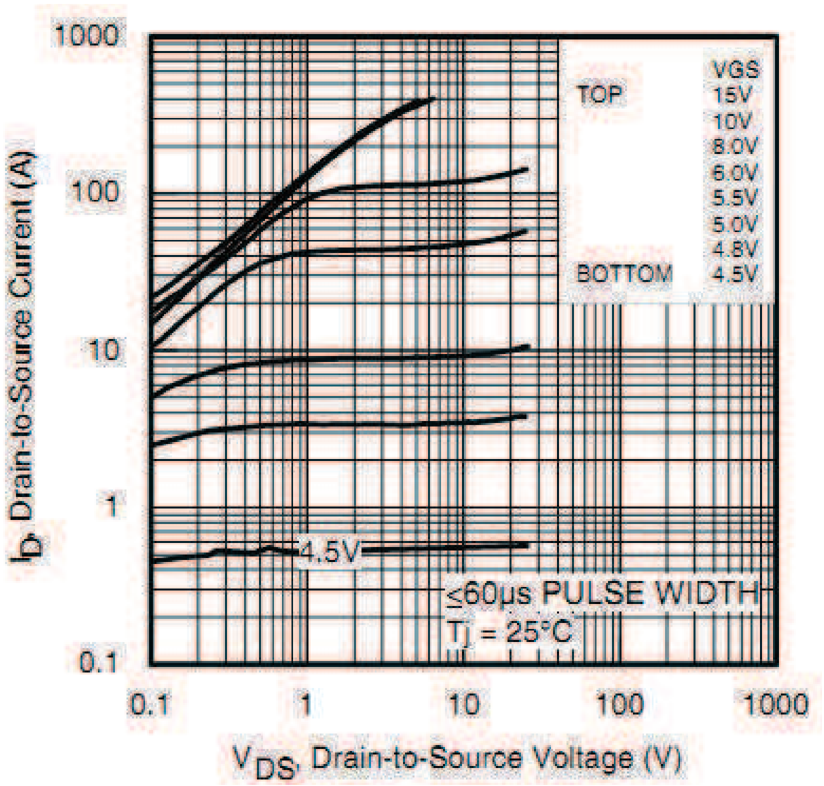


Figure 2.1 Typical output characteristics of MOSFET (junction temperature – 25˚C)

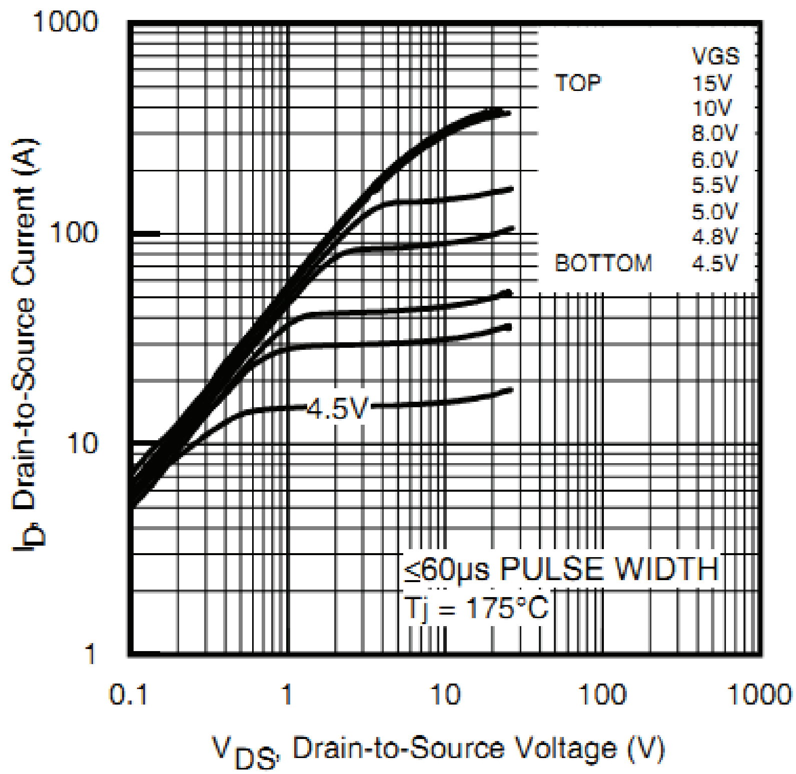


Figure 2.2 Typical output characteristics of MOSFET (junction temperature – 175˚C)

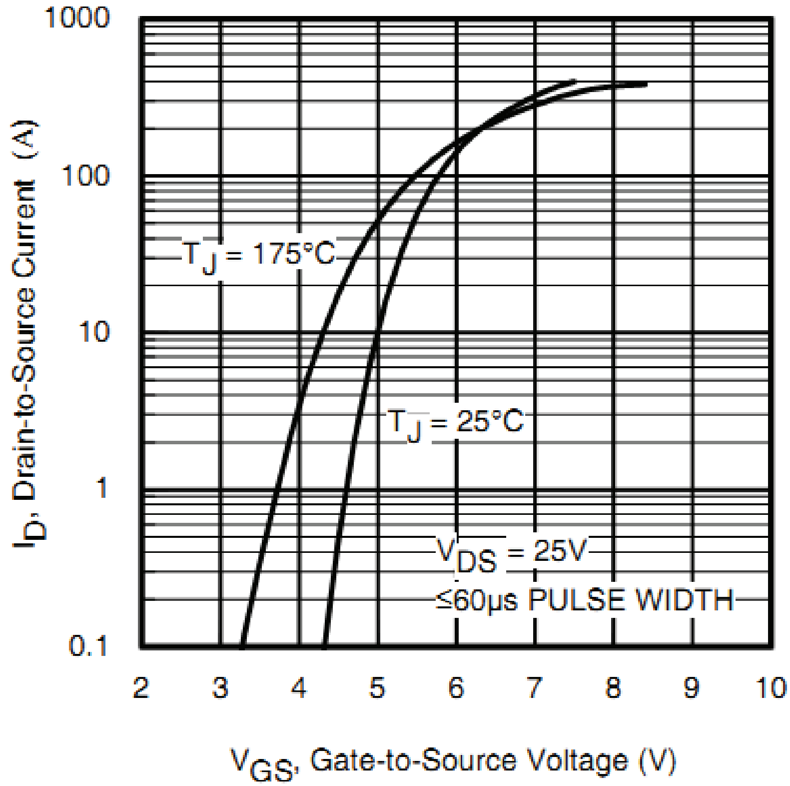


Figure 2.3 Typical transfer characteristics of MOSFET

CHAPTER 3

PSPICE SIMULATIONS

3.1 Half - Bridge Inverter Circuit

As the first simulation model, a basic half - bridge inverter circuit is built. MOSFET`s (IRFS4410) netlist is verified by this primary circuit. For only testing of basic switching 70 V (35 V + 35 V) DC power supply is used and circuit is operated as a DC chopper instead an inverter. For output load 10 Ω resistor and 200 uF inductor are chosen.

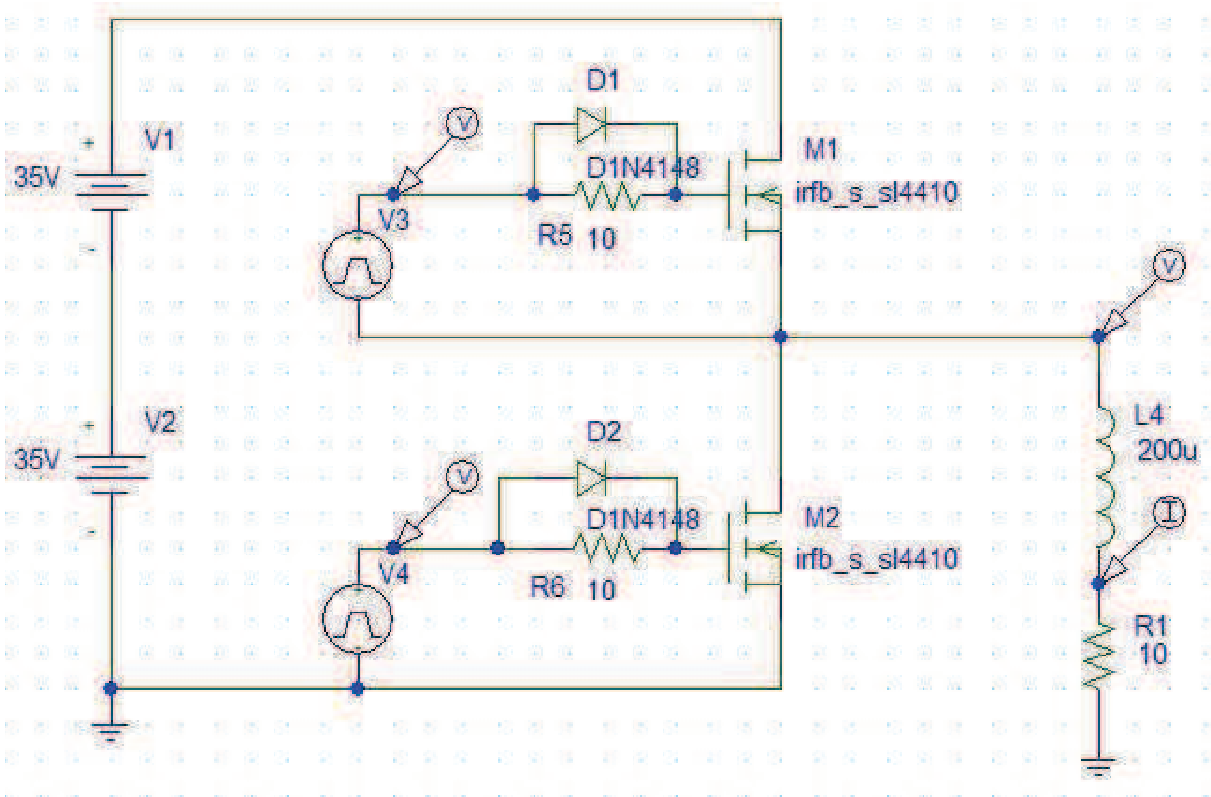


Figure 3.1 Basic half - bridge inverter circuit with MOSFETs IRFS4410

Amplitude of the gate signal of upper MOSFET (V3) is specified as 10 Volts. The signal period is 10 us and the switching frequency is 10 kHz;

It is necessary to interpolate a switching delay time in pulse width modulation signals which control MOSFETs. Thus, inverter is prevented from a short - circuit in the DC - link. This causes the dead - time effect which is detrimental for performance of the output voltage. Delay time (TD) to prevent short - circuit is defined as 1 us as seen in the properties of V3 (Figure 3.2).

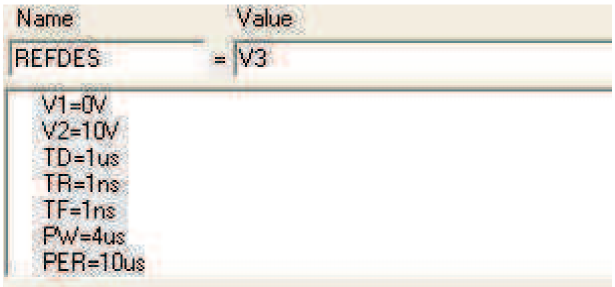


Figure 3.2 Values of V3 (gate signal of upper MOSFET)

The gate signal (square wave pulse width modulation) of higher MOSFET (V3) is shown below (Figure 3.3);

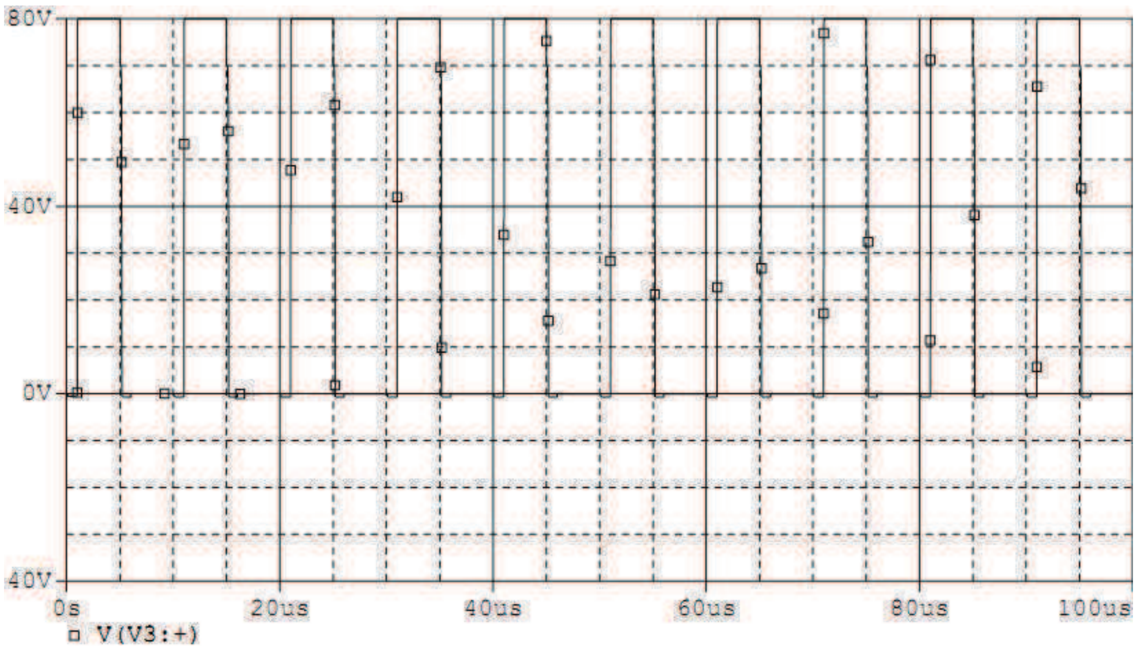


Figure 3.3 Waveform of V3 (gate signal of higher MOSFET)

The properties of the gate signal of lower MOSFET are shown below (Figure 3.4). These two control signals V3 and V4 complete each other and provide PWM signals of primitive half – bridge inverter circuit.

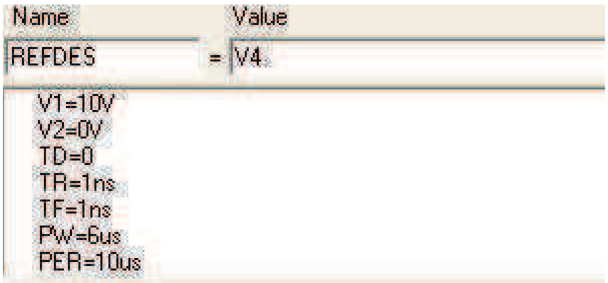


Figure 3.4 Values of V4 (gate signal of lower MOSFET)

The gate signal (square wave pulse width modulation) of lower MOSFET (V3) is shown below (Figure 3.5);

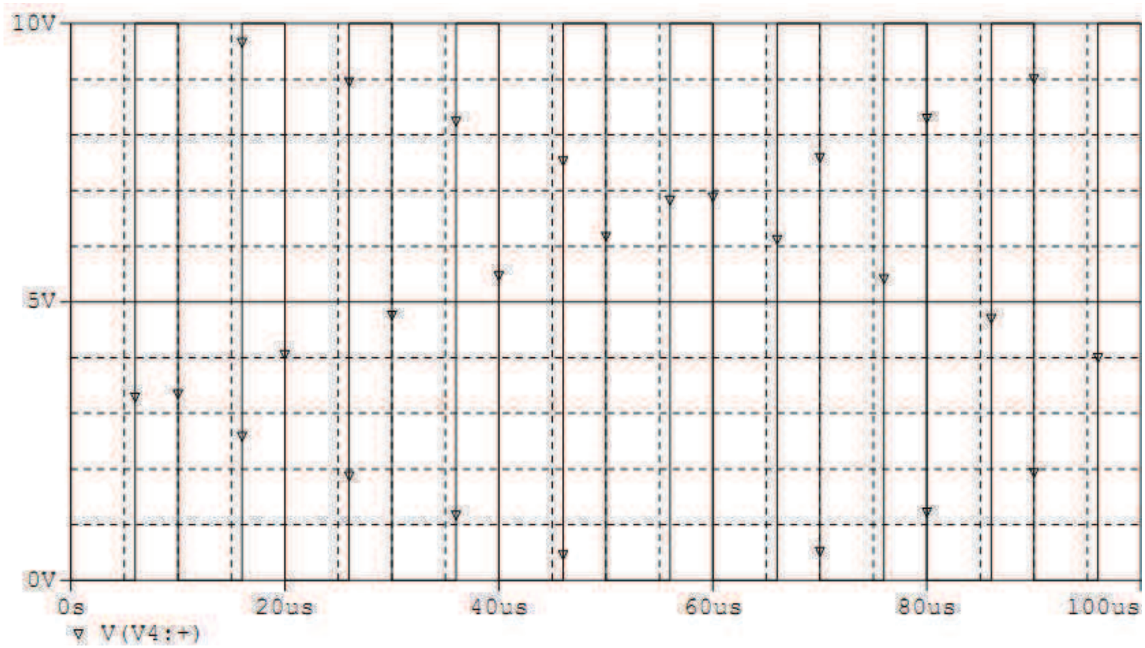


Figure 3.5 Waveform of V4 (gate signal of lower MOSFET)

The output voltage and current of the half - bridge inverter circuit is shown below (Figure 3.6 and Figure 3.7). According to given output waveforms, the half - bridge inverter circuit with IRFS4410 power MOSFETs run properly.

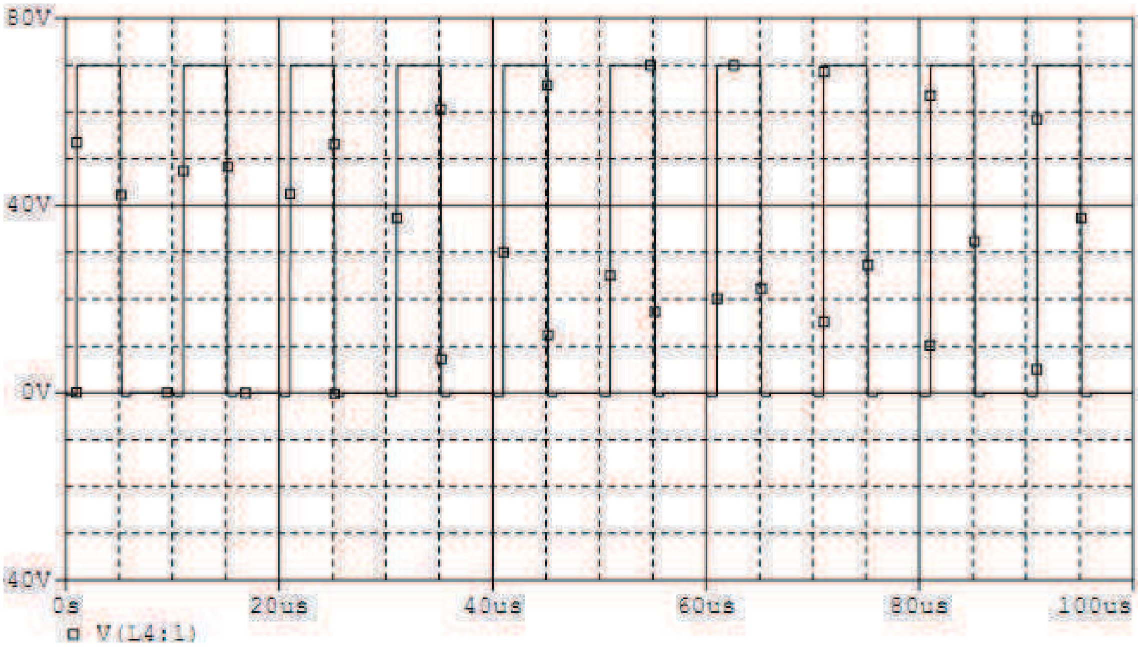


Figure 3.6 Waveform of output voltage

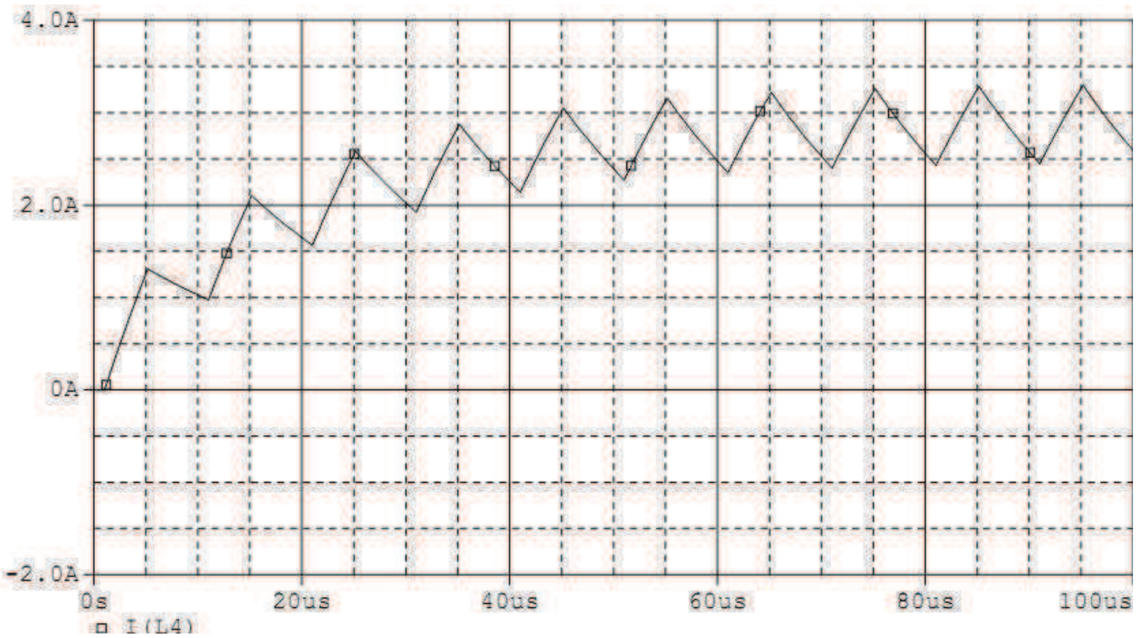


Figure 3.7 Waveform of output current

3.2 Half - Bridge Inverter Circuit Controlled by AC – PWM Signal

As the next step of simulation works, half - bridge inverter circuit is switched by AC - PWM control signal (Figure 3.8). Two 35 V DC sources supply the half - bridge inverter circuit and output load values is defined as 10 Ω and 200 uF.

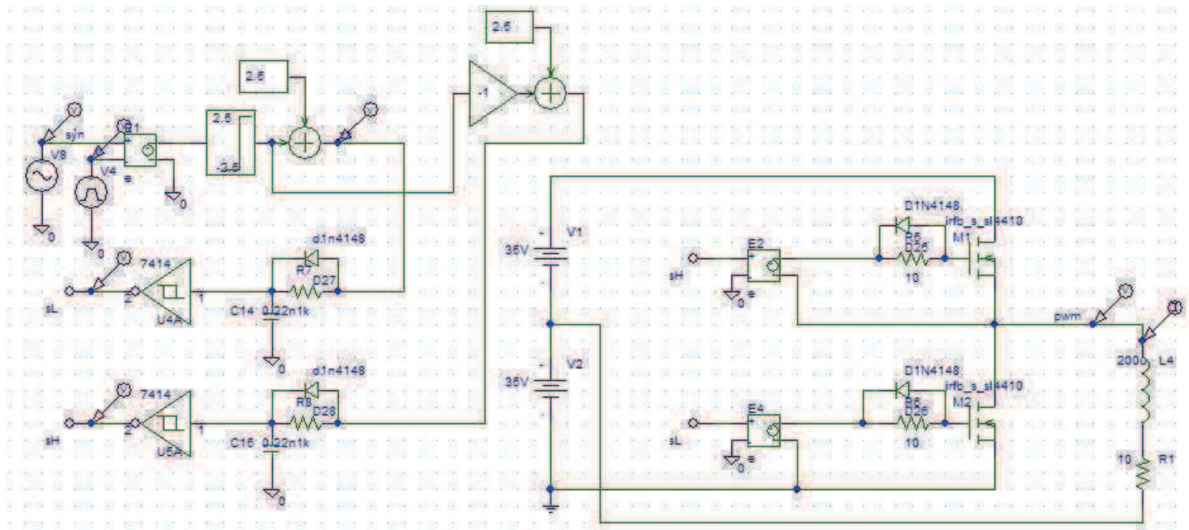


Figure 3.8 Half - Bridge inverter circuit controlled by AC - PWM

For generating these gate signals a sinus wave signal (Figure 3.9) and a triangle wave signal (Figure 3.10) are used. By comparing these two signals, an AC - PWM signal is produced and split two different signals by reversing the signal. An offset is added with a value of 2.5 to produce appropriate signals. Then a delay is added to upper MOSFET`s gate signal and either signals are isolated by E3 and E4 components.

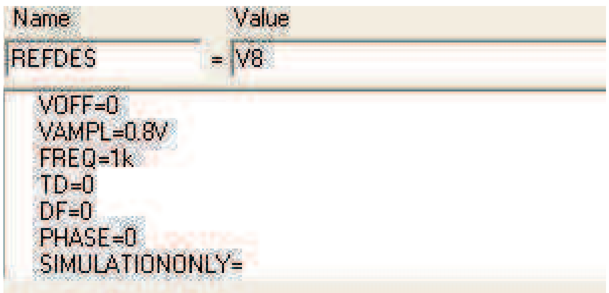


Figure 3.9 Values of V8 (sinusoidal wave)

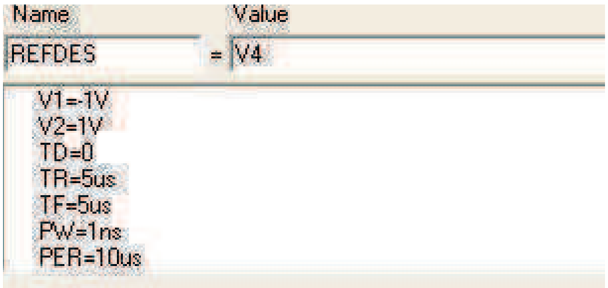


Figure 3.10 Values of V4 (triangle wave)

Amplitudes of the triangular wave and sinusoidal wave are compared to obtain PWM waveform. In this way, by using analog comparators; sinusoidal PWM signal is generated as is shown below (Figure 3.11).

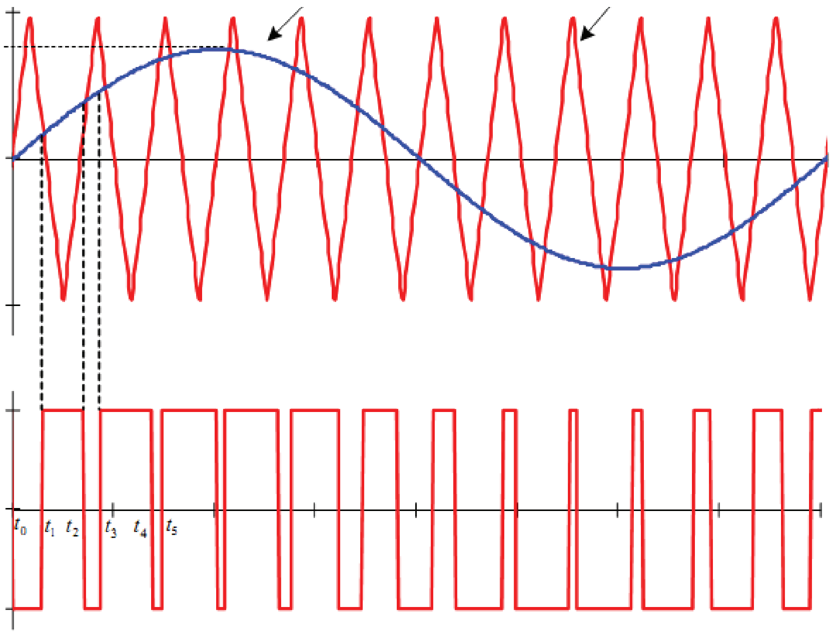


Figure 3.11 Sinusoidal pulse width modulation method

Waveforms of gate signals are given below (Figure 3.12). The maximum value of gate signals is indicated with approximately 3.5 Volts. These signals are measured from inputs of E3 and E4 components. These components run with a gain of 3 and so appropriate gate signals are maintained by these two components and apply to gate of MOSFETs.

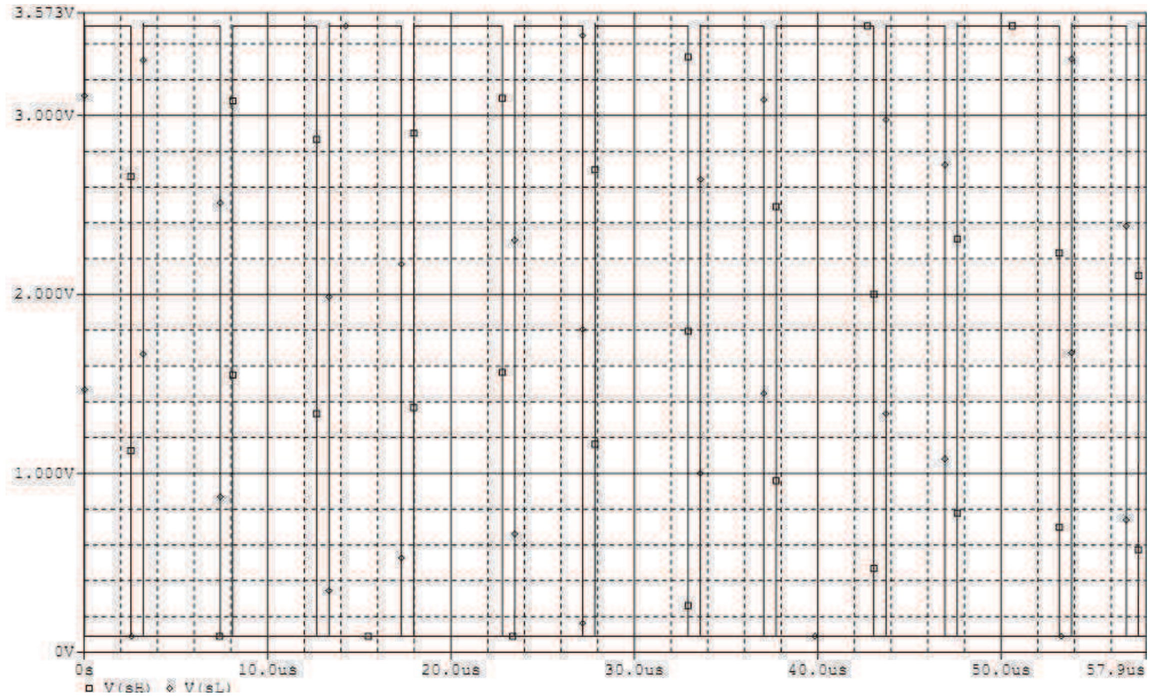


Figure 3.12 Waveforms of gate signals

The sinusoidal PWM signal which is digitally generated and applied to gates of switching components is also seen in the waveform of output voltage. The output voltage and output current waveforms between the time values of 0 and 1.0 ms are shown below (Figure 3.13 and Figure 3.14).

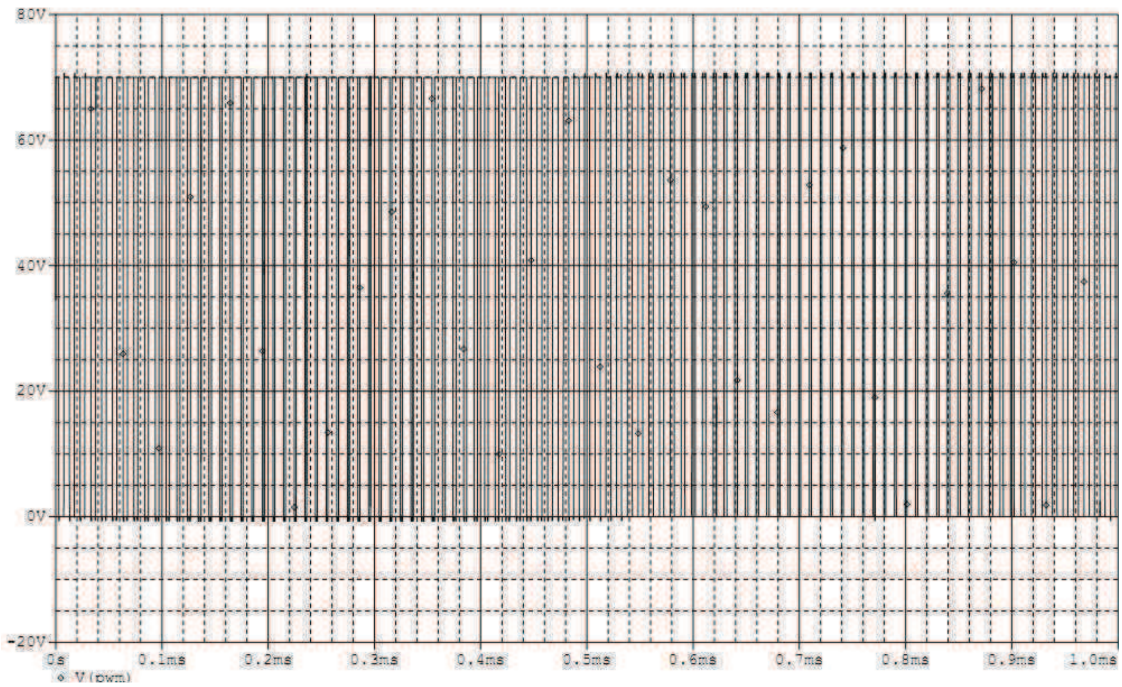


Figure 3.13 Waveform of output voltage

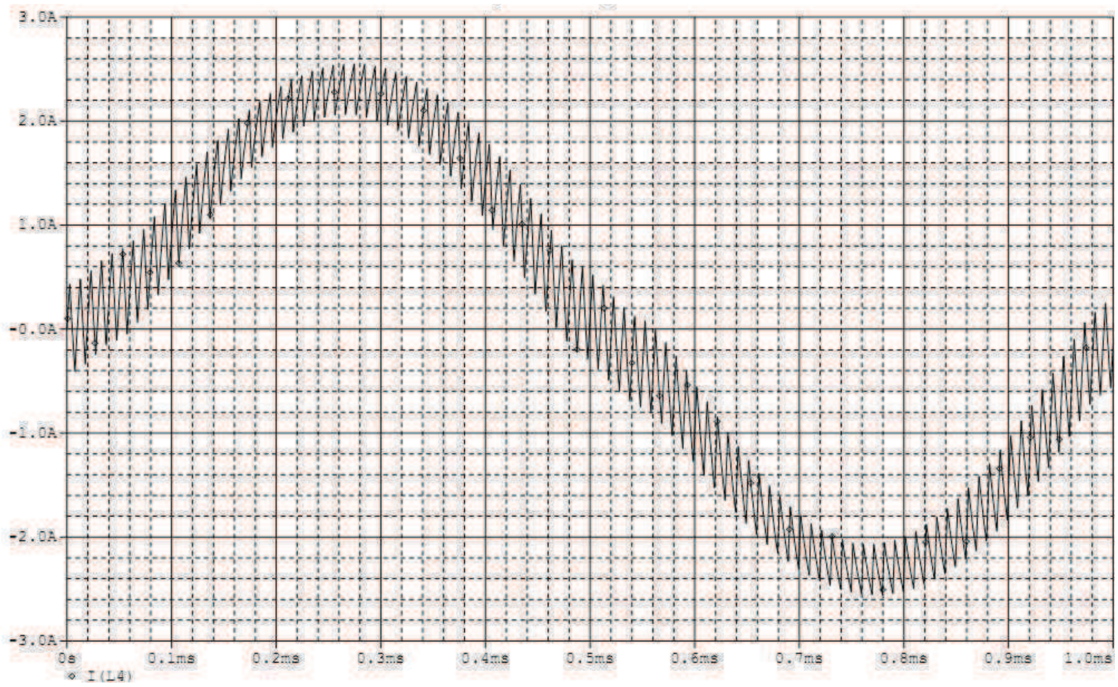


Figure 3.14 Waveform of output current

3.3 Half - Bridge Inverter Circuit with 2 MOSFETs in Series

In this step of simulations half - bridge inverter circuit is built with 4 MOSFETs "2 MOSFETs in Series" (Figure 3.15). For each two branch of inverter, two MOSFETs are used. For this circuit; the value of the DC power supply was doubled and two 70 Volts of DC sources are used. In this way, a DC source of 140 Volts for total supplies the half - bridge inverter circuit with 4 MOSFETs. The inverter circuit which is loaded with the values of 10 ohm resistor and 200 uH inductor is shown below (Figure 3.15).

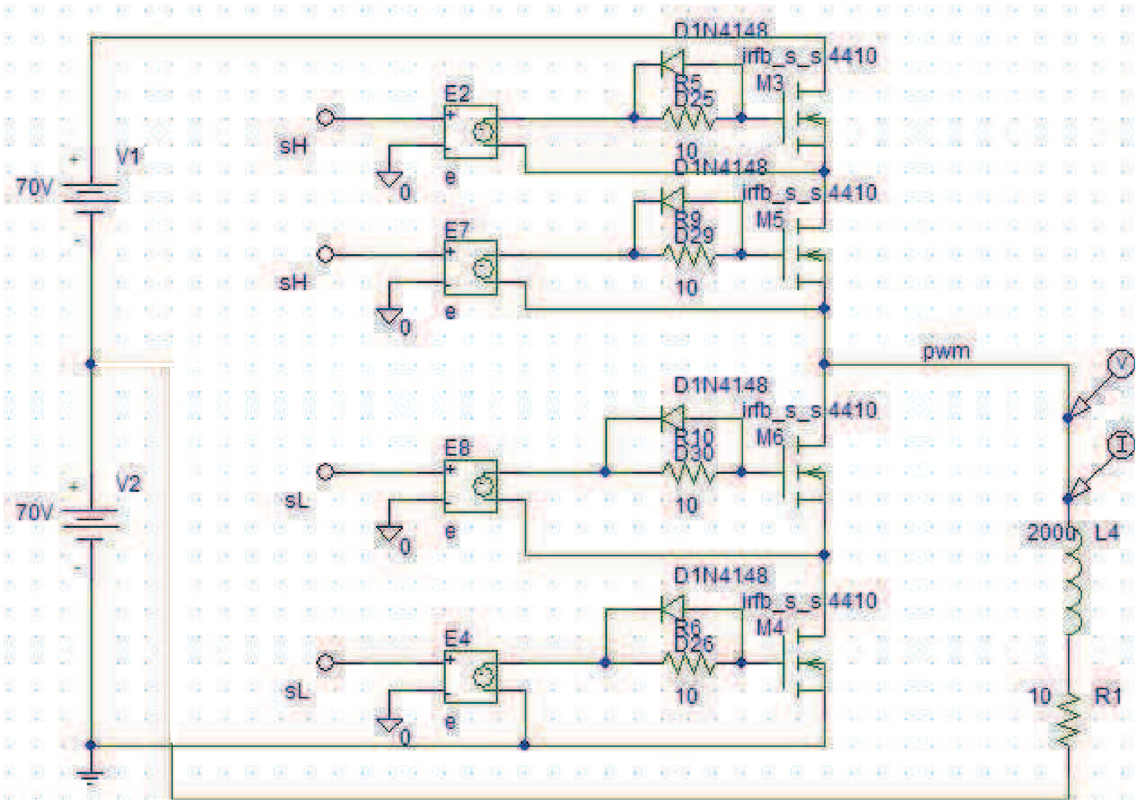


Figure 3.15 Half - Bridge inverter circuit operating with 4 MOSFETs

In the circuit (Figure 3.15) every gate signal is isolated by E2, E4, E7 and E8 components. Also by these isolation components the weak gate signals are multiplied by 3 and arranged the appropriate form of switching signals. For generating these gate signals a sinus wave signal and a triangle wave signal are used. By comparing these two signals, an AC – PWM signal is produced and split two different signals by reversing the signal. An offset is added with a value of 2.5 to produce appropriate signals. Then a delay is added to upper MOSFETs` gate signals. The circuit which generates these signals is separately shown below (Figure 3.16).

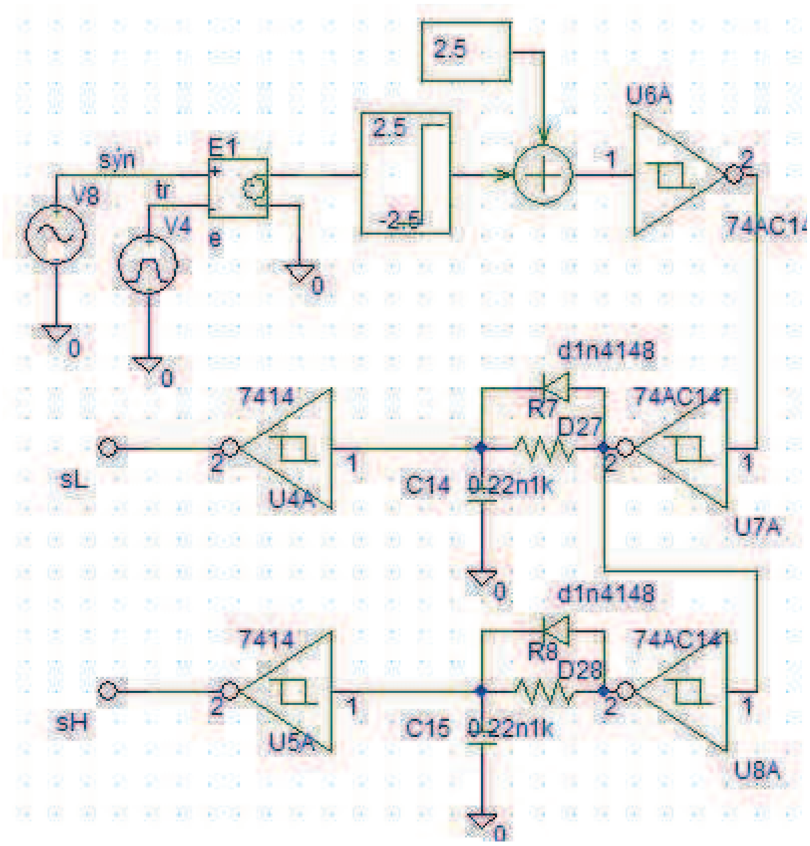


Figure 3.16 Control signal circuit for half - bridge inverter

The output waveforms of voltage and current of the circuit are shown below (Figure 3.17 and Figure 3.18). These output waveforms point that IRFS4410 model MOSFETs perfectly run together. The output waveforms of the circuit with 4 MOSFETs are similar with the circuit with 2 MOSFETs but values multiplied by 2. For next test stage; 3 serial MOSFETs will be used for both branches of inverter circuit.

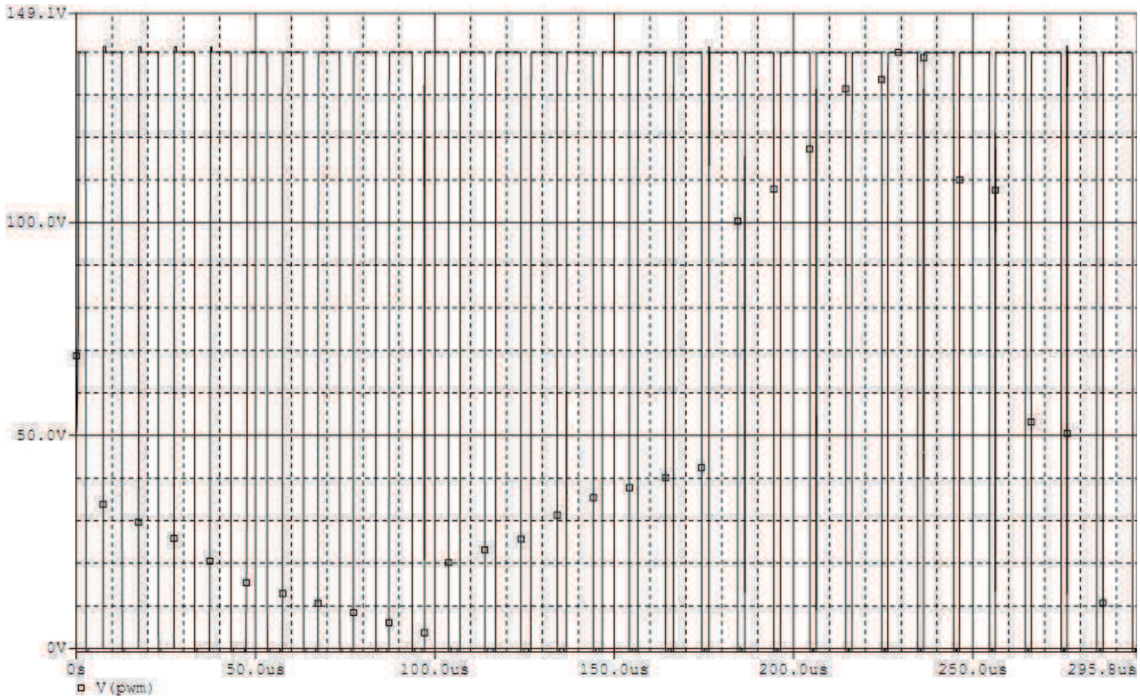


Figure 3.17 Waveform of output voltage

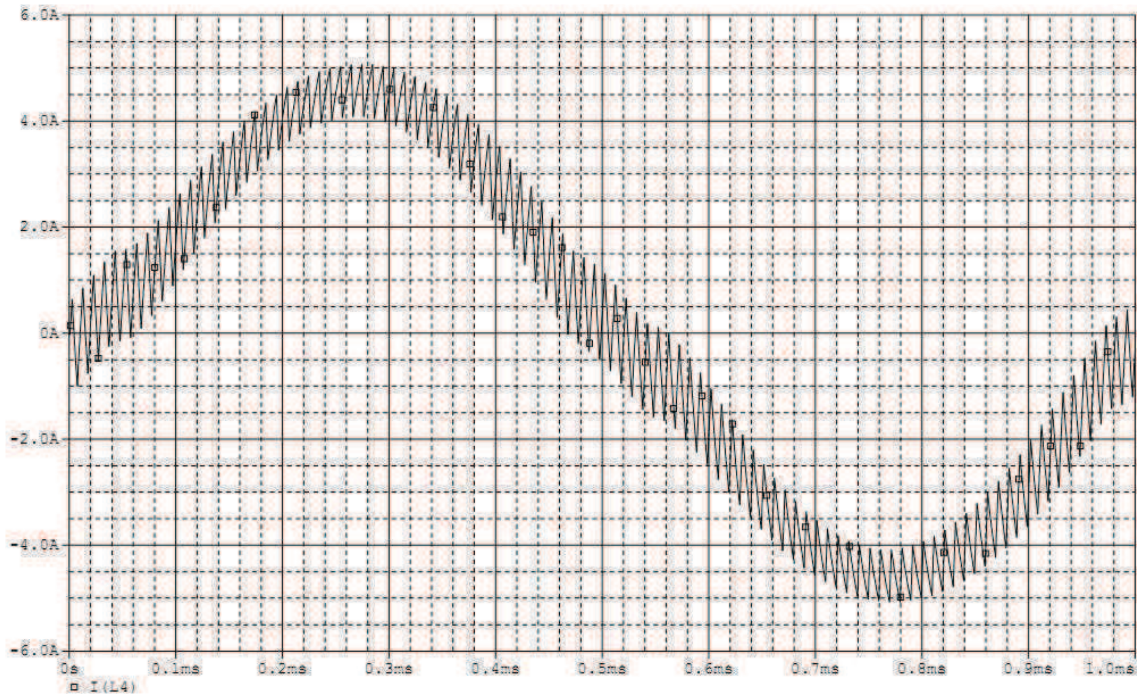


Figure 3.18 Waveform of output current

Next two waveforms indicate the drain voltage values of first and third MOSFETs "M4 and M5" (Figure 3.19 and Figure 3.20). These two waveforms point that the MOSFET components run together with harmony. Drain voltages properly share total circuit voltage and current, and complete each other.

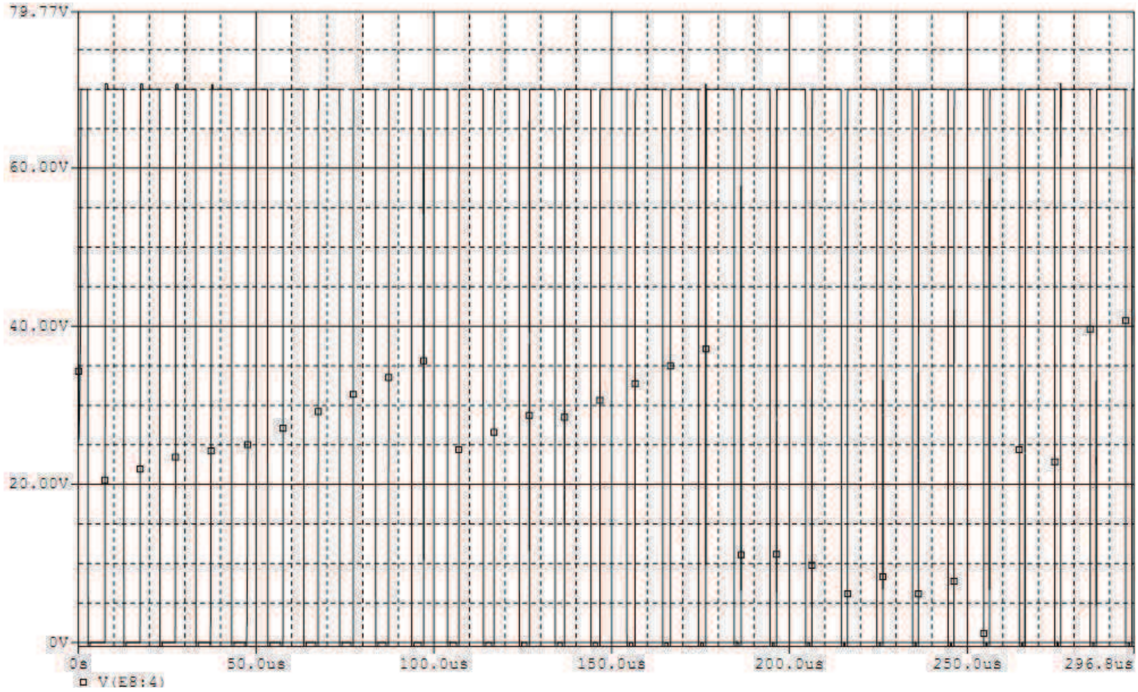


Figure 3.19 Waveform of first MOSFET`s (M4) drain voltage

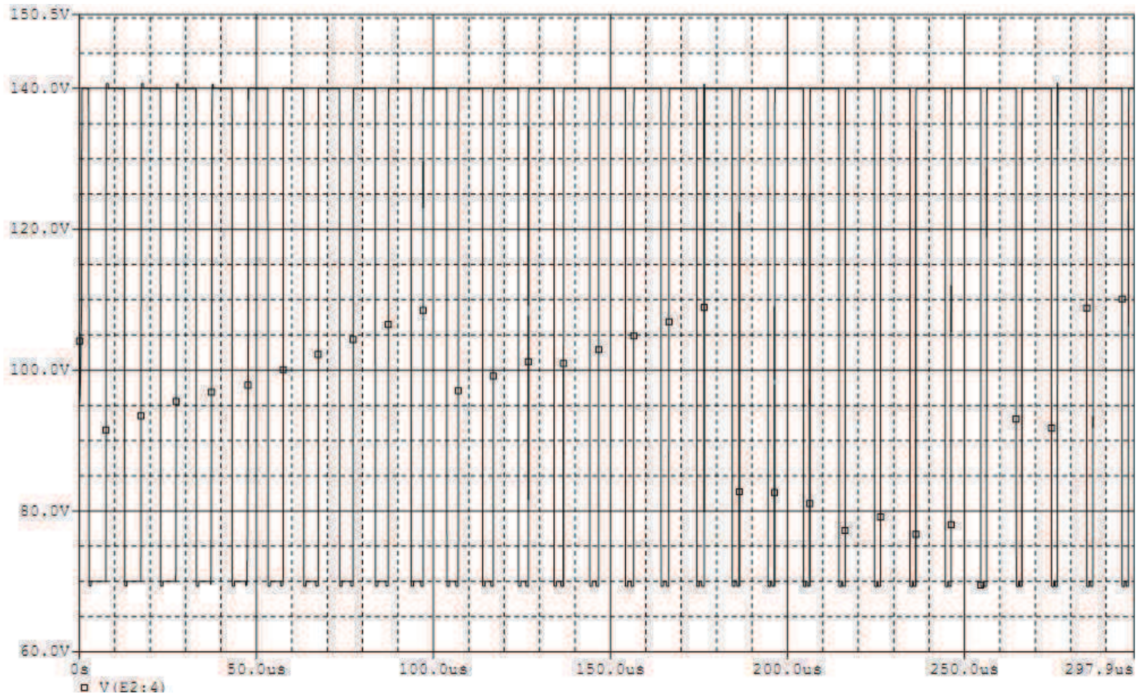


Figure 3.20 Waveform of third MOSFET`s (M5) drain voltage

3.4 Half - Bridge Inverter Circuit with 3 MOSFETs in Series

In this stage, half - bridge inverter circuit with 6 MOSFETs "3 devices in series" is built (Figure 3.21). A current source with value of 5 Amps connected to load stage of circuit. The circuit is supplied by a DC source of 200 Volts (100 V + 100 V). 5 Amps valued current source which is connected output of circuit behaves like an inductor with infinite inductance to obtain continuous current.

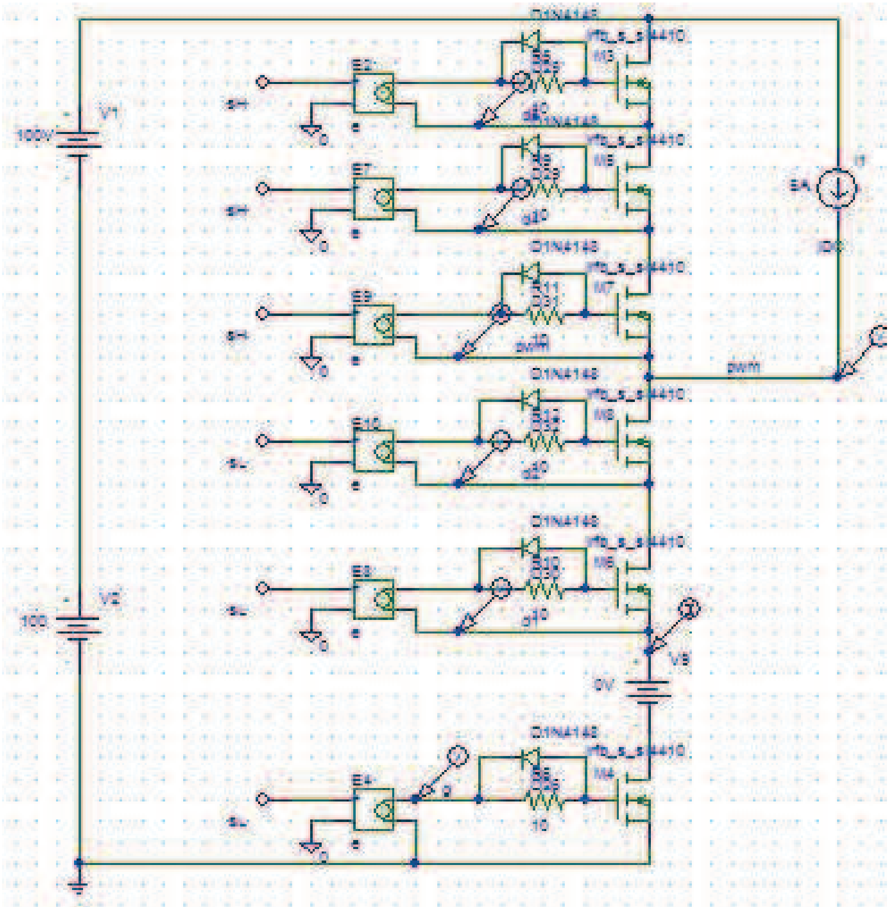


Figure 3.21 Half - Bridge inverter circuit with 6 MOSFETs

The isolation of gate signals of MOSFETs is maintained by E2, E4, E7, E8, E9 and E10 components. The DC voltage source with value of 0 Volt is added to circuit for only measuring MOSFET M4`s drain current.

The control signals which are applied to gates of MOSFET components via isolation components (E2, E4, E7, E8, E9 and E10) are generated by the oscillator of previous circuits (Figure 3.22).

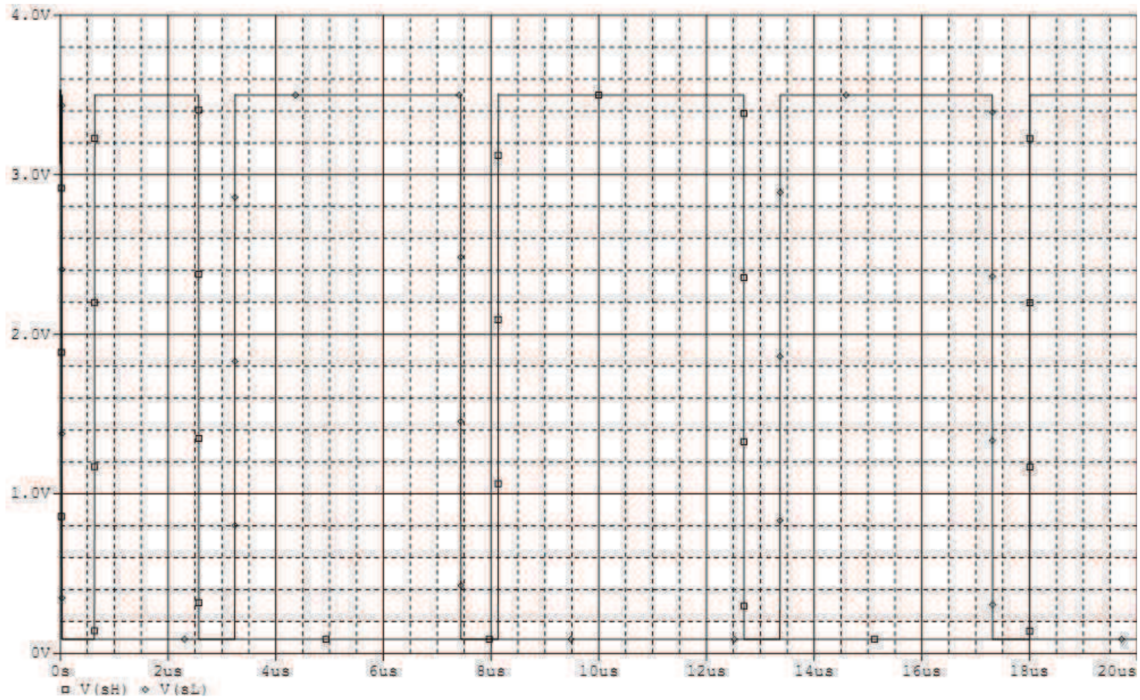


Figure 3.22 Waveforms of control signals

This sinusoidal PWM signals are generated by a comparative circuit and a delay with the value of 700 ns is added between two signals. Signal - high “sH“ is applied to higher MOSFETs`gates and signal - low “sL“ is applied to lower MOSFETs` gates after passing signal isolation stage.

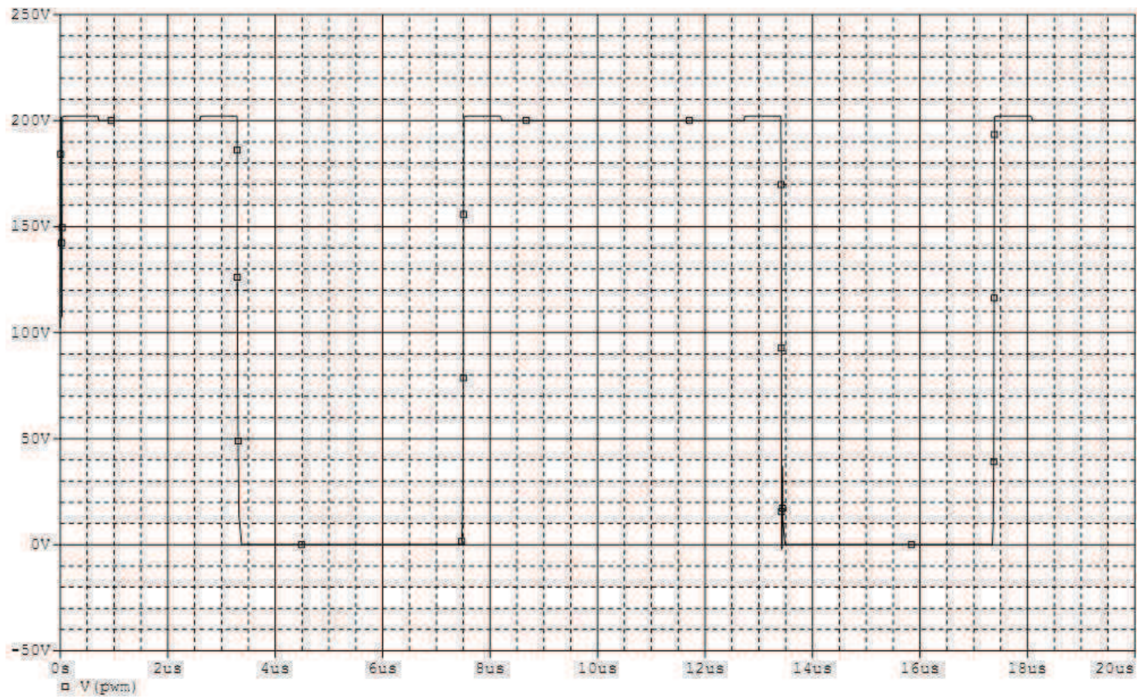


Figure 3.23 Waveform of output voltage

The output voltage waveform of half - bridge inverter with 3 MOSFETs in series proved that these switching devices are theoretically capable to run while they are serially connected. Also drain voltages of MOSFETs in series are equal as seen below (Figure 3.24).

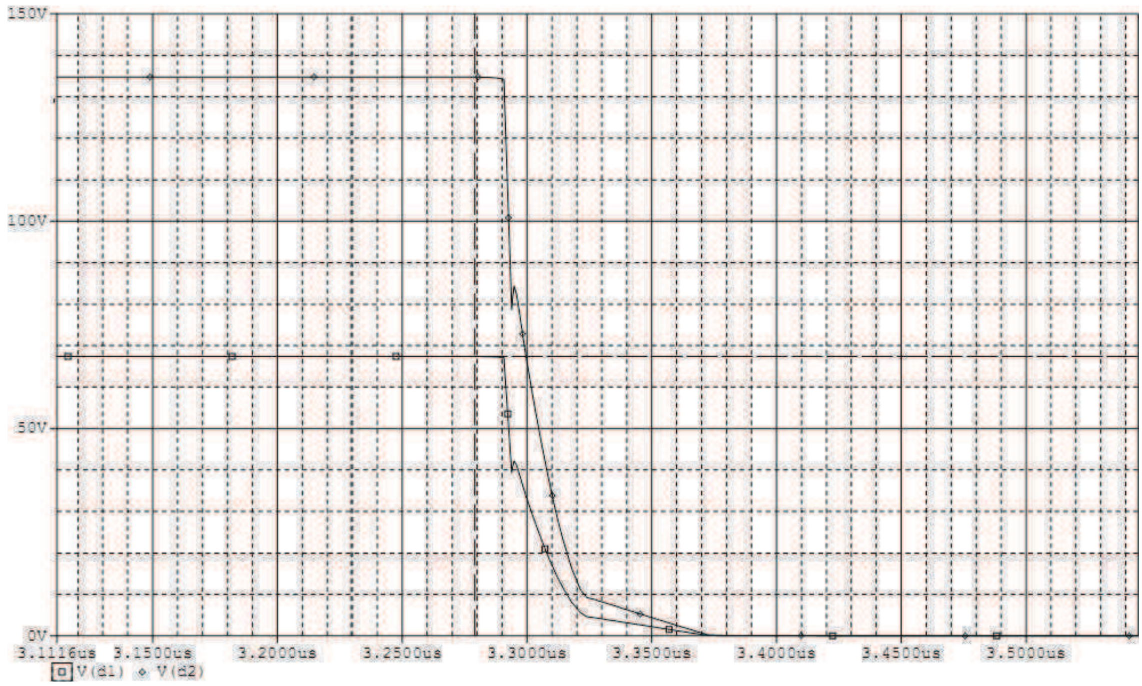


Figure 3.24 Drain voltage waveforms of MOSFETs in series in switch - on period

In this waveform of drain voltages, the voltage value of first MOSFET was measured via probe cursor. The measured values are shown below (Figure 3.25). These measurements are also repeated for the next waveform; subtraction of first MOSFET`s drain voltage from second MOSFET`s drain voltage.

Probe Cursor		
A1 =	3.2295u,	67.399
A2 =	3.2790u,	67.400
dif=	-49.524n,	-83.282u

Figure 3.25 Measurements of drain voltages via probe cursor

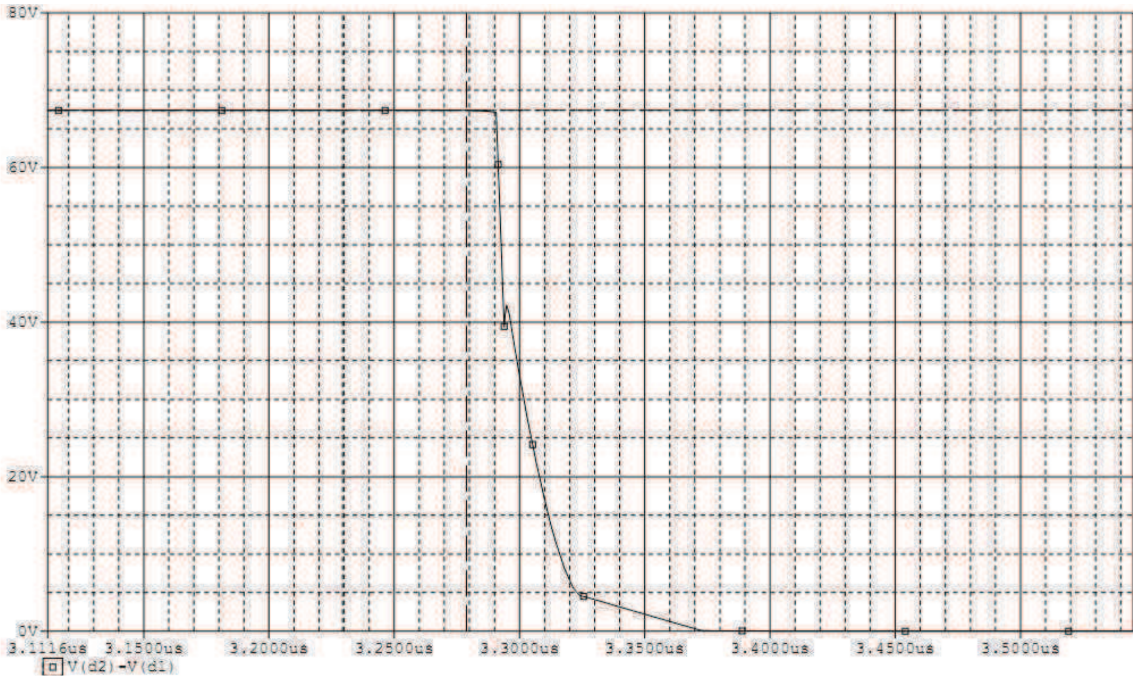


Figure 3.26 Waveform of subtraction of series MOSFETs` drain voltages

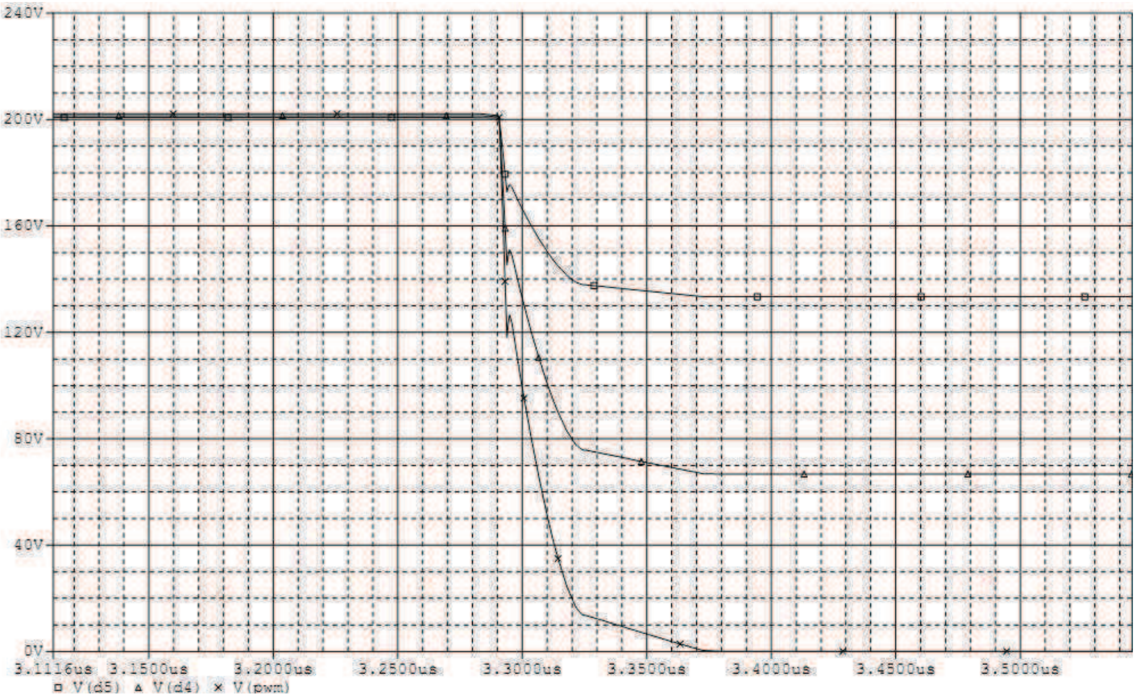


Figure 3.27 Waveforms of drain voltages of higher three series MOSFETs

When a rectifier is reverse biased while it is conducting a high forward current a finite amount of time is required to clear it of charge carriers [5]. So the rectifier can block the reverse voltage in the meantime. The reverse recovery characteristics of IRFS4410 power MOSFET is given below (Figure 3.28). The reaction of MOSFET to control signal is shown at the second waveform (Figure 3.28). This characteristic is also specified in the datasheet of rectifier. Because of MOSFET`s reverse recovery behavior; a shottky diode with better reverse recovery characteristic will be used in the circuit within the following works.

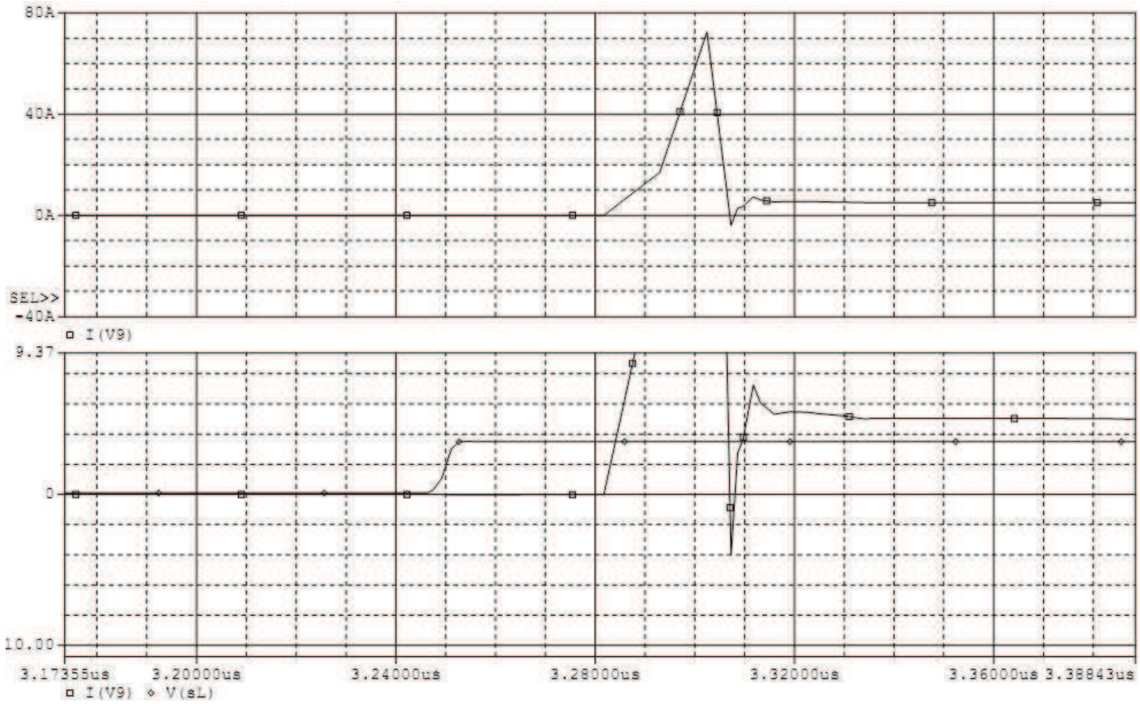


Figure 3.28 Waveform of reverse recovery current of MOSFET M4

CHAPTER 4

REMODELLING CIRCUIT SCHEMATIC TO REALIZE CIRCUIT

Half - bridge inverter circuit with IRFS4410 MOSFETs was remodeled to realize circuit in laboratory and compare practical results with simulation results. Remodeled circuit`s PSpice schematic and hand - drawn schematic are shown below (Figure 4.2 and Figure 4.3). For preparing appropriate control signals; 5 V logic components (74ACT14) are used in circuits. A PWM signal from an external oscillator was applied to signal input of circuit. The input signal which shown below (Figure 4.1) has a period time as 10 us and consequently switching frequency of circuit is 10 kHz;

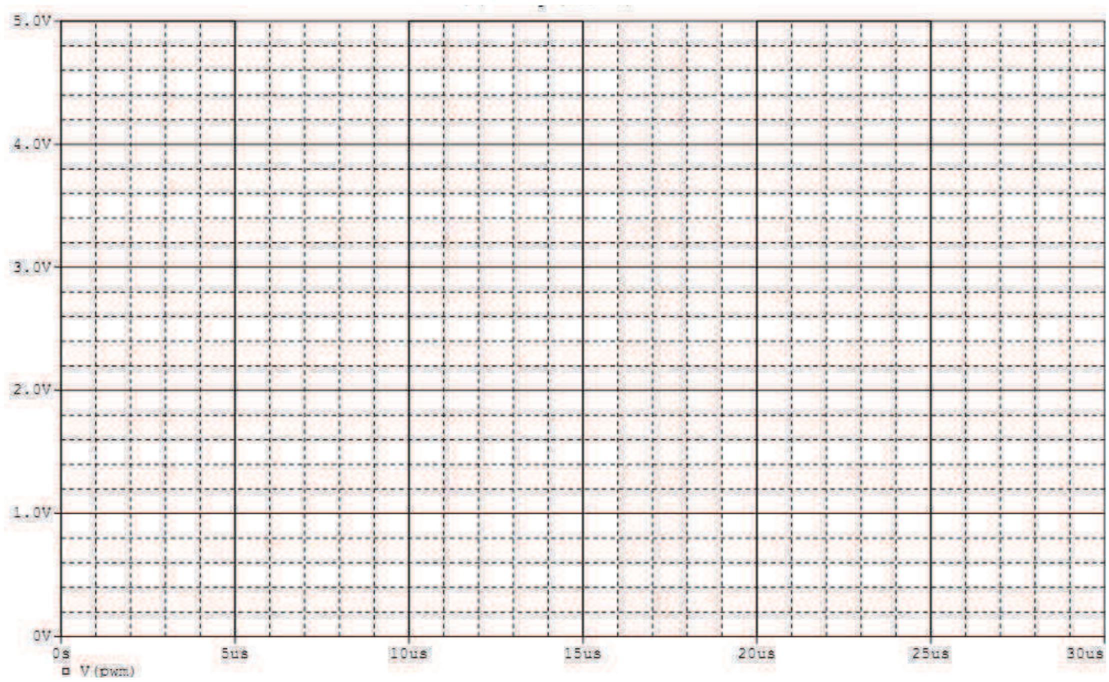


Figure 4.1 PWM Signal which is applied by an external oscillator

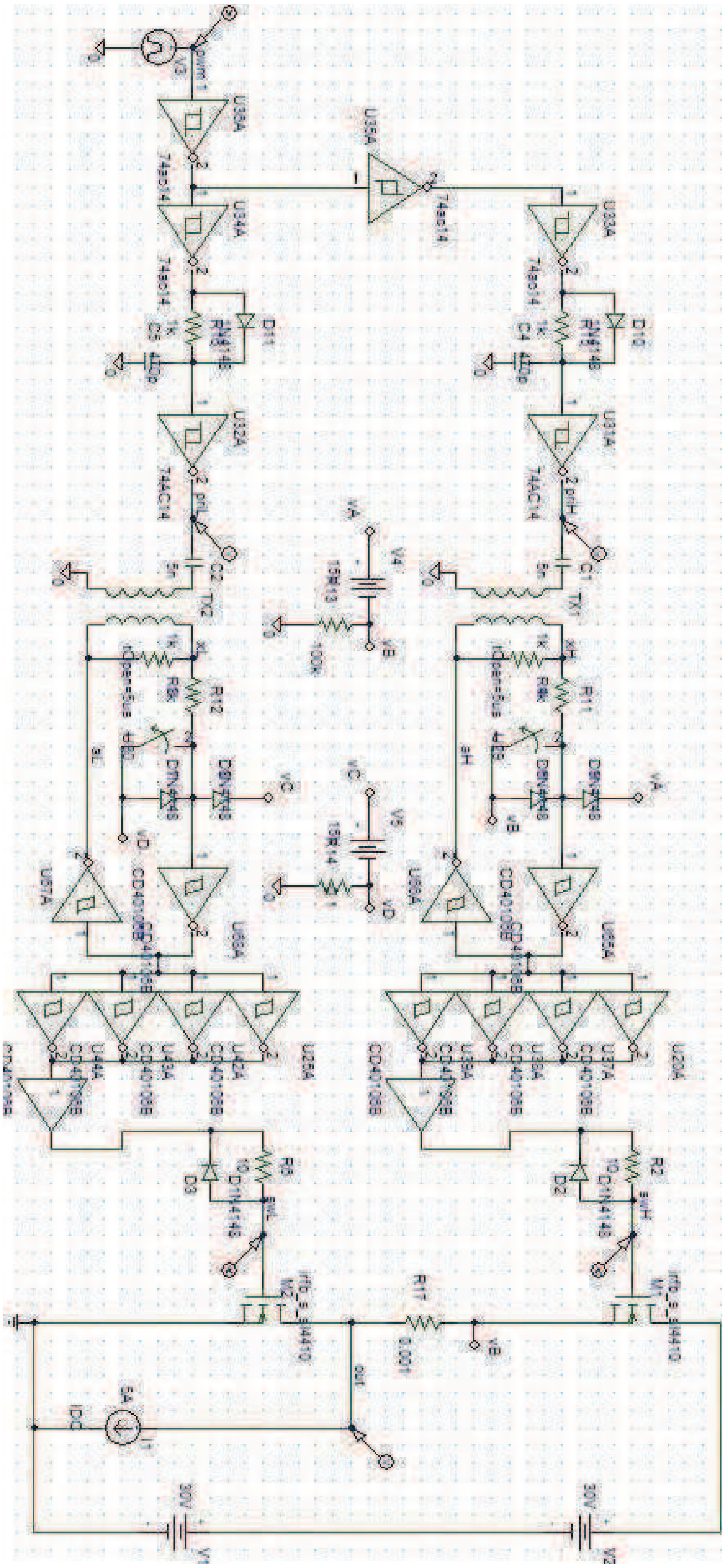


Figure 4.2 Remodeled circuit PSpice schematic

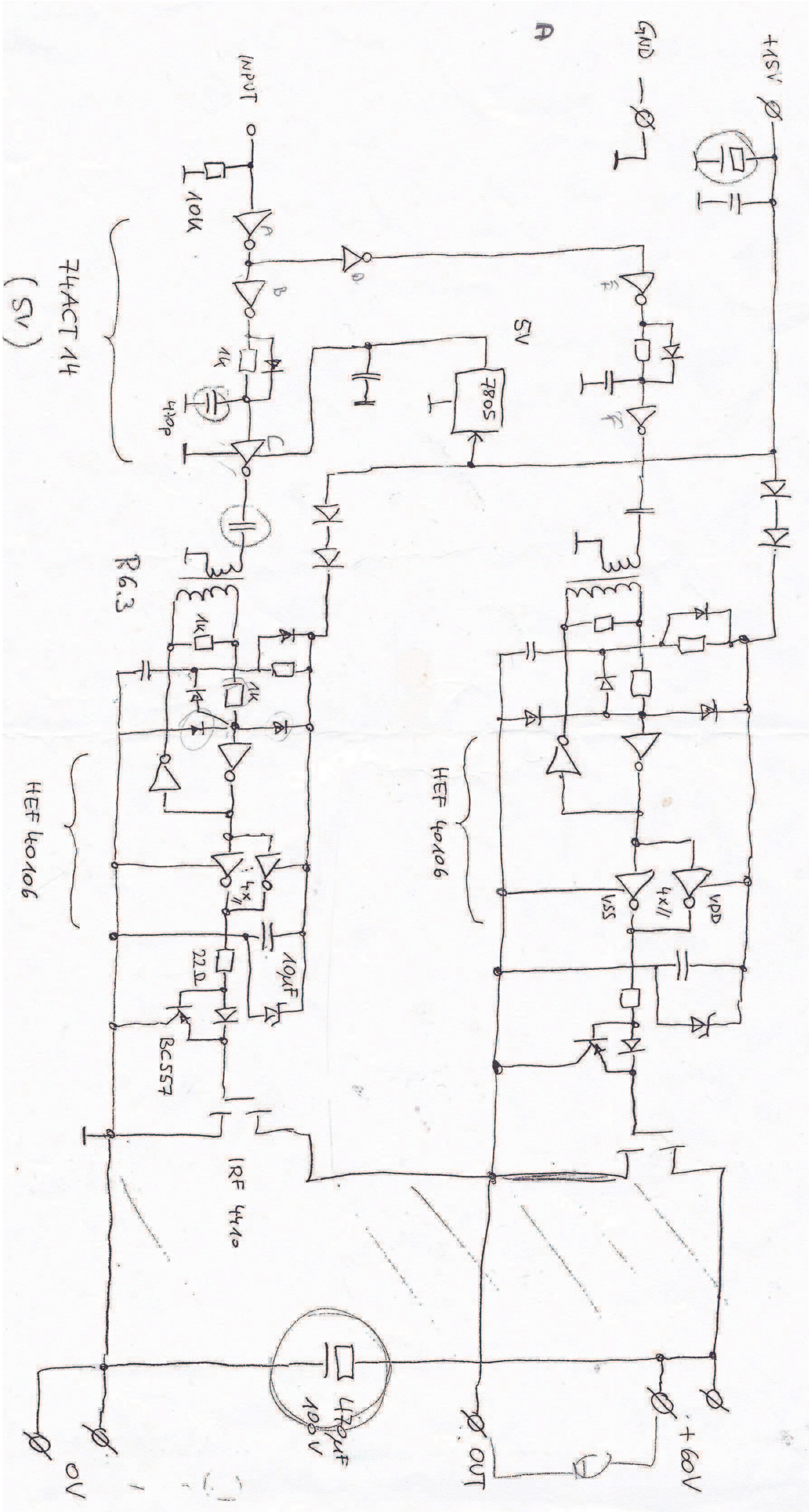


Figure 4.3 Remodeled circuit hand - drawn schematic

By these 74ACT14 components which are supplied by a 7805 regulator (5 Volts), external PWM signal is split two different signals. These two signals which are arranged by 5 V logic components also get a delay between them to prevent short - circuit. Lower switching unit signal “V(priL)” and higher switching unit signal “V(priH)” are shown below (Figure 4.4).

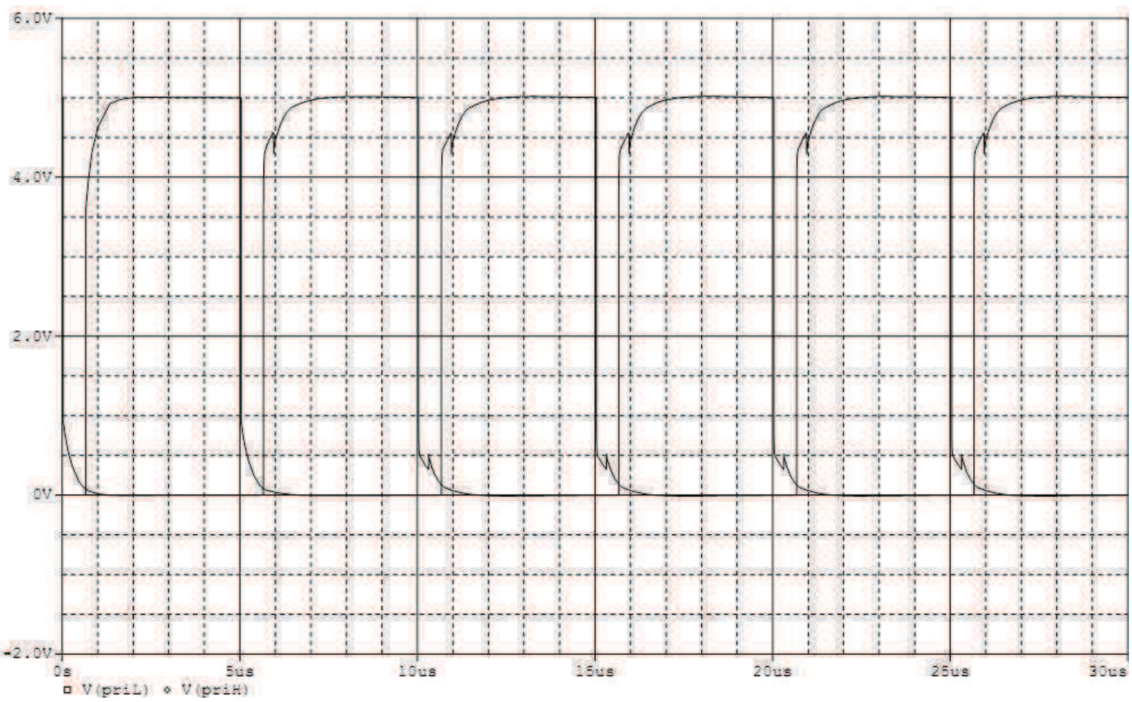


Figure 4.4 Waveform of 5 V logic circuit stage`s output signals

These two signals pass by 5 nF valued capacitors and then signals are applied to primary windings of signal transformers. Control signals that activate signal transformers are given below (Figure 4.5).

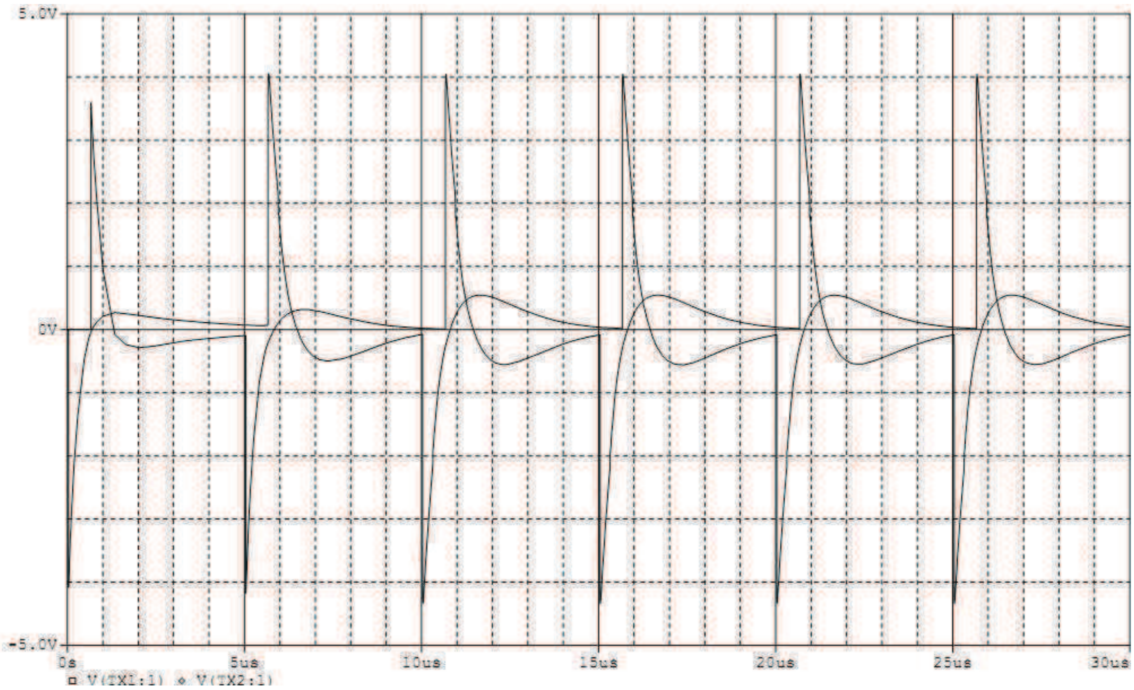


Figure 4.5 Waveforms of signal transformers` primary windings` input signals

In the table which is shown below, dimensions and characteristics of coils which are used for cores` of signal transformers are given (Figure 4.6).

R 6.30 × 3.80 × 2.50 B64290P0037

R 8.00 × 4.00 × 4.00 B64290P0751

- Parylene coating

R 6.30 × 3.80 × 2.50 (mm)
R 0.248 × 0.150 × 0.098 (inch)

Dimensions

d_a (mm)	d_i (mm)	Height (mm)	d_a (inch)	d_i (inch)	Height (inch)	
6.30 ±0.15	3.80 ±0.12	2.50 ±0.12	0.248 ±0.006	0.150 ±0.005	0.098 ±0.005	uncoated[1)]
Coating thickness 0.012 mm						coated

Characteristics and ordering codes

Mate-rial	A_L value nH	μ_i (approx.)	Ordering code	Magnetic characteristics				Approx. weight g
				$\Sigma l/A$ mm^{-1}	l_e mm	A_e mm^2	V_e mm^3	
N87	560 ±25%	2200	B64290P0037X087	4.97	15.21	3.06	46.5	0.2
N30	1090 ±25%	4300	B64290P0037X830					
T65	1160 ±30%	4600	B64290P0037X065					
T38	2530 ±30%	10000	B64290P0037X038					
T46	3600 ±30%	14000	B64290P0037X046					

Figure 4.6 Properties of signal transformers` cores

Coils with "T38" material code are used for following circuits. A_L value which specifies inductance per definite number of turns is given as 2530 nH in the table. The input signal of primary windings has a level between 4 Volts and -4 Volts. The outputs of secondary windings should be in 15 V logic level. Therefore the turn ratio of transformer is chosen as 3.5 Volts. Signal transformers` primary and secondary windings inductance values correspondingly calculated as shown belorw (4.1 and 4.2).

$$N_P = 7 \qquad L_P = 2.53\mu H \cdot 7^2 = 124\ \mu H \tag{4.1}$$

$$N_S = 25 \qquad L_S = 2.53\mu H \cdot 25^2 = 1581\ \mu H \tag{4.2}$$

The inductance values of primary windings are chosen as 124 uH and secondary windings` values are 1581 uH for both signal transformers (Figure 4.7).

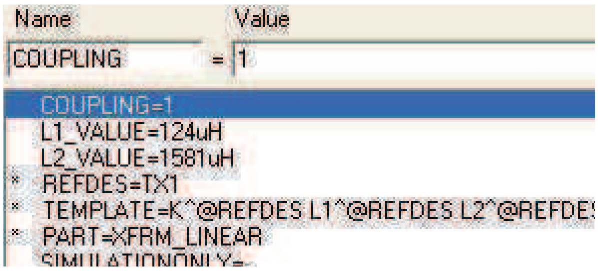


Figure 4.7 Signal transformer`s windings` inductance values

Control signals while passing by signal transformers are amplified with a 3.5 valued multiplier. Due to turn – ratio of signal transformers, amplitude of control signals reached around 15 Volts. Then signals are arranged to appropriate forms by HEF 40106 components. These components are supplied by 15 Volts by an external power source and generate proper signals to apply gates of MOSFET components. The final waveforms of control signals which are applied to MOSFETs` gates are shown below (Figure 4.8). V(swL) indicates lower MOSFET`s switching signal and V(swH) indicates upper one.

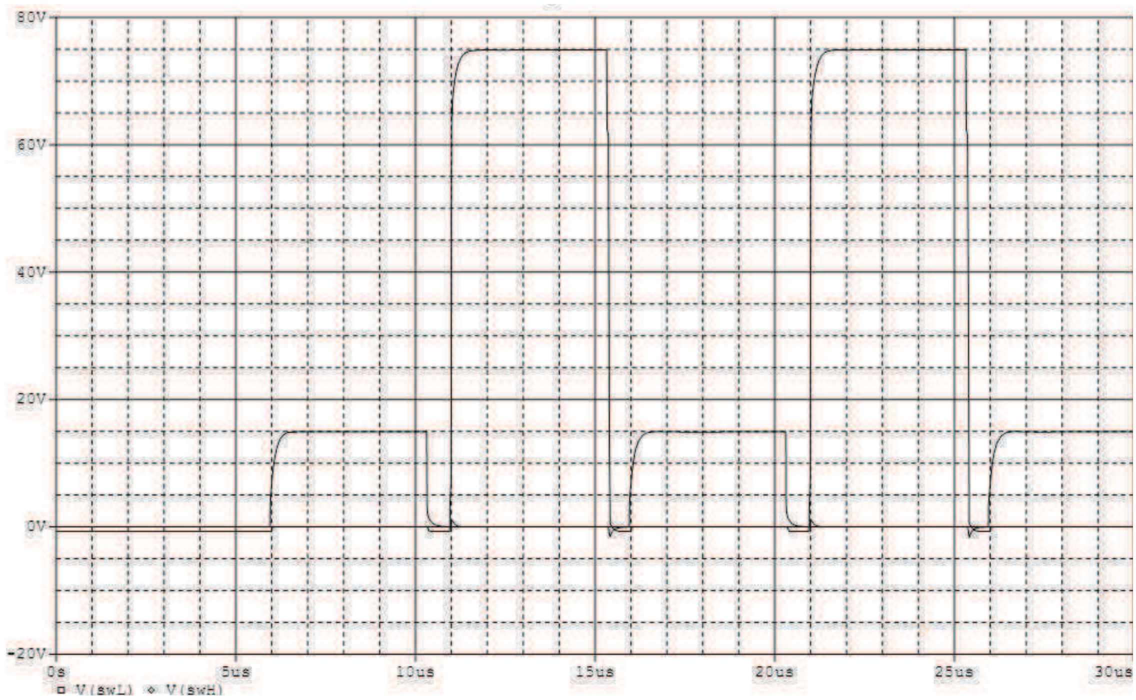


Figure 4.8 Waveforms of MOSFETs` gate signals

The waveform of output voltage of circuit which is shown below (Figure 4.9), points that the circuit is ready to realize. Consequently the next step of thesis work is to draw printed circuit board schematics and build circuits for testing and comparing results between simulations and realized circuits.

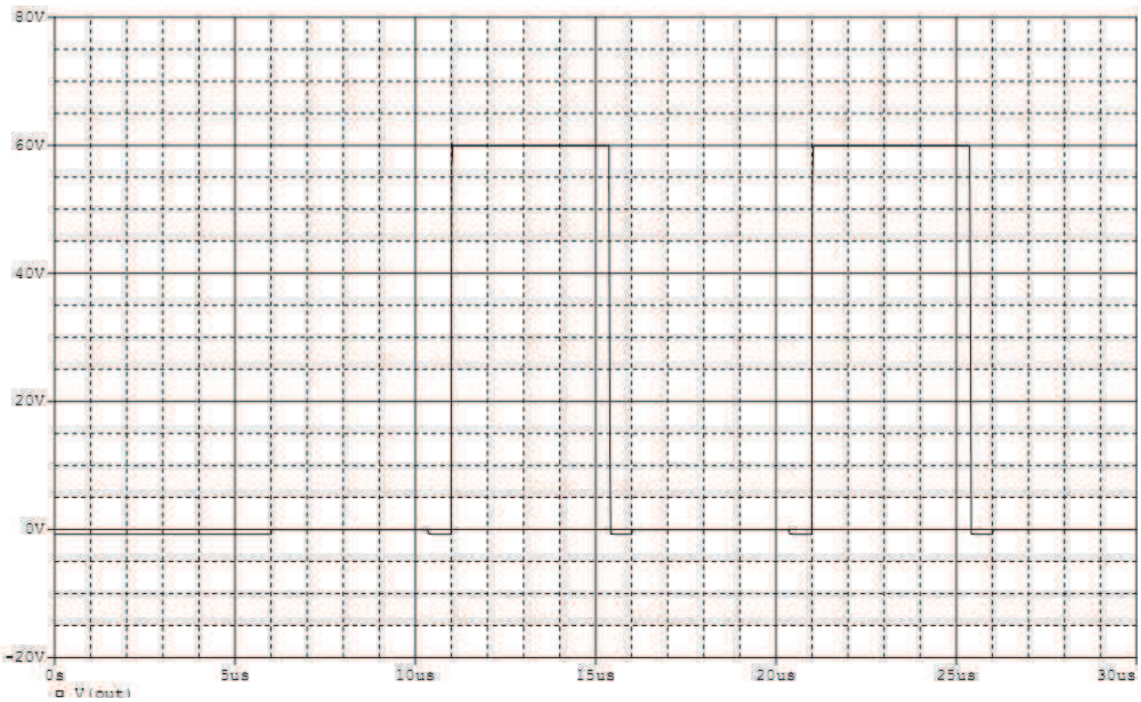


Figure 4.9 Waveform of output voltage

CHAPTER 5

BUILDING HALF - BRIDGE INVERTER CIRCUIT

5.1 Printed Circuit Board Schematics of Half - Bridge Inverter Circuit

As the first step of building half – bridge inverter circuit; printed circuit board schematic was drawn. For preparing printed circuit board, sprint – layout 5.0 was used. Printed circuit board schematic and printed circuit board schematic with components are given below (Figure 5.1 and Figure 5.2).

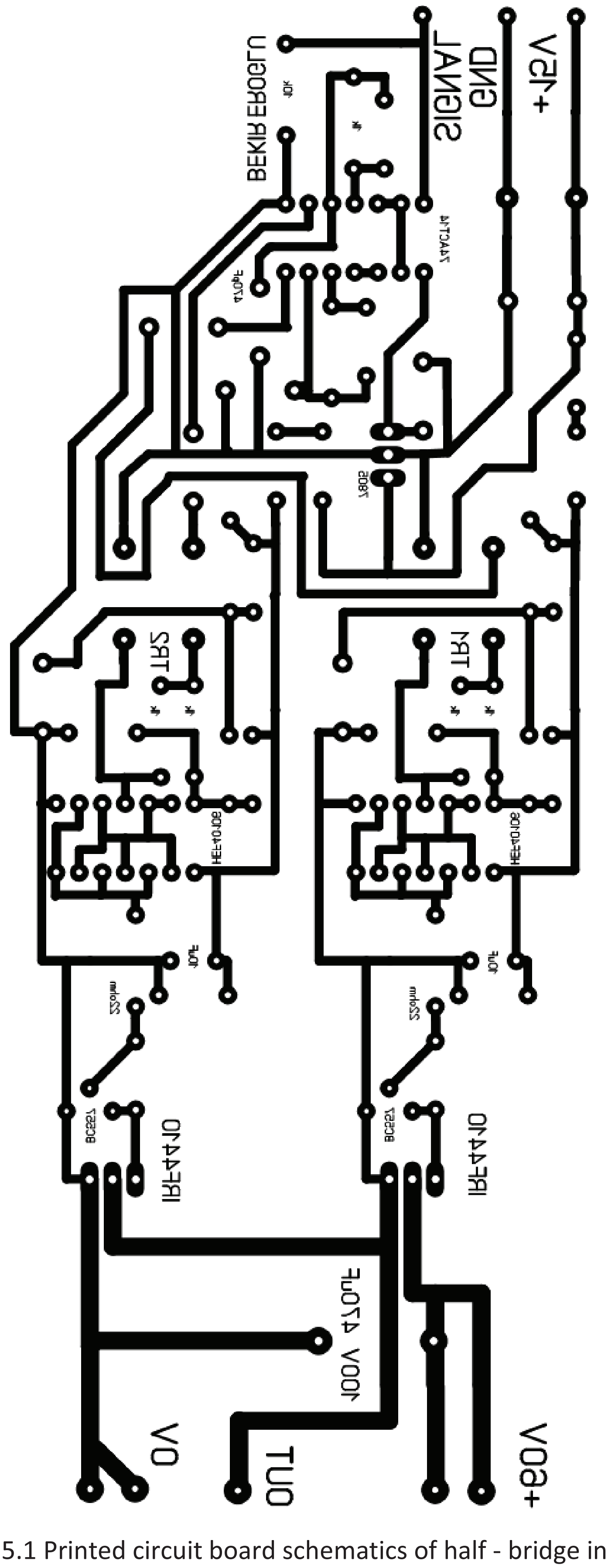


Figure 5.1 Printed circuit board schematics of half - bridge inverter

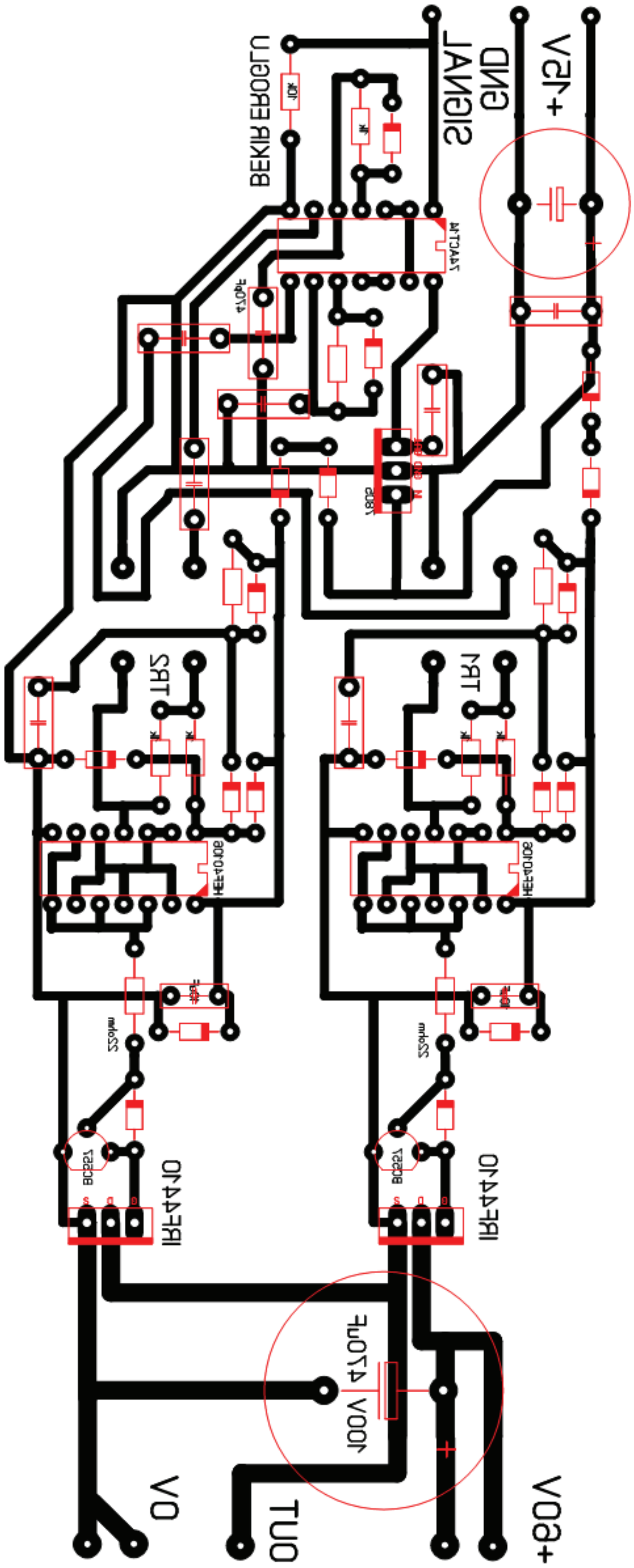


Figure 5.2 Printed circuit board schematics with components of half - bridge inverter

5.2 Building Half – Bridge Inverter Circuit

Half - Bridge inverter circuit was built in accordance with simulation circuit. Bill of materials and prepared circuit are shown below (Chart 5.1).

Chart 5.1 Bill of materials for half – bridge inverter circuit

Component	Value - Model	Quantity
Capacitor (Electrolytic)	100 uF, 25 V	1
Capacitor (Electrolytic)	470 uF, 100 V	1
Capacitor (Polyester)	3,3 nF	2
Capacitor (Polyester)	470 pF	2
Capacitor (Polyester)	1 uF	2
Capacitor (Polyester)	10 uF	4
Resistor	22 Ω	2
Resistor	1 k Ω	6
Resistor	10 k Ω	1
Resistor	100 k Ω	2
Diode	1N4148	16
Zener Diode	15 V	2
Signal Transformer	1 : 3	2
Rectifier	7805	1
Hex Inverter	74ACT14 (5 V)	1
Hex Inverter	HEF40106 (15 V)	2
BJT	BC557	2
MOSFET	IRFS44010	2

Control stage of circuit is supplied by an external 15 Volts power source. External PWM signal which is applied from signal input of circuit is arranged by 5 Volts logic stage. This stage is supplied by the voltage regulator 7805. Through the 5 Volts logic stage external PWM signal is split two different PWM signals for both of switching components (MOSFETs). In the meantime also a delay is added between signals to prevent short – circuit. These control signals are applied to signal transformers with a turn – ratio of 3 through by 3.3 nF valued capacitors. In 15 Volts stage, by boot – strap circuit, these control signals are become appropriate form to switch MOSFETs.

Half - Bridge inverter circuit is built according to drawn printed circuit board schematic and shown below (Figure 5.3 and Figure 5.4).

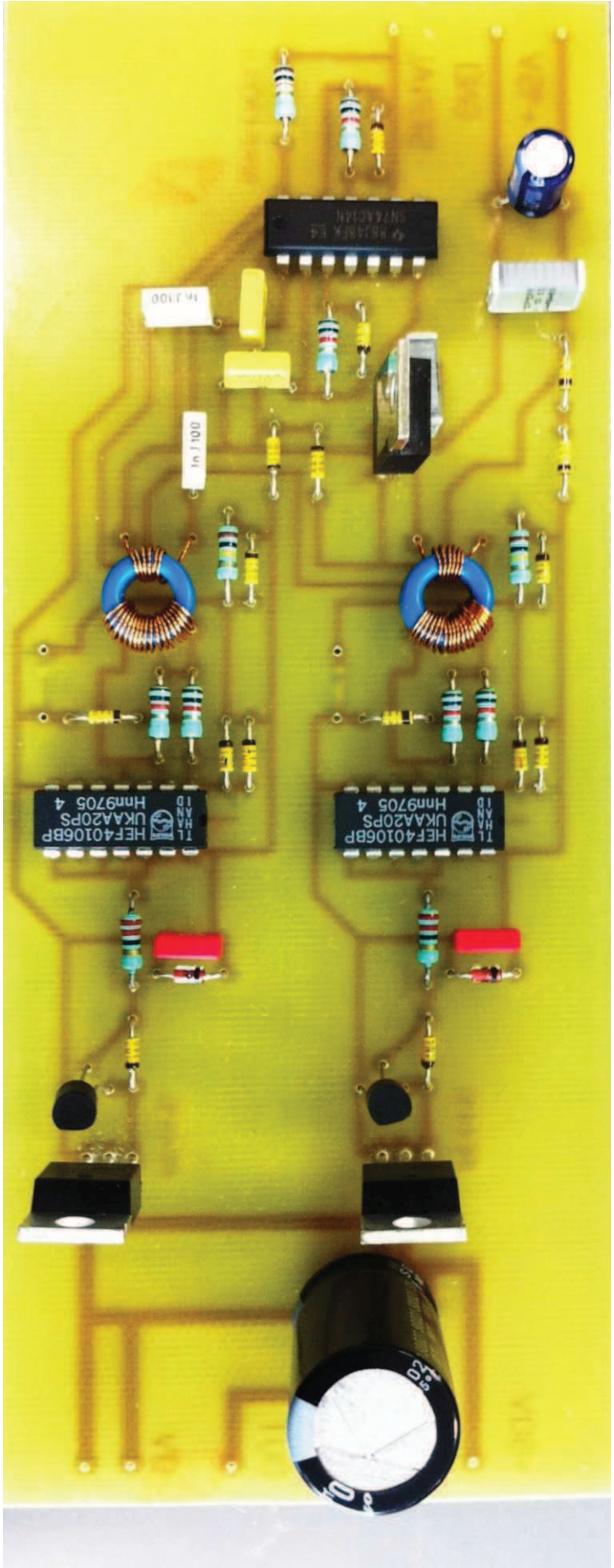


Figure 5.3 Front side of half - bridge inverter circuit

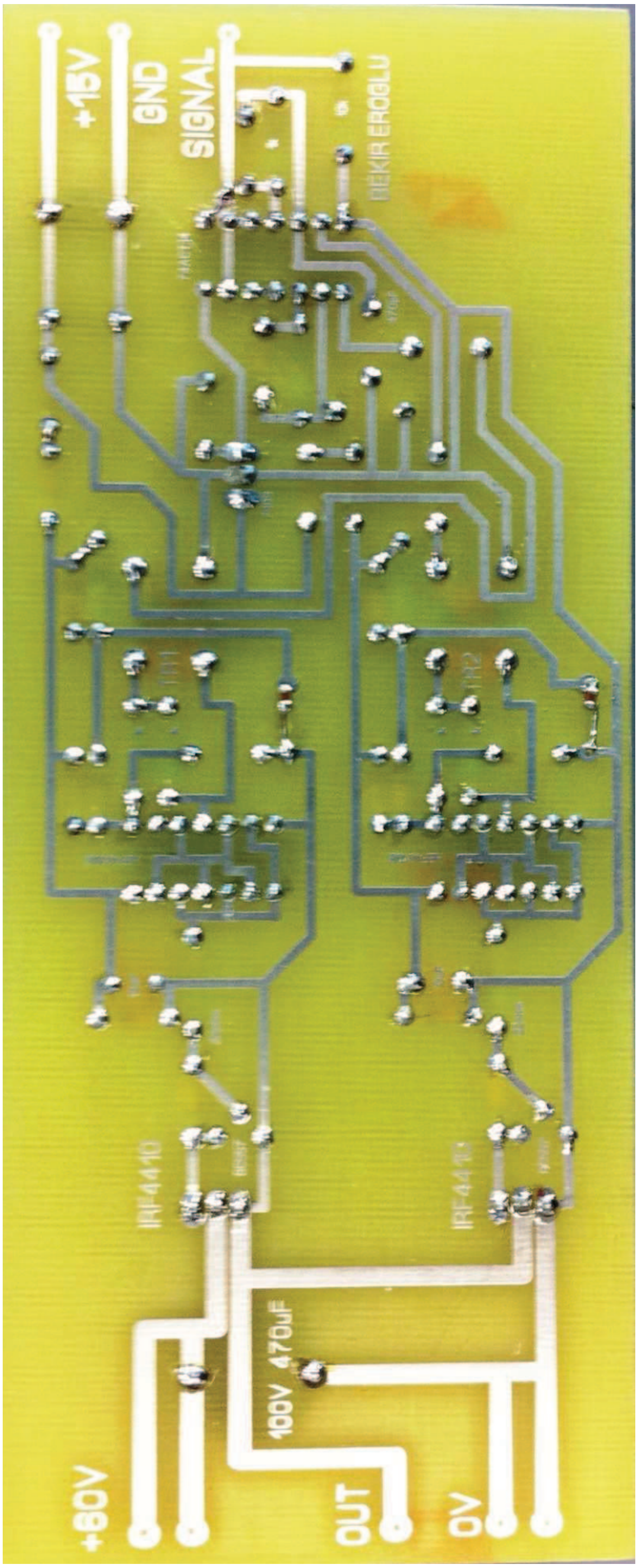


Figure 5.4 Reverse side of half – bridge inverter circuit

5.3 Testing Half – Bridge Inverter Circuit

The screenshot from oscilloscope which is given below PWM control signals for both switching branch of Inverter are shown (Figure 5.5). The amplitudes of signals are 5 Volts as it is seen and the value of duty cycle is chosen as 90 percent and the frequency value is 1 kHz. These signals are also contain a delay between them to prevent short – circuit. This PWM control signal was applied by an external oscillator device from the signal input of circuit.

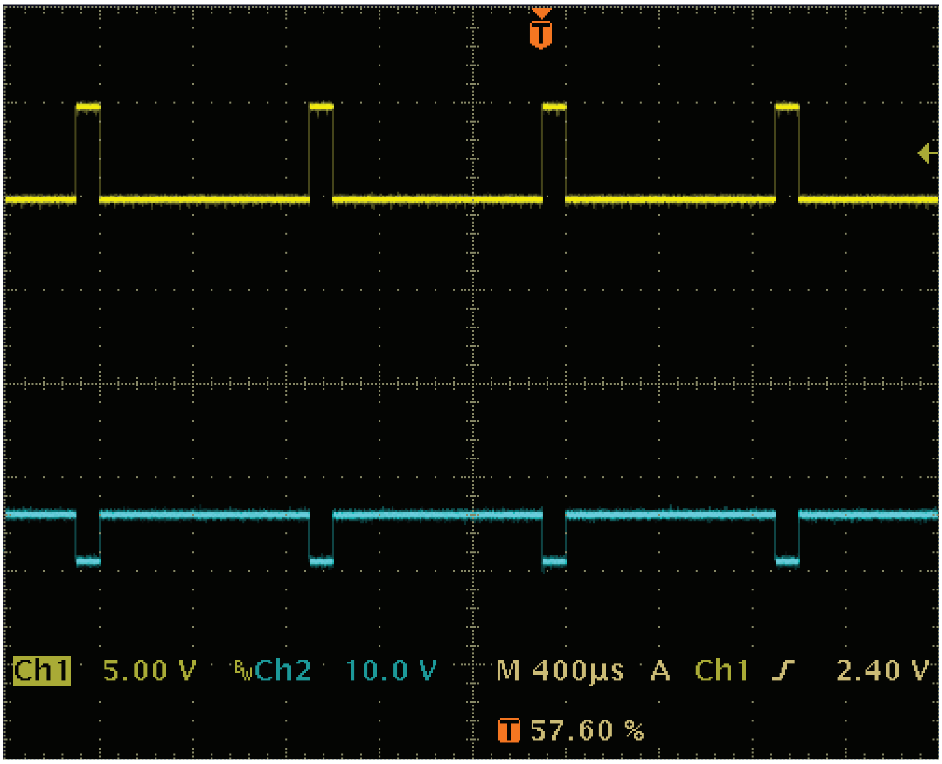


Figure 5.5 PWM control signals arranged by 5 V control stage

The waveform is shown below; output voltage and current values` reaction to PWM control signal of half – bridge inverter circuit is indicated (Figure 5.6).

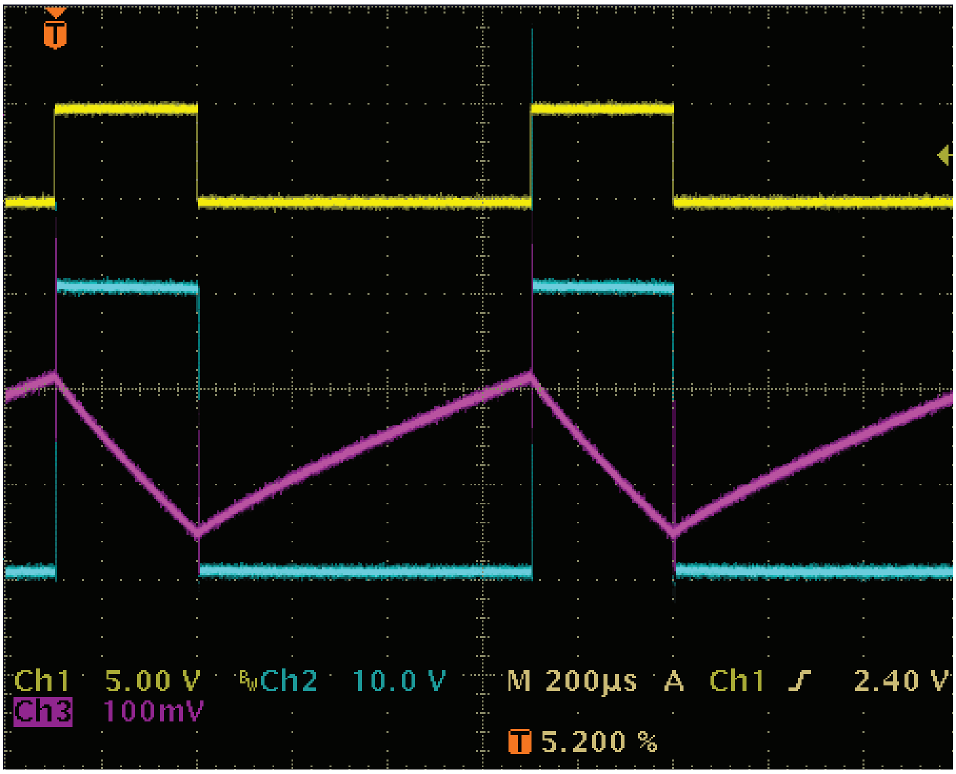


Figure 5.6 Waveforms of output voltage and current

In the figures below MOSFETs` switch - on and switch - off drain voltage waveforms are shown (Figure 5.7 and Figure 5.8).

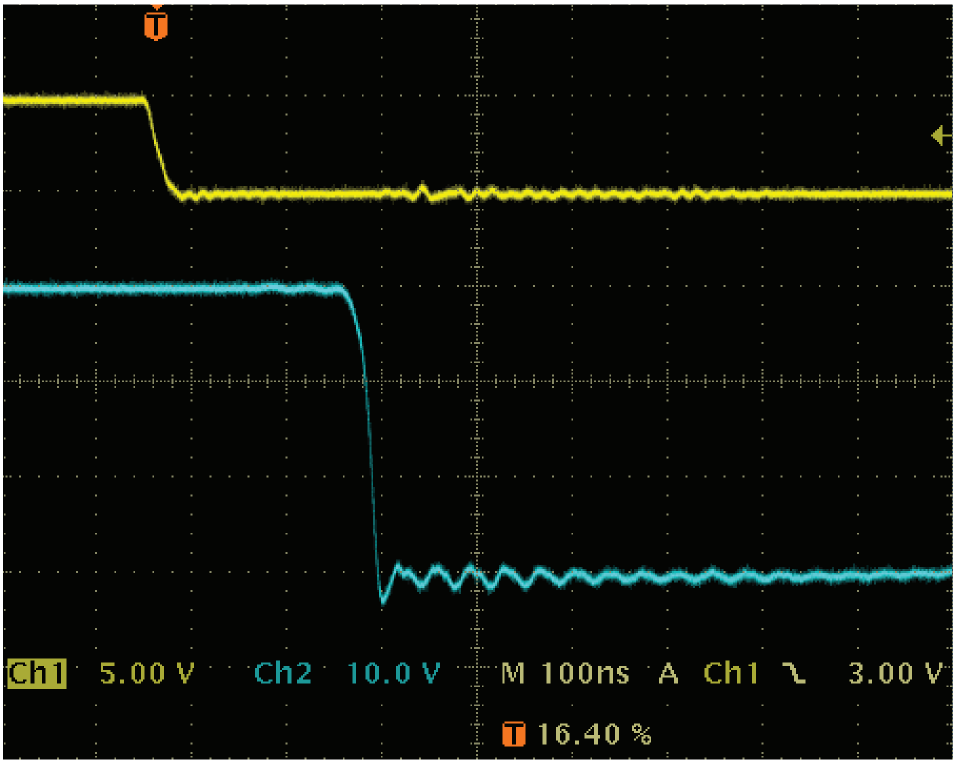


Figure 5.7 Switch - On MOSFET drain voltage waveform

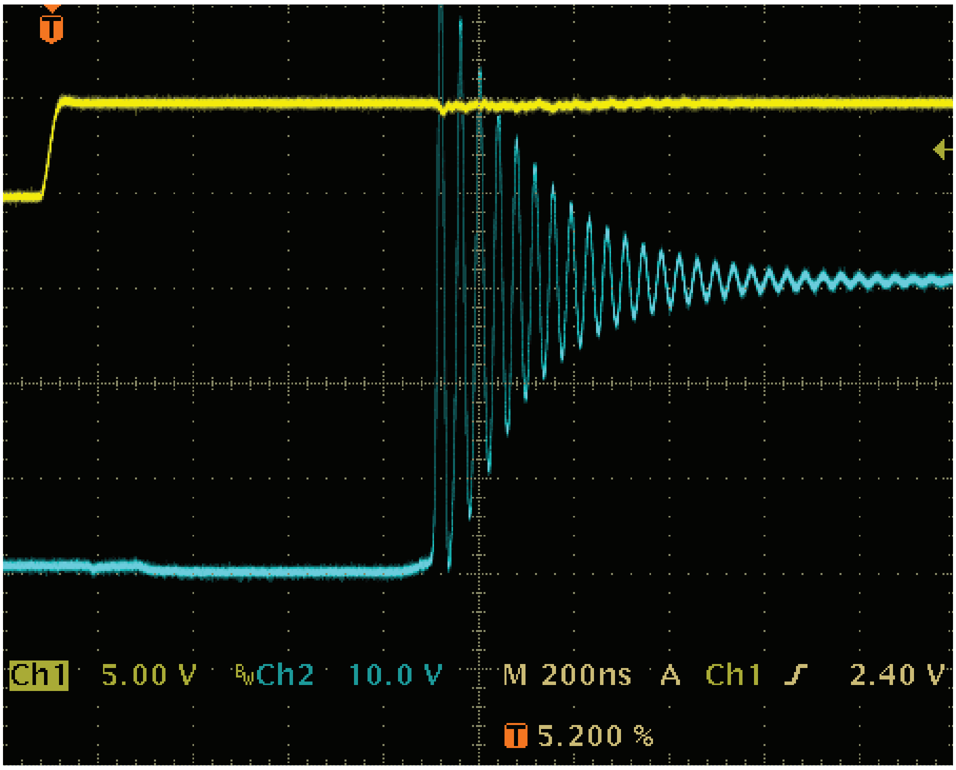


Figure 5.8 Switch - Off MOSFET drain voltage waveform

5.3.1 Half - Bridge Inverter Circuit with RC Snubbers

RC snubber is also known as the simplest snubber which contains a resistor in series with a small capacitor. The combination of resistor and capacitor components in series is used to suppress the rapid rise in voltage across a switching component [6]. In the figures below MOSFETs` switch – on and switch – off drain voltage waveforms after addition of RC snubber are shown (Figure 5.9 and Figure 5.10). The R (resistance) value of snubber was chosen as 20 Ω and the C (capacitance) value is 5 nF. By the help of RC snubber; inconvenient oscillations in the waveforms are overcome.

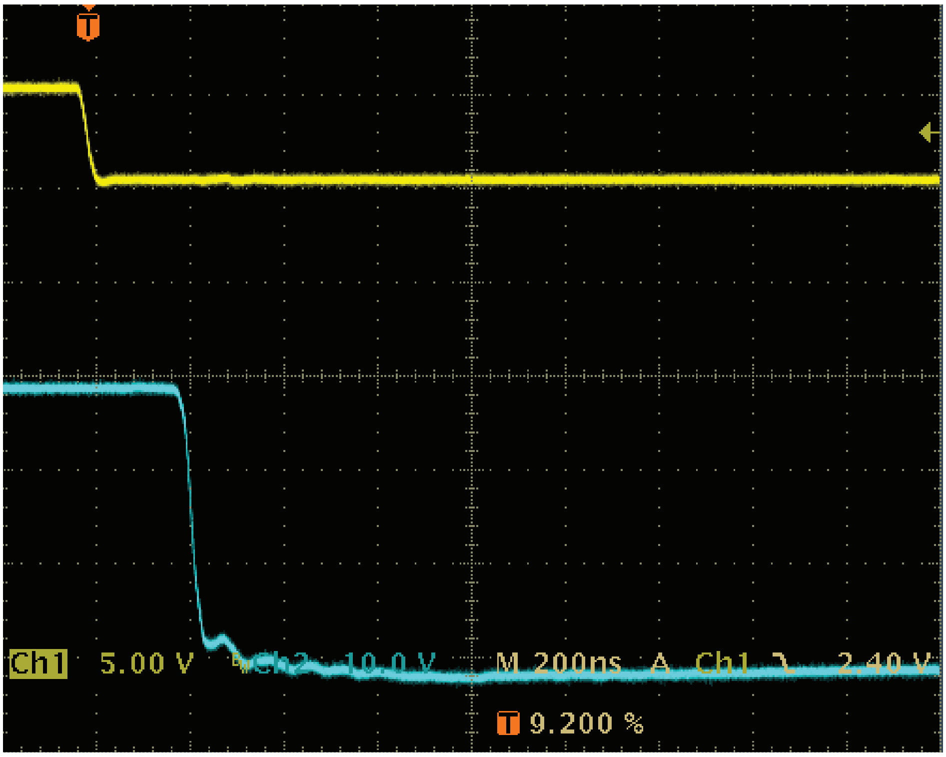


Figure 5.9 Switch – On MOSFET drain voltage waveform after addition of RC snubber

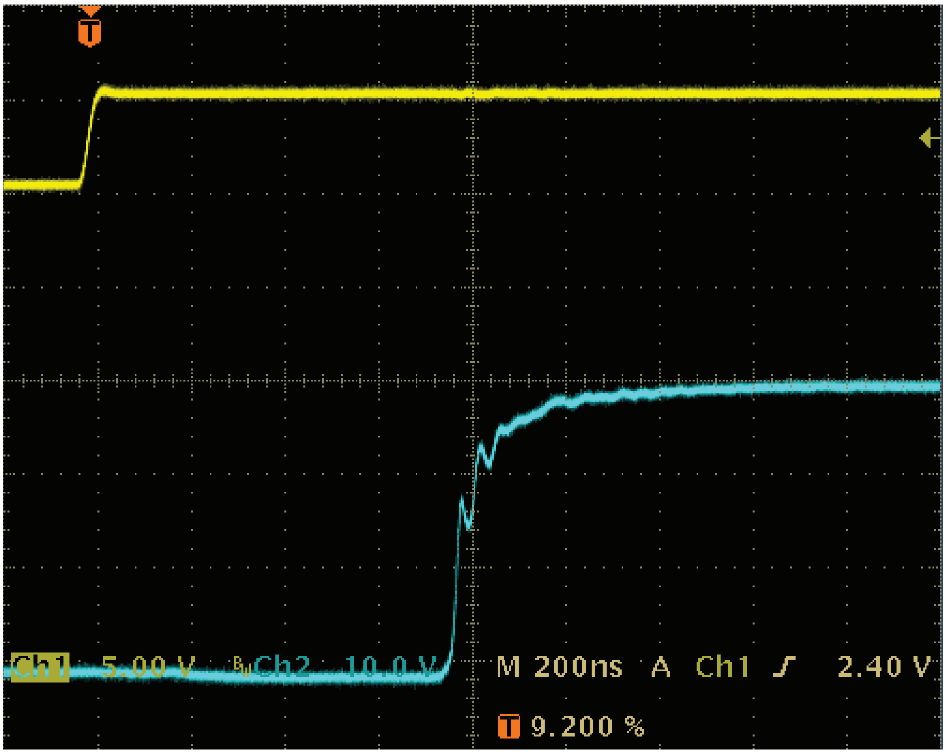


Figure 5.10 Switch - Off MOSFET drain voltage waveform after addition of RC snubber

CHAPTER 6

BUILDING HALF BRIDGE INVERTER CIRCUIT WITH 2 MOSFETS IN SERIES

6.1 PCB Schematics of Half - Bridge Inverter with 2 MOSFETs in Series

As the first step of building half - bridge inverter circuit with 2 MOSFETs in series; printed circuit board schematic was drawn. For preparing printed circuit board, sprint – layout 5.0 was used. Due to complexity of circuit, conductor lines for both sides of board were used. Printed circuit board schematic and printed circuit board schematic with components are shown below (Figure 6.1 and Figure 6.2).

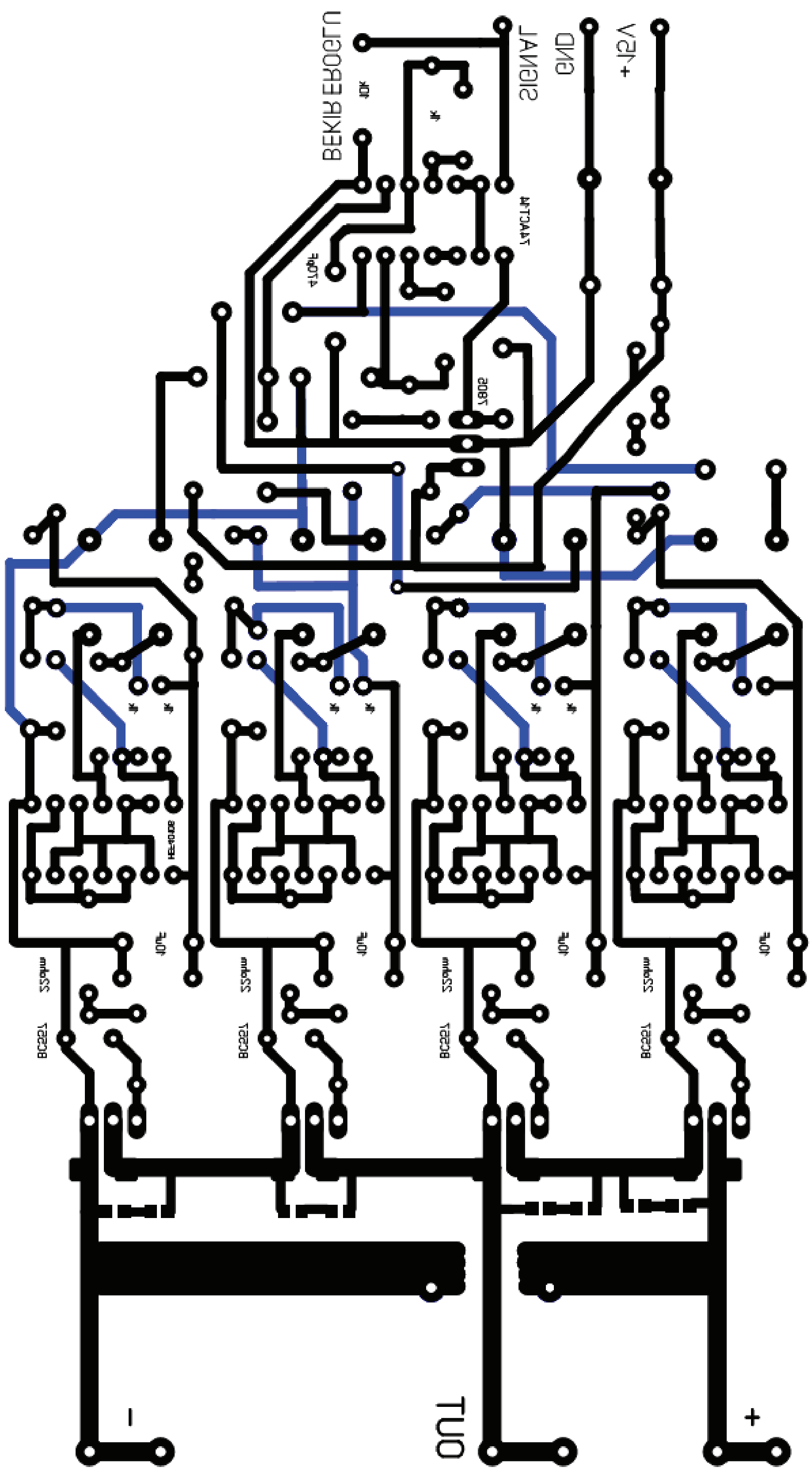


Figure 6.1 PCB Schematic of half - bridge inverter with 2 MOSFETs in series

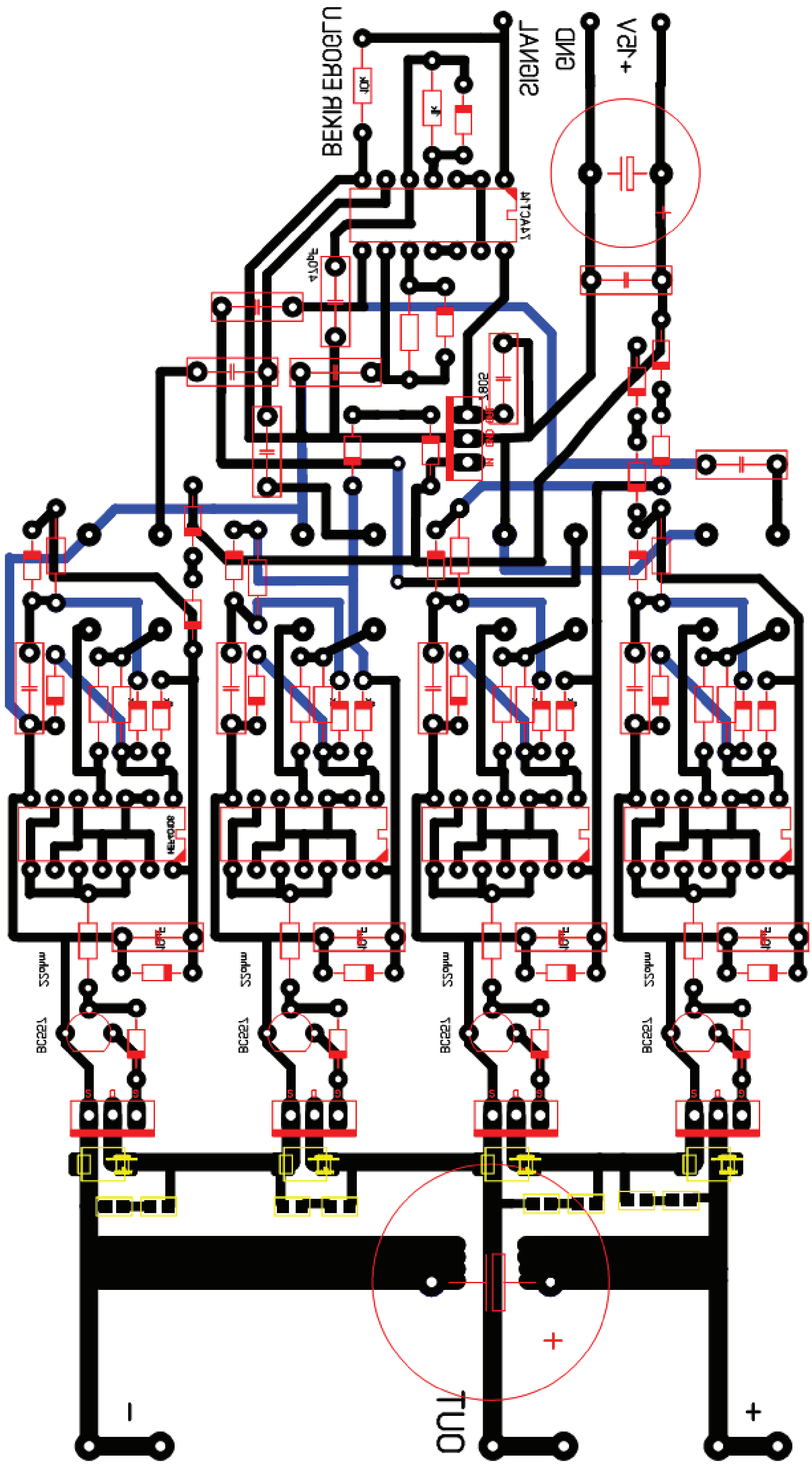


Figure 6.2 PCB Schematic with comp. of half - bridge inverter with 2 MOSFETs in series

6.2 Building Half - Bridge Inverter Circuit with 2 MOSFETs in Series

Half - Bridge inverter circuit with 2 devices in series was built in accordance with simulation circuit. Bill of materials and prepared circuits are shown below (Chart 6.1, Figure 6.3 and Figure 6.4).

Chart 6.1 Bill of materials for half – bridge inverter circuit with 2 MOSFETs in Series

Component	Value - Model	Quantity
Capacitor (Electrolytic)	100 uF, 25 V	1
Capacitor (Electrolytic)	470 uF, 100 V	1
Capacitor (Polyester)	3,3 nF	4
Capacitor (Polyester)	470 pF	2
Capacitor (Polyester)	1 uF	4
Capacitor (Polyester)	10 uF	6
Resistor	22 Ω	4
Resistor	1 k Ω	10
Resistor	10 k Ω	1
Resistor	100 k Ω	4
Diode	1N4148	30
Schottky Diode	100V	4
Zener Diode	15 V	4
Signal Transformer	1 : 3	4
Rectifier	7805	1
Hex Inverter	74ACT14 (5 V)	1
Hex Inverter	HEF40106 (15 V)	4
BJT	BC557	4
MOSFET	IRFS44010	4

Control stage of the half - bridge inverter circuit is supplied by an external 15 Volts power source. External PWM signal which is applied from signal input of circuit is arranged by 5 Volts logic stage. This stage is supplied by the voltage regulator 7805. Through the 5 Volts logic stage external PWM signal is split two different PWM signals for both of switching branches (2 MOSFETs in series). In the meantime also a delay is added between signals to prevent short – circuit. These control signals are applied to signal transformers with a turn – ratio of 3 through by 3.3 nF valued capacitors. In 15 Volts stage, by boot – strap circuit these control signals are become appropriate form to switch MOSFETs.

Half - Bridge inverter circuit with 2 MOSFETs in series was built in accordance with drawn printed circuit board schematics. Pictures of prepared circuit are shown below (Figure 6.3 and Figure 6.4).

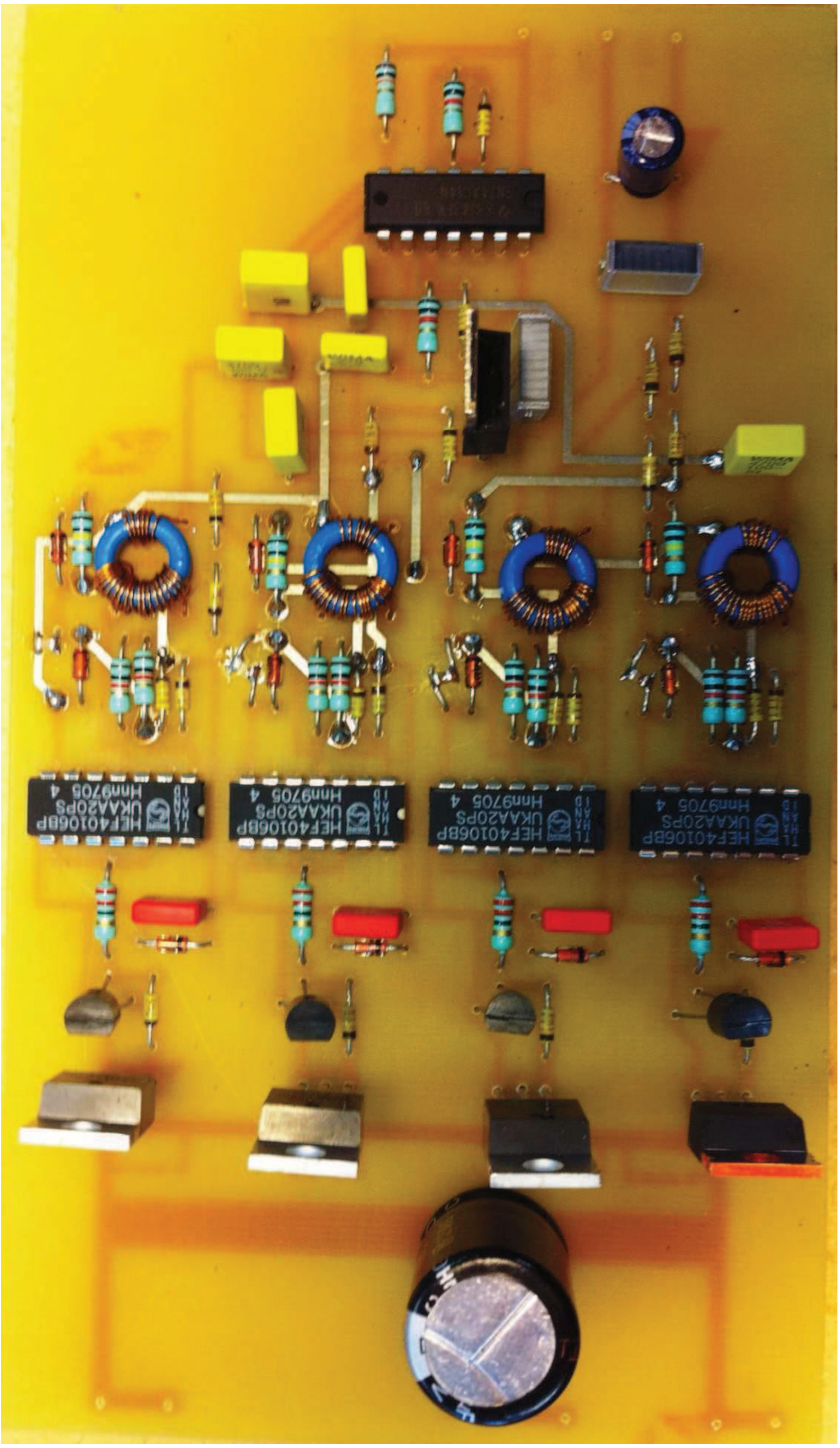


Figure 6.3 Front side of half - bridge inverter circuit with 2 devices in series

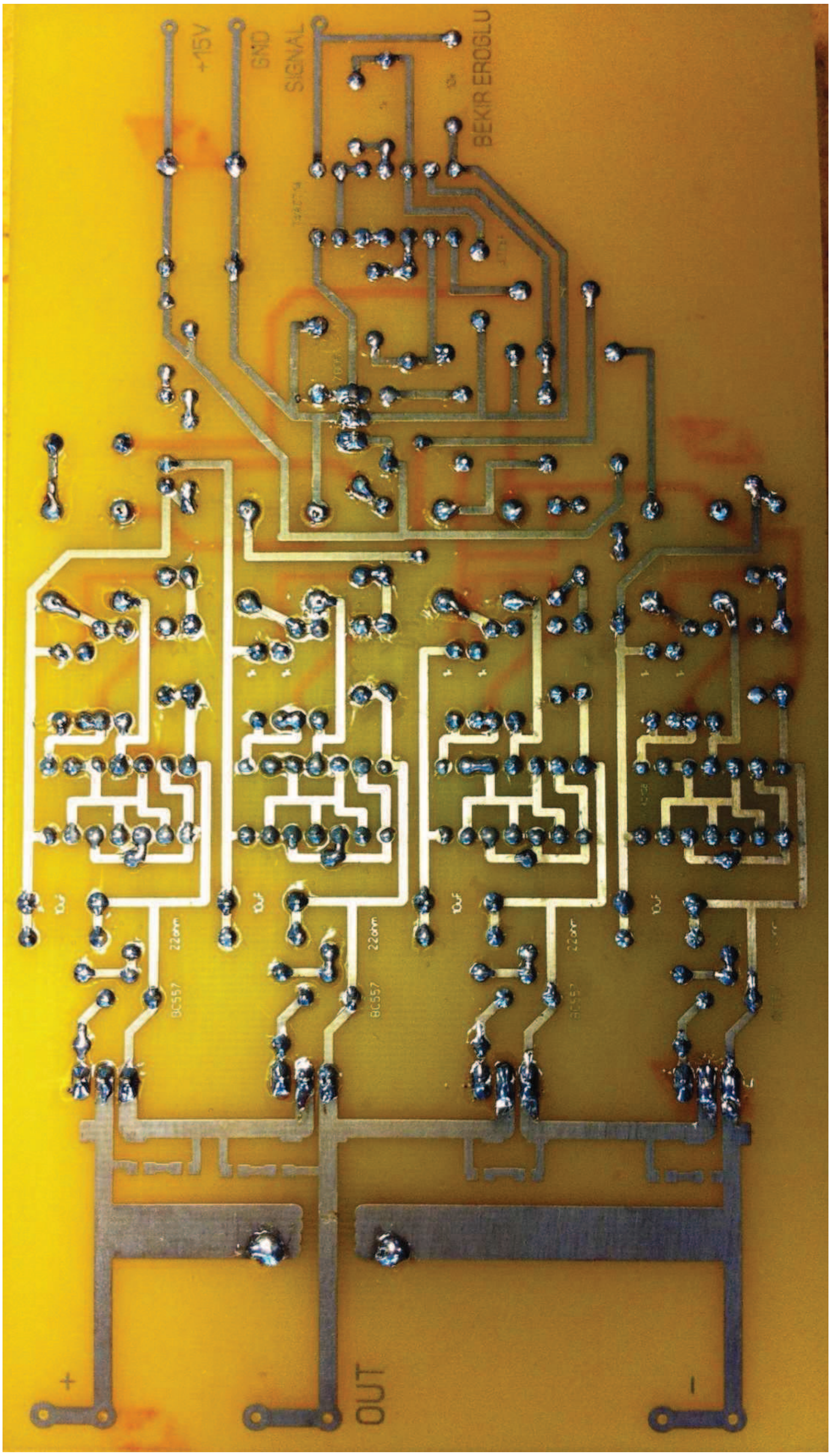


Figure 6.4 Reverse side of half - bridge Inverter circuit with 2 devices in series

6.3 Testing Half - Bridge Inverter Circuit with 2 MOSFETs in Series

Screenshot from oscilloscope which is given below the waveform of output current and MOSFETs sharing capability of main output voltage are shown (Figure 6.5). The amplitudes of MOSFETs` drain voltages are 10 Volts as it is seen and the value of duty cycle is chosen as 50 percent and the frequency value is 1 kHz. PWM signals which are received from an external oscillator device also contain a delay between them to prevent short – circuit. Waveforms that are copied from oscilloscope as screenshot show drain voltages of serially connected MOSFETs and output currents under the conditions of 20 Volts and 50 Volts supplies with 50% duty – cycle (Figure 6.5 and Figure 6.6).

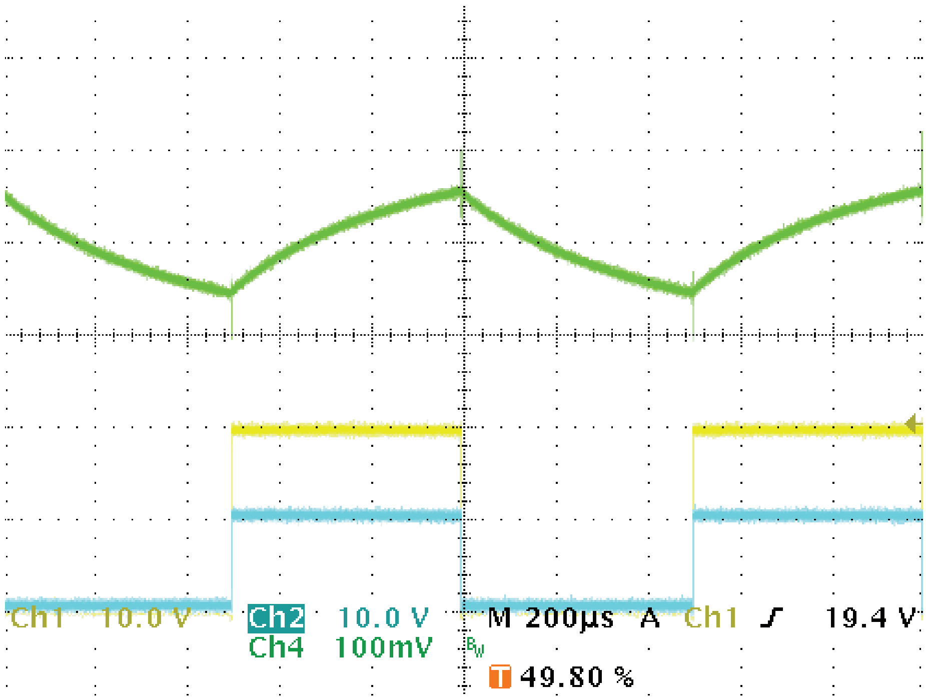


Figure 6.5 Waveforms of MOSFETs` drain voltages and output current (inverter is supplied by 20 V DC source, PWM control signal`s duty cycle is 50%)

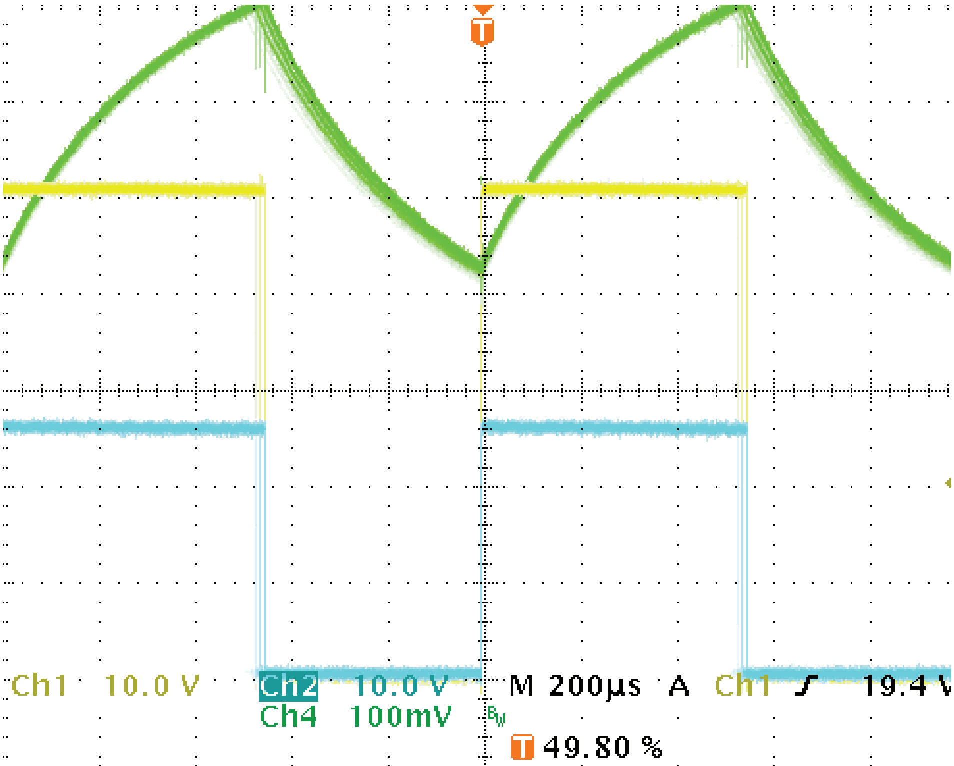


Figure 6.6 Waveforms of MOSFETs` drain voltages and output current (inverter is supplied by 50 V DC source, PWM control signal`s duty cycle is 50%)

In respect to following test works, duty cycle of input PWM signal was increased. While increasing duty cycle percentage; a failure in modulation occurred.

Using a schottky diode prevents the slow built – in reverse current diode of the MOSFET from turning on. Therefore serial shottky diodes are connected between drain and source pins of MOSFETs to run instead of their built – in reverse current diodes. The following figure shows waveforms of MOSFETs` drain voltages and the output current of circuit after addition of serial shottky diodes while inverter is supplied by 50 Volts DC source and PWM control signal`s duty cycle is 90% (Figure 6.7).

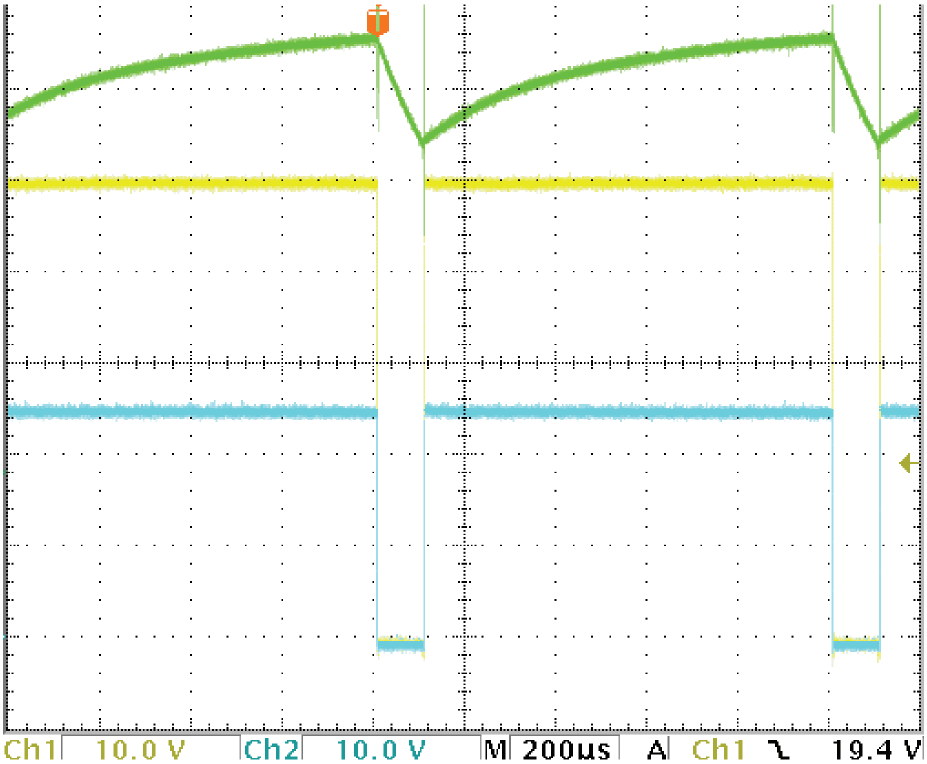


Figure 6.7 Waveforms of MOSFETs` drain voltages and output current (inverter is supplied by 50 V DC source, PWM control signal`s duty cycle is 90%)

Drain voltages of serially connected MOSFETs while switch - off and switch – on periods are shown in the next figures (Figure 6.8 and Figure 6.9). In the course of switch - off period an undesired sinusoidal ringing is seen in the next figure (Figure 6.8). This problem will be solved in the last step by adding RC Snubbers between the drain and source pins of MOSFETs.

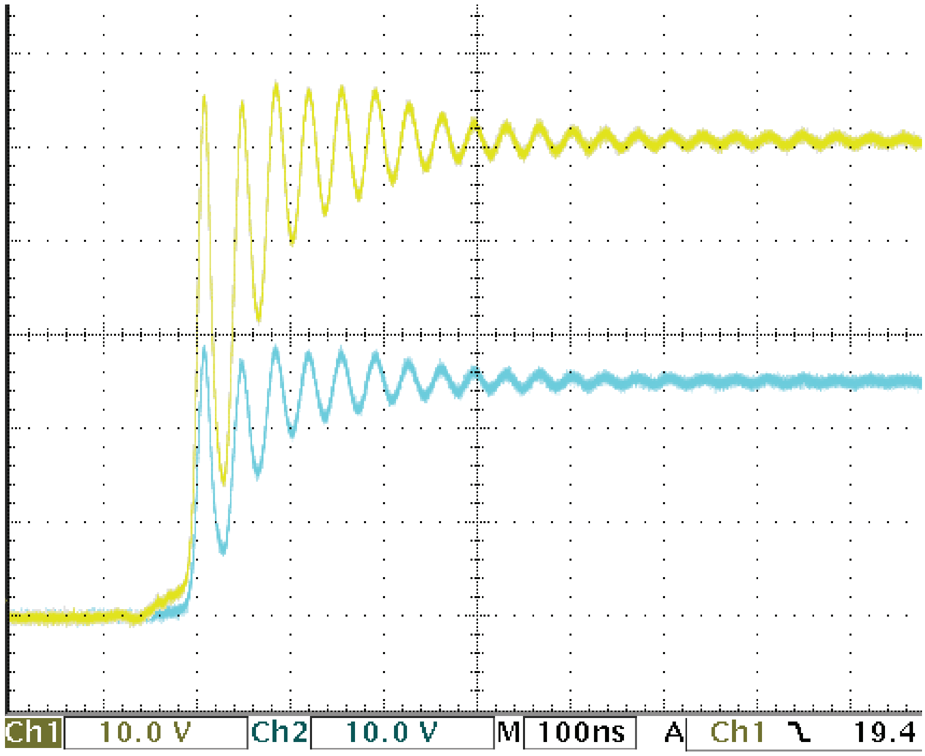


Figure 6.8 Drain voltages of MOSFETs in series while switch - off period

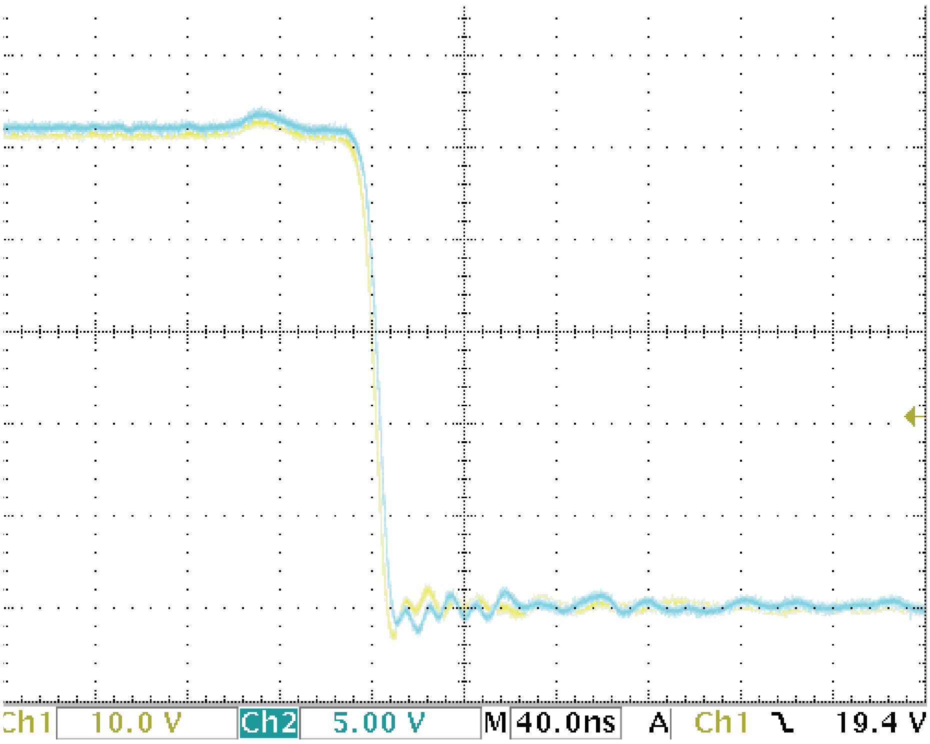


Figure 6.9 Drain voltages of MOSFETs in series while switch - on period

6.3.1 Half - Bridge Inverter Circuit with 2 MOSFETs in Series and RC Snubbers

RC snubbers placed across the MOSFETs as shown in half - bridge inverter with 2 MOSFETs in series (Figure 6.3) are used to reduce the peak voltage at turn-off and to damp the ringing. RC snubber is a combination of resistor and capacitor components in series is used to suppress the rapid rise in voltage across a switching component. In the figures below MOSFETs` switch - on and switch - off drain voltage waveforms after addition of RC snubber are shown (Figure 6.10 and Figure 6.11). The R (resistance) value of snubber is chosen as 20 Ω and the C (capacitance) value is 10 nF. By the help of RC snubber inconvenient oscillations in the waveforms are overcome. The following two waveforms indicate drain voltages of MOSFETs in series while switch - off and switch - on periods after addition of RC Snubbers. The next figure which represents drain voltages of series MOSFETs during switch - off period (Figure 6.10), the overcoming of sinusoidal ringing is obviously seen.

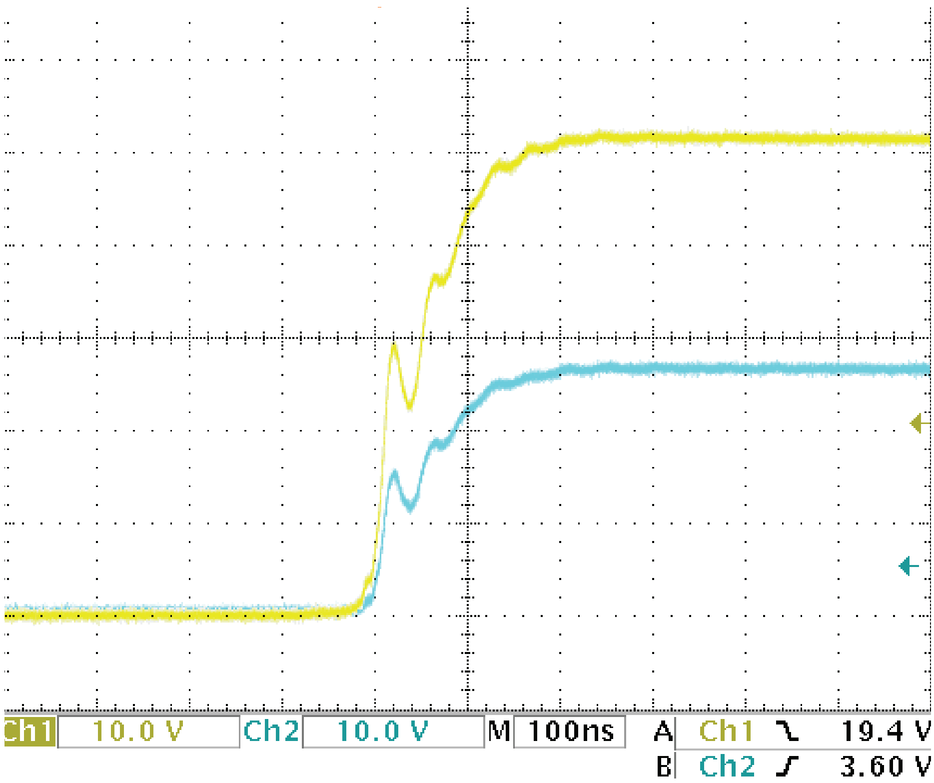


Figure 6.10 Drain voltages of MOSFETs in switch - off period after addition of snubbers

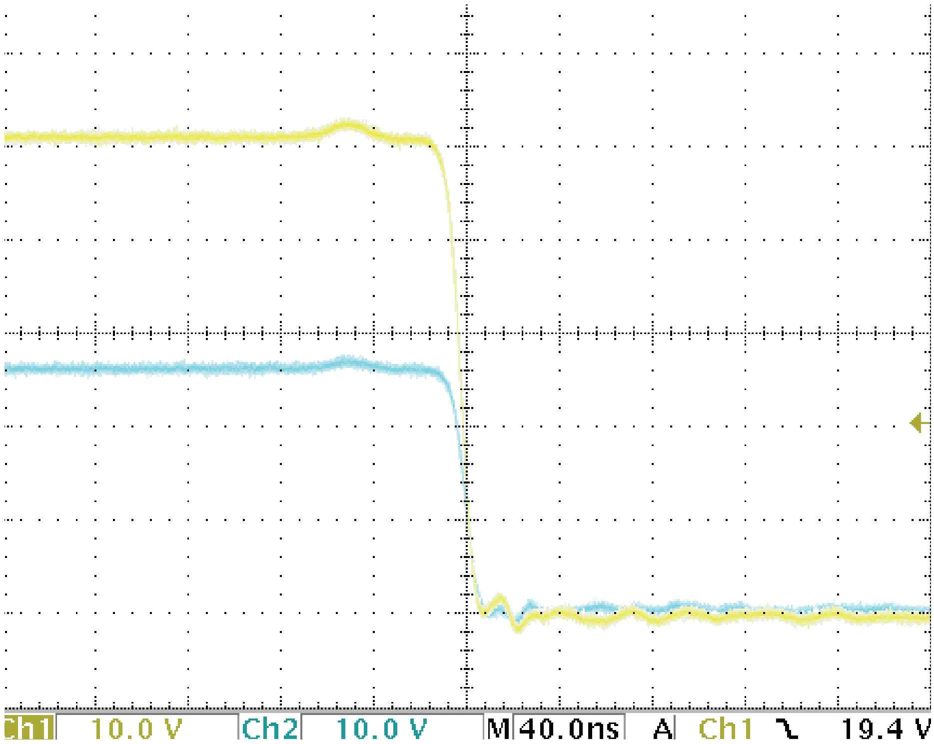


Figure 6.11 Drain voltages of MOSFETs in switch - on period after addition of snubbers

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Waveforms of drain voltages of series MOSFETs indicate that devices share the voltage equally while they are connected in series. Consequently, MOSFETs in series are suitable to run compatibly.

Using devices in series for a power inverter becomes with several advantages such as facilitating high – power inverter applications, allowing to build affordable inverters for same power and utilizing better characteristics (fast switching, short reverse – recovery time, poor parasitic capacitor etc.) of low - power transistors and MOSFETs.

But using devices in series also causes some problems such as [3]:

- The entire DC voltage appears across each switch while off – state of switches. This voltage is higher than the voltage rating of the individual MOSFETs.

- MOSFETs may not automatically share the voltage in the off - state due to differences in leakage current. The best possible way to overcome this issue is using of high value parallel resistors with MOSFETs.

- The devices may not share the voltage during switching due to variations in switching speed.

Using devices in series also provides some advantages instead multilevel power inverters. The simplicity of using traditional pulse – width modulation signals to control circuits, reducing the total cost of inverter circuit and improving reliability can be given as significant advantages.

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RESUME

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2007	Istanbul Anatolian Side Electricity Distribution Corporation	Intern
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