

**UNIVERSITY OF BRITISH COLUMBIA**



**DEPARTMENT OF ELECTRICAL AND COMPUTER  
ENGINEERING**

**POWER ELECTRONICS LAB**

**HANDBOOK**

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## 1 AIM

The aim of the project is to design, construct and test a 24V dc to 240V ac (50Hz), 150W inverter to given specifications. The inverter has an application as a backup mains power supply for use on a boat.

## 2 SPECIFICATION

1. Input: 24V dc, from two car type batteries
2. Output: 230V ac +10% / -6% , 50±0.5 Hz., 0-150 W Power.
3. Output waveform is to be square, for supplying tungsten filament lamps.
4. Target efficiency of 85% at 150W output.
5. Should operate between 0 and 45 Deg.C.
6. Construction cost to be as low as possible.
7. Must not require any special precautions when switched on or off.

## 3 PROCEDURE

In principle, the choice of components is not limited, but students are advised that the case for ordering components must be made clearly and convincingly in your reports.

The project is arranged in stages as follows:

Week	Thursday	Monday (Hand in)	Comments
2 and 3	Conceptual design		
4		Report 1	4 sides
	Oscillator; design, build, test		
5	Power stage design, build and test		Order components
6	Transistor Choice		Order components
7	Drive circuit design, build and test		Order components
8	Oscillator/transistor interface; design, build and test		Order components Draw Final Circuit
9	Final Assembly		
10	Commissioning		
11	Tests		
12		Final report	6 sides + appendix

Each stage should take about one 3-hour laboratory session.

Most design tasks are performed prior to the laboratory session. Have your final designs, checked by a demonstrator. This is merely to avoid you wasting time and effort on small mistakes.

## 4 CONCEPTUAL DESIGN

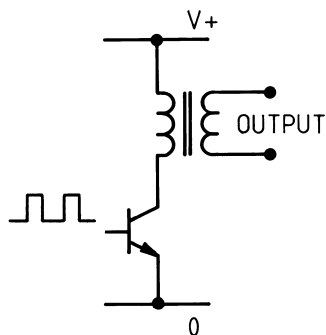
### 4.1 Introduction

Inversion is the conversion of dc power to ac power at the desired frequency and voltage. Central to a stand-alone inverter will be an oscillator, which produces the required output frequency. This frequency is then used in the control of power electronic switching devices. The switching devices supply current from the dc source to the next stage. An output transformer is commonly used. Switching the devices changes the voltage applied to the primary. The secondary of the output transformer thus produces a voltage, with its magnitude being determined by the transformer turns ratio.

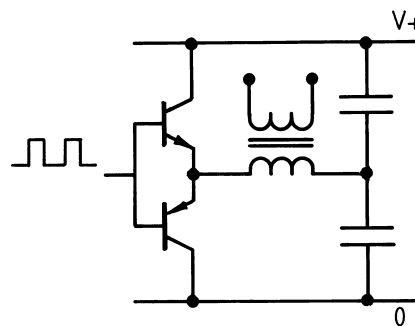
Thus your conceptual design needs to consider the topology of power stage, the drive circuits required for the switching devices and the oscillator.

### 4.2 The power stage

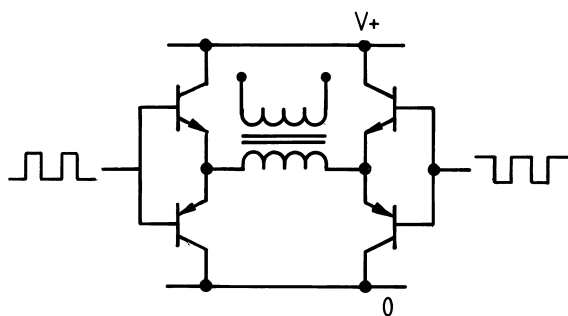
There are four topologies of interest for a single phase inverter<sup>1</sup>:



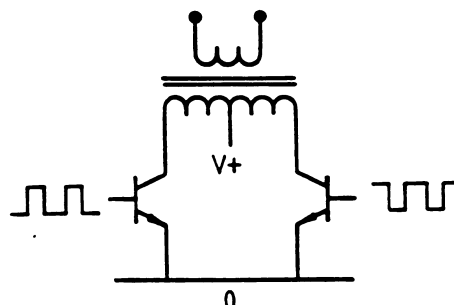
4.1.a. Single ended



4.1.b. Half bridge



4.1.c. Full bridge



4.1.d. Push-pull

<sup>1</sup>Power Electronics, Mohan, Undeland and Robbins, Wiley

A comparison should be made in terms of the total power semiconductor Volt-Amp product required (a simple measure of cost) and the relative costs of the other power components required. Your comparison may well conclude that the push-pull converter is the preferred arrangement.

### 4.3 The driver stage

Having chosen a circuit for the output stage, verify that the 2N3055 or similar transistor is a suitable switching device. The drive requirements of the transistors may then be estimated. The transistors used in the output stage of the push-pull converter require complementary base drive signals. A simple method of obtaining such signals is to use two secondaries on a transformer. Using a transformer is also an efficient way of matching the oscillator output voltage to the transistor base voltage requirement. Thus the driver stage becomes a small inverter in its own right. Show that the half-bridge converter is the most suitable circuit for the driver stage, and estimate the current that the oscillator circuit must be able to supply.

### 4.4 The oscillator

The oscillator must operate from a single 24V dc supply. It must produce a square wave of 50Hz, with a unity mark-space ratio. It should be stable over a wide range of supply voltage and temperature (why?). Such a square-wave generator may be made in a variety of ways. Investigate different oscillator circuits and show that the relaxation oscillator of figure 4.2, based on an operational amplifier, will satisfy the stability and voltage rail requirements.

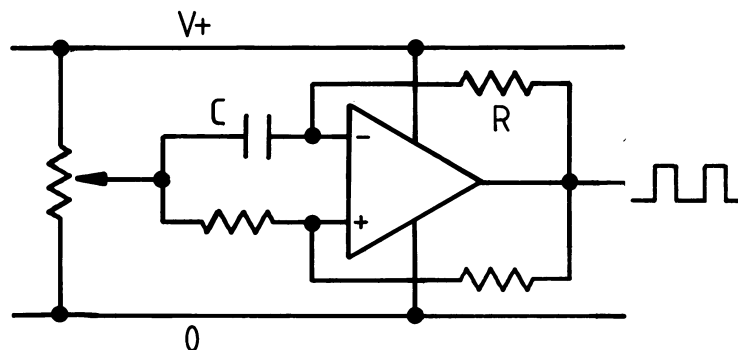


Fig. 4.2 Relaxation Oscillator

An operational amplifier will be unlikely to be able to supply enough current to drive the power transistors via the coupling transformer. A class B amplifier stage may be added to the oscillator circuit to increase its available output current<sup>2</sup>.

<sup>2</sup>The Art Of Electronics, Horowitz and Hill, CUP, 1980

## **5 OSCILLATOR DESIGN**

### **5.1 Introduction**

Generate a square wave of  $50 \pm 0.5$  Hz over the temperature range of  $0-45^{\circ}\text{C}$  and voltage range of  $24 \pm 6$  V.

### **5.2 Design principles**

Consider the relaxation oscillator design of figure 4.2. When power is applied, the operational amplifier output goes to the positive rail. The capacitor charges to  $+V$  with a time constant  $RC$ . When its voltage exceeds  $0.75 V$ , the operational amplifier switches to  $0 V$  and the capacitor discharges with time constant  $RC$ . The cycle repeats with period  $2.2 RC$ , ideally independent of the supply voltage.

### **5.3 Construction and test**

Build the oscillator on the circuit board provided. Use a balanced pair of load resistances for the following tests:

- Regulation: Measure the output voltage versus output current, with a constant 24 V supply.
- Frequency Stability 1: Measure the output frequency and Mark-Space Ratio versus supply voltage over the range 12-32 V (a wider range than that expected with two lead acid batteries).
- Frequency Stability 2: Measure the output frequency versus temperature. The temperature may be measured using a hand held temperature probe. The temperature may be varied using freezer spray and heat gun.
- Waveform: Measure the rise time and fall time of the output voltage waveform.

## **6 TRANSISTOR CHOICE**

### **6.1 Introduction**

In order to reduce the on-state voltage and hence power losses, the transistors are required to operate fully saturated. Consider carefully the manufacturer's data for the 2N3055 power transistor.

MOSFET data is usually more detailed, but still requires very careful consideration.

## 6.2 Operating conditions

For the push-pull design, an estimate of the operating collector current may be made by calculating the power to be supplied to the primary of the output transformer and the voltage across it. The power will include some estimate of the transformer losses. The peak magnetising current should be considered also.

Also consider the power stage design and operation and determine the requirements for the transistor's off-state. Show that freewheel diodes in anti-parallel with the transistors are necessary to avoid over voltages appearing on the transistors. Taking into account the requirements contained in the specification, the transistor type, arrangement, on-state voltages and currents may now be chosen.

## 6.3 Choice

Investigate  $h_{fe}$  for the values of  $V_{ceSAT}$  offered in the data sheet curves. Note the data book value of  $V_{ce}$  in your lab book.

Consider  $V_{ce}$  and  $V_{be}$  with varying base current for the chosen collector current. As the load is variable and a change in  $V_{ce}$  will affect the output voltage of the inverter, the transistor operation at a range of current levels should be determined. Record your findings.

## 6.4 Design

Consider the results obtained and decide if your initial choice of transistor is suitable regarding its on-state. You may want to repeat stage 7.3 for alternate choices.

Having chosen the transistor type and its operating conditions, the power dissipation in the device may be estimated (ignoring switching losses). Using the simple thermal model below, a heatsink may be chosen.

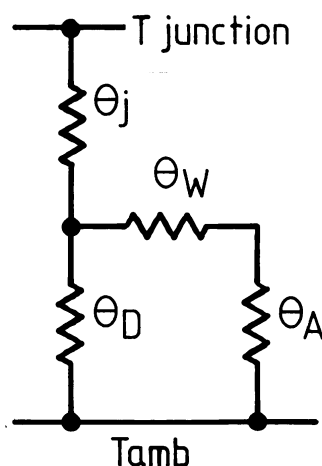


Fig. 6.1 Thermal equivalent circuit transistor to ambient

The transistors will have a specified maximum junction temperature. They also have a specified thermal impedance, in degrees C per Watt, from junction to case. Heatsinks have specified thermal impedances to ambient air. Knowing the loss power in the transistors, and assuming an ambient temperature of 45 °C, a heatsink impedance may be found and an appropriate heatsink chosen. If an insulating washer is used between the transistor and the heatsink, the situation is modelled as shown in Fig. 6.1.

## ***7 DRIVE STAGE***

### ***7.1 Introduction***

Using the chosen transistor characteristics, and an approximate design for the coupling circuit, an estimate may be made of the current required from the oscillator circuit. It will probably be necessary to add a drive stage to the oscillator circuit.

Various designs may be used, including proprietary ICs (recommended).

### ***7.2 Design principles***

The drive current required is set by the driver voltage and the series resistance, as well as the transistor's input impedance. Consider carefully how a transistor switches. (MOSFETs have capacitance, Bipolar Transistors have a low impedance).

The driver's input voltage rating is that of the supply rail, if no extra rail is provided.

If using a half bridge arrangement to supply the primary of a coupling transformer, it is necessary to design the split-rail capacitors. A value for the capacitors may be found by assuming the current required in the primary of the transformer (from the secondary current found above) and assuming a maximum drift of 5% in the split-rail voltage.

### ***7.3 Construction and test***

The driver stage may be added to the oscillator circuit board. Using a constant dc supply of 24V, conduct the following tests:

- Regulation: Measure the output voltage versus output current. Hence obtain the output impedance.
- Waveform: Photograph the waveform as before.

Comment on your results, and their correspondence with theory.

## 8 POWER OUTPUT TRANSFORMER DESIGN

### 8.1 Introduction

The basis of transformer operation is application of Faraday's law:

$$V = N \frac{d\phi}{dt}$$

where  $\phi$  is the flux linking the  $N$  turns. To aid understanding, also consider Ampere's law:

$$\oint H dl = NI$$

where  $H$  is the mmf,  $l$  the path length of the flux and  $I$  the current generating the mmf.

For a voltage transformer, the flux,  $\phi$ , hence mmf,  $H$  are determined by the voltage on the primary. By Faraday's law, a voltage also appears on the secondary in proportion to the ratio of turns between the secondary and primary. A load resistance connected to the secondary will allow secondary current  $I_2$  to flow, which will act to reduce the mmf by  $N_2 I_2$ , where  $N_2$  is the number of secondary turns.

However, the mmf is set by the voltage, so a primary current  $I_1$  must flow to restore the mmf. Thus  $N_1 I_1 = N_2 I_2$ , where  $N_1$  is the number of primary turns. The current that sets up the flux to begin with is known as the magnetizing current.

### 8.2 Design principles

For the square-wave inverter, the flux,  $\phi$ , merely ramps to a peak value and then reverses, ramping to a negative peak value. Hence,

$$V t = NAB_{pk}$$

where  $B_{pk}$  is the peak flux density and  $A$  is the core area. For a given period,  $t$ , voltage,  $V$ , and maximum flux density  $B_{sat}$ , an  $N.A$  product may be found.

To choose a bobbin size, an estimate must be made for the maximum current density,  $J$ , allowable in the winding. A value of  $2 \times 10^6$  A m<sup>-2</sup> is often quoted. The current density in the winding window will be reduced because of poor packing of round conductors, so a packing factor,  $k$ , is introduced. Hence,

$$\sum N_i I_i = WJk$$

Note: Taking the same current density for all the windings means that the losses are



evenly distributed.

Considering a transformer with a single primary and single secondary. From above:  $N_1 I_1 = N_2 I_2$ , thus neglecting the (small) magnetizing current,

$$2N_1 I_1 = W J k$$

The primary and secondary of a simple transformer will share the window area equally.

Knowing the current required from the primary,  $I_1$ , a ratio of window area,  $W$ , to number of primary turns,  $N_1$ , is found:

$$\frac{W}{N_1} = 2 \frac{I_1}{J k}$$

Now the number of turns may be eliminated, leaving an expression for  $WA$  :

$$WA = 2 \frac{V I t}{k J B_{pk}}$$

While the current density,  $J$ , is related to the copper losses, there are also magnetizing losses to be considered. These are primarily due to the area enclosed by the B-H curve for the magnetic material used (iron at this frequency). These losses are proportional to the mass of material and increase with  $B_{pk}$  (see the Project data book).

Standard bobbins for 50Hz use are designed to have approximately equal copper and magnetizing losses at full load, which leads to approximately maximum efficiency and good distribution of losses<sup>3</sup>. Thus the  $W : A$  ratio is fairly fixed and only a few bobbin shapes are available (see the Project data book).

Thus finding the  $WA$  product leads to a particular bobbin and iron laminations to fit and the design is completed by working back through the equations to find the number of turns of wire and its diameter. Note that wire also comes in a 'preferred' range of sizes (see the Project data book)

### ***8.3 Inverter transformer design***

In the push-pull inverter design (fig. 4.1d), the output transformer has one secondary and two primaries, with each primary carrying the current for half the time (a 50% duty cycle). Thus the design approach used above for a simple transformer must be modified appropriately.

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<sup>3</sup> Alternating Current Machines 5th Ed., M.G. Say, Longmans

The simplified equivalent circuit for the transformer (figure 8.1) may be obtained from ampere's law. The winding resistance may be found once the bobbin size, number of turns of wire and copper diameter have been calculated. Using this equivalent circuit, the full load regulation may be estimated.

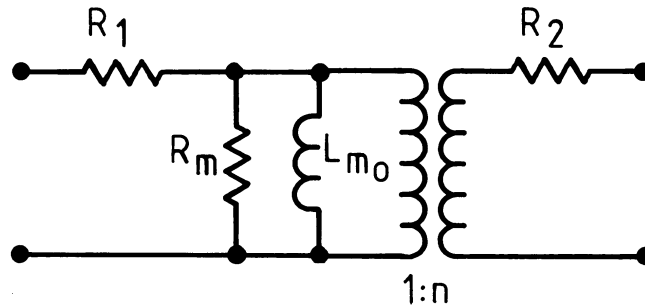


Figure. 8.1 Simplified Transformer Equivalent Circuit

Since the regulation is a constraint on the design of the inverter, it may be necessary to trade off some of the efficiency of the transformer. Using a higher  $B_{pk}$  value will increase the iron losses but allow for a larger wire size, thus achieving a lower winding resistance and therefore less regulation. In this way it is possible to iterate to a working design.

#### 8.4 Construction and test

*Before ordering parts, have your design checked by a demonstrator.*

Bobbins, cores, frames and wire are available to order.

Hand winding should be used. Great care should be exercised, when winding, to avoid damaging the fairly fragile insulation of the wire. Neatness is also important if a low packing factor is to be obtained. A nylon headed mallet may be useful to help pack thick wires. Thin transformer tape should be used between primary and secondary, to ensure adequate insulation. Finally, take care of the wire insulation, when assembling the cores and frame.

Until the whole inverter is assembled, only rudimentary tests may be conducted on the transformer. The winding resistances may be measured using a suitable meter. Low voltage open circuit tests and short circuit tests<sup>4</sup> may be conducted on a component tester bridge, to obtain all the values required for the equivalent circuit shown in figure 8.2.

When the transformer equivalent circuit parameters are known, a more precise estimate may be made of the transistor collector current required at full load.

<sup>4</sup>Elementary Electric Power and Machines, P.G. McLaren, Ellis-Horwood, 1984

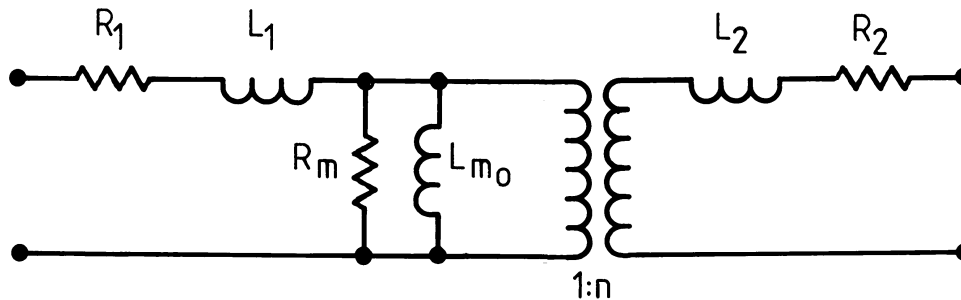


Figure 8.2 Standard Transformer Equivalent Circuit

## 9 INTERFACE CIRCUITS

### 9.1 Introduction

A coupling transformer may conveniently provide two or more isolated, complementary base drive currents. The primary of this transformer must interface with the oscillator. Use of a coupling transformer makes it possible to 'match' the oscillator output voltage to the input voltage requirement,  $V_{be}$  ( $V_{gs}$ ), of the power transistors. This would be very efficient, the only extra losses being those of the transformer, those in the transistor bases being inevitable. However, from the transistor design work conducted previously, it will be seen that the base-emitter voltage varies considerably with the collector current for 2N3055 transistors. Also, due to variations in manufacture and temperature, the value of  $V_{be}$  ( $V_{gs}$ ) required for a particular collector current may vary widely (review MOSFET data-sheets).

Thus with a simple matching transformer, bipolar transistors may be heavily oversaturated at low collector currents with a very large base current being drawn. Alternatively, they may not be sufficiently saturated at high collector currents. A base resistor becomes important to keep the base current is fairly constant with variations in  $V_{be}$ .

The MOSFET gate voltage is independent of the load, but should be sufficient to drive the MOSFETs on well. Driving them too quickly will cause inductive overvoltages. The switching is slowed down by using a gate resistor.

### 9.2 Design procedure

From the transistor test results, a base current (MOSFET: gate voltage) may be chosen that will saturate the transistor under all collector currents up to the expected maximum.

The base-emitter voltage, at this base current, for the expected maximum collector current, may be found from the  $V_{be}$ - $I_b$  graph of datasheet results. This point may be taken as the maximum operating condition, which the base drive must meet.

The performance of the base drive may be predicted by a graphical solve for the base resistor and the  $V_{be}-I_b$  characteristic, in the manner of a load-line. In this way the base resistor and coupling transformer secondary voltage may be chosen for good performance and high efficiency. The coupling transformer (if used) may then be designed using the same iterative approach as used for the power output transformer.

If using a drive IC with MOSFETs consider how the MOSFET gate voltage may be set.

### ***9.3 Construction and test***

The output of the oscillator may be linked to the drive and interface circuits and then to the the power transistors remembering the base resistors. The circuit may be powered-up and the operation checked.

- Output transistors: Base (Gate) Voltage and current magnitudes
- Output transistors: Base (Gate) Voltage rise and fall times.
- Synchronisation: Measure the Base (Gate) voltages at the power transistors on a single oscilloscope screen to check polarity and synchronisation.
- Waveform: Photograph the waveforms.

A further test may be conducted if the power transistors are mounted on their heatsinks and a chassis. Variable resistors may be connected to the collectors of the transistors and the base drives may be tested up to the maximum collector current required. Additional freewheel diodes will be necessary (where?).

## ***10 FINAL ASSEMBLY AND TEST***

### ***10.1 Introduction***

Before final assembly, the expected efficiency for the whole inverter should be calculated. An estimate of the output voltage regulation should also be made. The parts of the inverter are to be assembled into a steel chassis provided.

### ***10.2 Construction***

Care should be taken to ensure that the 240V AC output is completely isolated from the chassis. A 1A fuse should be connected in series with the 240V AC output, and a 10A fuse connected in series with the 24V DC input. A neon warning light should also be included in the high voltage output circuit. An on-off switch is also necessary.

### ***10.3 Performance tests***

For the following tests, consider the suitability of the test equipment, since the output is a square wave. Measure;

- Regulation: Output voltage versus output current.
- Efficiency versus output power.
- Temperatures versus output power.
- Output transistors; Currents ( $I_C, I_D$ ) and voltages ( $V_{CE}, V_{DS}$ ) versus output power.
- Output transistors; Transient voltages and currents on switching.
- Voltages and currents at 150W output, to be noted on the final circuit diagram.
- Output voltage and current waveforms, photograph or use plotter.

Compare the circuit currents, voltages, efficiency and regulation with those expected.

## **APPENDIX A: Report Writing**

*The following are guides to content as regarding the design provided. You should base your reports on these models, carefully considering the information needed.*

### **Report 1**

#### 1. Conceptual Design

Compare the alternative circuit configurations for the power stage stating clearly the basis for your choice. Discuss your choice of power transistor and driver stage. Comment on your choice of oscillator circuit.

Prepare a provisional circuit diagram of the square wave inverter, marking on it the approximate values of the key currents and voltages, assuming 'ideal' components, wherever necessary. Specify the component values as far as possible. List the major cost items.

#### 2. Oscillator Design and Test

Give a concise account of your oscillator design.

Report on the oscillator performance by preparing graphs of your test results. These may be presented as four graphs on one page, for easy reference.

Photocopy your report, as you will need to refer to it later on. Hand in the original.