

assignment 1

by Liesel Williams

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PSDE 6015

Electronic Design

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Assignment 1

Power Supply

Liesel Williams

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1. Introduction

The aims of the assignment are to demonstrate an understanding of advanced design methodologies and issues concerned with modern implementation technologies in electronic design.

This report aims to use theory and practical testing to analyse requirements and design advanced electronic systems i.e. a power supply unit (PSU), to perform an analogue function to meet customer needs, adapting designs to meet new applications.

In conjunction with the customer, a design specification considering electrical, physical and thermal requirements was agreed. Then, advanced design methods were adopted to specify each stage, which was then simulated and evaluated. The PSU is to supply a fixed output of 15V capable of delivering 1A with a maximum of 1mV ripple.

This PSU will be part of a bench mounted instrumentation panel supporting a differential pressure transducer and a digital display. The mounting plate shown below carries the transducer, bourdon tube and regulator. The PSU can either be mounted on the DIN rail or laid flat on the base of the mounting plate, leaving the DIN rail free for the digital display.

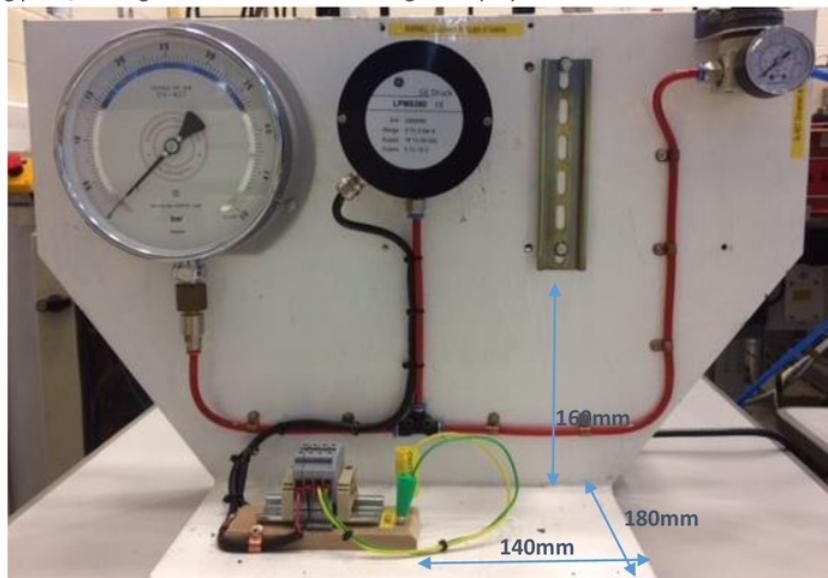


Figure 1 - Requirement for PSU

SPECIFICATION

The PSU as agreed with the customer had the following specification:

- Output Voltage 15V
- Output Current 1A
- Maximum ripple 1mV
- Dimensions 160x140x180mm
- Weight < 1.5kg

2. Research and Background Theory

2.1 General design

The design process will have an influence on any modelling and simulation activities i.e. when to build models/simulate, accuracy, disassembly of complex building blocks into smaller and simpler functional blocks etc.

Two tried and tested methods exist namely, top-down and bottom-up design, each has advantages and disadvantages.

Top-Down design involves breaking down a large, complex system into smaller sub-parts with the advantage that the overall performance and functionality that is required is the starting point for the overall design. Here simulation begins early in the development and helps with decision making in the design cycle. The weakness of this approach being that sub-parts and individual components decided upon during the decomposition process may be difficult/impossible to find.

Bottom-Up design involves combining individual parts into a larger system. This means each part has known parameters and behaviour. On the down side when all the individual known parts are combined the system performance may not be exactly as required.

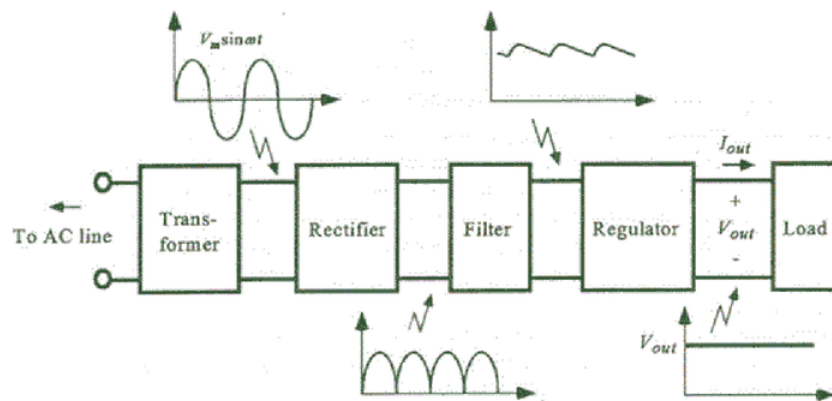


Figure 2 - System block diagram

The system block diagram above shows each sub-part of the design and so a combination of both design approaches best suits this application. Start with a top-down design, which is confirmed by bottom-up verification at each major decomposition stage i.e. build in a feedback loop comprising a decompose – design – verify – adjust cycle which comes from the general system functionality to specify the hardware at each point. (Leventhal and Green, 2006)

The system design :-

1. Electrical characteristics of voltage, current, power, frequency
2. Physical characteristics of size, weight, portability, mounting requirements etc.
3. Environmental considerations of temperature, humidity, vibration, cooling etc.

Starting with the electrical outputs the regulator is the first sub-system for consideration, this then leads to electrical requirements from the filter, rectifier and transformer, which is the second stage of the design cycle and then design of the heat management system.

2.2 Voltage Regulators

A voltage regulator is an essential part of a power supply and acts as a power management device. There are various packages available which can deliver regulation to different specifications, some options for consideration are outlined in this section.

Basically the disadvantage of a linear DC regulator compared to a switching regulator is that they must dissipate power in the form of heat in order to regulate the output voltage.

In linear regulators efficiency is determined by two main factors i.e. the difference between the input and output voltages and the current. Circuit designs to limit the input voltage to 2-3 volts above the output voltage is a method employed to avoid heat damage. Another reason for heat leading to inefficiency in linear regulators is the amount of current being taken by the load.

Power dissipated as heat is waste and a simple calculation shows how much power is being used :-

$$\text{Power} = (V_{in} - V_{out}) * I$$

As an example consider the case where V_{in} is 9V, V_{out} is 5V and the total current drawn is 2A

$$\text{Power} = (9 - 5) * 2 = 8W$$

This is a considerable amount to be dissipated in a small component and this is why heat sinks are used.

LM7818CT – Linear Voltage Regulator

LM78xx series is a family of self-contained fixed linear voltage regulator integrated circuits. They are a 3 terminal, 1A positive voltage regulator. The two numbers after the 78 identify the fixed voltage output it delivers. They are commonly used as they are inexpensive and simple to use.

The LM7818CT shown below also has in-built thermal overload protection and short-circuit protection. They are considered indestructible due to current limiting, thermal shut down and safe operating area protection. With suitable heatsink employed it can deliver over 1A and by adding suitable external components the fixed output voltage and current can become adjustable.

LM7818CT - Linear Voltage Regulator, 7818, Fixed, 21V To 33V In, 18V And 1A Out, TO-220AB-3

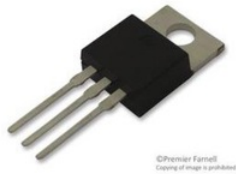


Figure 3 - LM7818CT

Manufactured by ON SEMICONDUCTOR/FAIRCHILD its features are:

- Input voltage range 21-33V
- Fixed output voltage 18V
- Output current 1A
- Linear regulator case TO-220AB
- Operating Temp range -40 to 125 degC

Block Diagram

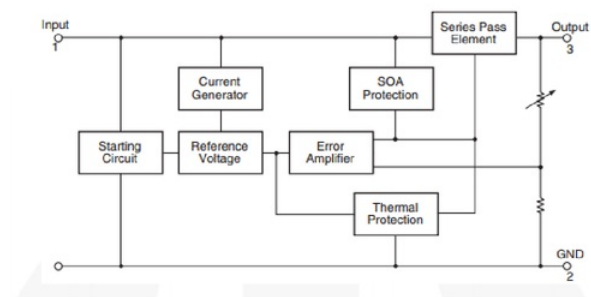


Figure 4 - Block diagram LM7818CT

Electrical Characteristics (LM7818)

Refer to the test circuit, $-40^{\circ}\text{C} < T_J < 125^{\circ}\text{C}$, $I_O = 500\text{ mA}$, $V_I = 27\text{ V}$, $C_I = 0.33\text{ }\mu\text{F}$, $C_O = 0.1\text{ }\mu\text{F}$, unless otherwise specified.

Symbol	Parameter	Conditions	Min.	Typ.	Max.	Unit
V_O	Output Voltage	$T_J = +25^{\circ}\text{C}$	17.3	18.0	18.7	V
		$I_O = 5\text{ mA to }1\text{ A}$, $P_O \leq 15\text{ W}$, $V_I = 21\text{ V to }33\text{ V}$	17.1	18.0	18.9	
Regline	Line Regulation ⁽¹⁶⁾	$T_J = +25^{\circ}\text{C}$	$V_I = 21\text{ V to }33\text{ V}$	15	360	mV
			$V_I = 24\text{ V to }30\text{ V}$	5	180	
Regload	Load Regulation ⁽¹⁶⁾	$T_J = +25^{\circ}\text{C}$	$I_O = 5\text{ mA to }1.5\text{ A}$	15	360	mV
			$I_O = 250\text{ mA to }750\text{ mA}$	5	180	
I_Q	Quiescent Current	$T_J = +25^{\circ}\text{C}$		5.2	8.0	mA
ΔI_Q	Quiescent Current Change	$I_O = 5\text{ mA to }1\text{ A}$			0.5	mA
		$V_I = 21\text{ V to }33\text{ V}$			1.0	
$\Delta V_O/\Delta T$	Output Voltage Drift ⁽¹⁷⁾	$I_O = 5\text{ mA}$		-1		mV/ $^{\circ}\text{C}$
V_N	Output Noise Voltage	$f = 10\text{ Hz to }100\text{ kHz}$, $T_A = +25^{\circ}\text{C}$		110		μV
RR	Ripple Rejection ⁽¹⁷⁾	$f = 120\text{ Hz}$, $V_I = 22\text{ V to }32\text{ V}$	53	69		dB
V_{DROP}	Dropout Voltage	$I_O = 1\text{ A}$, $T_J = +25^{\circ}\text{C}$		2		V
R_O	Output Resistance ⁽¹⁷⁾	$f = 1\text{ kHz}$		22		m Ω
I_{SC}	Short-Circuit Current	$V_I = 35\text{ V}$, $T_J = +25^{\circ}\text{C}$		250		mA
I_{PK}	Peak Current ⁽¹⁷⁾	$T_J = +25^{\circ}\text{C}$		2.2		A

Notes:

16. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.

17. These parameters, although guaranteed, are not 100% tested in production.

Figure 5 - LM7818 electrical characteristics

The input and output voltages have a neutral common ground pin 2. The bigger the difference between input and output voltages the more heat is generated and a heatsink must be employed to dissipate excess heat otherwise overheating can cause damage and malfunction. Also, the current limitations of this device mean it can only be used in small applications.

LM317 3/4 Pin 1.5A Adjustable Positive Voltage Regulator

This regulator can be used to deliver over 1.5A load current over 1.25 to 37V, the 337 is an alternative which has an adjustable negative voltage output down to -37V.

Two external resistors set the output voltage and it has typical load regulation of 0.1%. Included is current limiting, thermal overload and safe operating area protection.

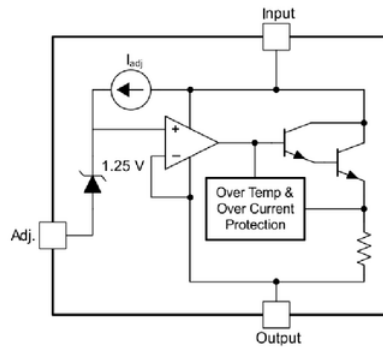


Figure 6 - LM317 configuration

Typical applications include battery charger circuit as shown below, also finds applications in Desktop PC, Digital camera, Mobile phone, refrigeration, signal generators etc.

LM317

SLVS044X–SEPTEMBER 1997–REVISED SEPTEMBER 2016

www.ti.com

6 Specifications

6.1 Absolute Maximum Ratings

over virtual junction temperature range (unless otherwise noted)⁽¹⁾

	MIN	MAX	UNIT
$V_I - V_O$ Input-to-output differential voltage		40	V
T_J Operating virtual junction temperature		150	°C
Lead temperature 1,6 mm (1/16 in) from case for 10 s		260	°C
T_{stg} Storage temperature	–65	150	°C

(1) Stresses beyond those listed under *Absolute Maximum Ratings* may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under *Recommended Operating Conditions* is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

6.2 ESD Ratings

	MAX	UNIT
V_{ESD} Electrostatic discharge	2500	V
	1000	

(1) JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process.

(2) JEDEC document JEP157 states that 250-V CDM allows safe manufacturing with a standard ESD control process.

6.3 Recommended Operating Conditions

	MIN	MAX	UNIT
V_O Output voltage	1.25	37	V
$V_I - V_O$ Input-to-output differential voltage	3	40	V
I_O Output current	0.01	1.5	A
T_J Operating virtual junction temperature	0	125	°C

6.4 Thermal Information

THERMAL METRIC ⁽¹⁾	LM317				UNIT
	DCY (SOT-223)	KCS (TO-220)	KCT (TO-220)	KTT (TO-263)	
	4 PINS	3 PINS	3 PINS	3 PINS	
$R_{\theta JA}$ Junction-to-ambient thermal resistance	66.8	23.5	37.9	38.0	°C/W
$R_{\theta JC(top)}$ Junction-to-case (top) thermal resistance	43.2	15.9	51.1	36.5	°C/W
$R_{\theta JB}$ Junction-to-board thermal resistance	16.9	7.9	23.2	18.9	°C/W
ψ_{JT} Junction-to-top characterization parameter	3.6	3.0	13.0	6.9	°C/W
ψ_{JB} Junction-to-board characterization parameter	16.8	7.8	22.8	17.9	°C/W
$R_{\theta JC(bottom)}$ Junction-to-case (bottom) thermal resistance	NA	0.1	4.2	1.1	°C/W

(1) For more information about traditional and new thermal metrics, see the *Semiconductor and IC Package Thermal Metrics* application report.

Figure 7 - LM317 electrical characteristics

This simple device has limited range and extendibility. Some IC versions have built in thermal cut off and surge protection. It does not allow for current increases using a by-pass transistor.

LM723C Voltage Regulator

This regulator is designed for series regulator applications in the main. Its load current is determined by the peripheral circuitry but by itself is limited to 150mA. The circuit has very low standby current drain and can be used for linear or foldback current limiting. Its useable temperature range is 0-70 °C

Features

- 150 mA output current without external pass transistor
- Output currents in excess of 10A possible by adding external transistors
- Input voltage 40V max
- Output voltage adjustable from 2V to 37V
- Can be used as either a linear or a switching regulator



Figure 8 - LM723C IC

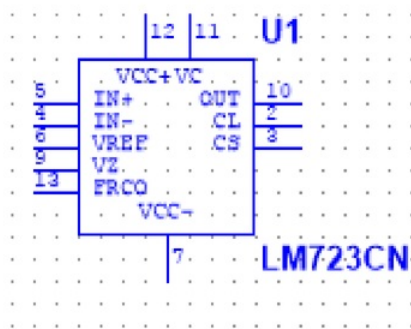
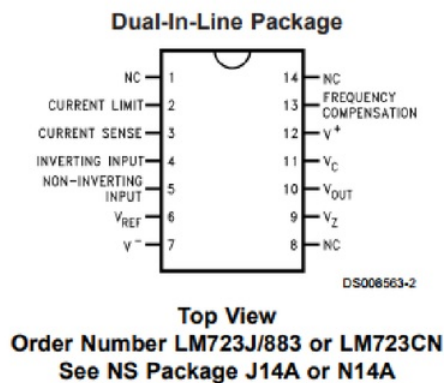


Figure 9 - LM723 pin out diagram



An extract of the data sheet is given below highlighting key information, the link to the datasheet is included in the reference section. This regulator suits the application well and technical design methods adopted are found in section 3.1.

Absolute Maximum Ratings (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/Distributors for availability and specifications.

(Note 10)

Pulse Voltage from V^+ to V^- (50 ms)	50V
Continuous Voltage from V^+ to V^-	40V
Input-Output Voltage Differential	40V
Maximum Amplifier Input Voltage (Either Input)	8.5V
Maximum Amplifier Input Voltage (Differential)	5V
Current from V_Z	25 mA
Current from V_{REF}	15 mA
Internal Power Dissipation Metal Can (Note 2)	800 mW

Cavity DIP (Note 2)	900 mW
Molded DIP (Note 2)	660 mW
Operating Temperature Range	
LM723	-55°C to +150°C
LM723C	0°C to +70°C
Storage Temperature Range	
Metal Can	-65°C to +150°C
Molded DIP	-55°C to +150°C
Lead Temperature (Soldering, 4 sec. max.)	
Hermetic Package	300°C
Plastic Package	260°C
ESD Tolerance	1200V
(Human body model, 1.5 kΩ in series with 100 pF)	

Electrical Characteristics (Note 3) (Note 10)

Parameter	Conditions	LM723			LM723C			Units
		Min	Typ	Max	Min	Typ	Max	
Line Regulation	$V_{IN} = 12V$ to $V_{IN} = 15V$		0.01	0.1		0.01	0.1	% V_{OUT}
	$-55^\circ C \leq T_A \leq +125^\circ C$			0.3				% V_{OUT}
	$0^\circ C \leq T_A \leq +70^\circ C$						0.3	% V_{OUT}
	$V_{IN} = 12V$ to $V_{IN} = 40V$		0.02	0.2		0.1	0.5	% V_{OUT}
Load Regulation	$I_L = 1$ mA to $I_L = 50$ mA		0.03	0.15		0.03	0.2	% V_{OUT}
	$-55^\circ C \leq T_A \leq +125^\circ C$			0.6				% V_{OUT}
	$0^\circ C \leq T_A \leq +70^\circ C$						0.6	% V_{OUT}
Ripple Rejection	$f = 50$ Hz to 10 kHz, $C_{REF} = 0$		74			74		dB
	$f = 50$ Hz to 10 kHz, $C_{REF} = 5$ μF		86			86		dB
Average Temperature Coefficient of Output Voltage (Note 8)	$-55^\circ C \leq T_A \leq +125^\circ C$		0.002	0.015				%/°C
	$0^\circ C \leq T_A \leq +70^\circ C$					0.003	0.015	%/°C
Short Circuit Current Limit	$R_{SC} = 10\Omega$, $V_{OUT} = 0$		65			65		mA
Reference Voltage		6.95	7.15	7.35	6.80	7.15	7.50	V
Output Noise Voltage	$BW = 100$ Hz to 10 kHz, $C_{REF} = 0$		86			86		μVrms
	$BW = 100$ Hz to 10 kHz, $C_{REF} = 5$ μF		2.5			2.5		μVrms
Long Term Stability			0.05			0.05		%/1000 hrs
Standby Current Drain	$I_L = 0$, $V_{IN} = 30V$		1.7	3.5		1.7	4.0	mA
Input Voltage Range		9.5		40	9.5		40	V
Output Voltage Range		2.0		37	2.0		37	V
Input-Output Voltage Differential		3.0		38	3.0		38	V
θ_{JA}	Molded DIP					105		°C/W
θ_{JA}	Cavity DIP		150					°C/W
θ_{JA}	H10C Board Mount in Still Air		165			165		°C/W
θ_{JA}	H10C Board Mount in 400 LF/Min Air Flow		66			66		°C/W
θ_{JC}			22			22		°C/W

Note 1: "Absolute Maximum Ratings" indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not guarantee specific performance limits.

Note 2: See derating curves for maximum power rating above 25°C.

Note 3: Unless otherwise specified, $T_A = 25^\circ C$, $V_{IN} = V^+ = V_C = 12V$, $V^- = 0$, $V_{OUT} = 5V$, $I_L = 1$ mA, $R_{SC} = 0$, $C_1 = 100$ pF, $C_{REF} = 0$ and divider impedance as seen by error amplifier ≤ 10 kΩ connected as shown in Figure 1. Line and load regulation specifications are given for the condition of constant chip temperature. Temperature drifts must be taken into account separately for high dissipation conditions.

Note 4: L_1 is 40 turns of No. 20 enameled copper wire wound on Ferroxcube P36/22-3B7 pot core or equivalent with 0.009 in. air gap.

Note 5: Figures in parentheses may be used if R1/R2 divider is placed on opposite input of error amp.

Note 6: Replace R1/R2 in figures with divider shown in Figure 13.

Note 7: V^+ and V_{CC} must be connected to a +3V or greater supply.

Note 8: For metal can applications where V_Z is required, an external 6.2V zener diode should be connected in series with V_{OUT} .

Figure 10 - LM723 electrical characteristics

MC1723C Voltage Regulator

The MC1723C is a positive or negative voltage regulator designed to deliver load current to 150 mA dc. Output current capability can be increased to several amperes through use of one or more external pass transistors. MC1723C is specified for operation over the commercial temperature range (0° to +70°C).

- Output Voltage Adjustable from 2.0 Vdc to 37 Vdc
- Output Current to 150 mA dc Without External Pass Transistors
- 0.01% Line and 0.03% Load Regulation
- Adjustable Short Circuit Protection

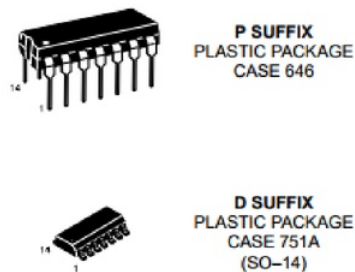


Figure 3. Typical NPN Current Boost Connection

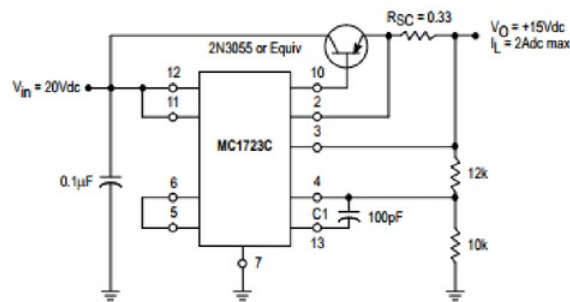


Figure 11 - MC1723C specifications

When selecting an IC regulator many factors are considered, the IC regulator acts as a driver to a boost transistor, thus the selection and design task are more complex and there are many overlapping choices.

The design process involves choosing a regulator, which exceeds requirements for line, and load regulation, consider output voltage and temperature of operation, then select a circuit, which meets output current, voltage and any particular features required. Circuit configuration can now be completed, and a decision considering cost, size, and complexity will limit the choices to an end. Using this criteria the LM723C regulator gave the most viable option.

2.3 Smoothing Capacitors

The DC output from transformer and rectifier contains a large unwanted AC component, which can be removed by a capacitor, which increases the average RMS output voltage and provides current when output voltage drops.

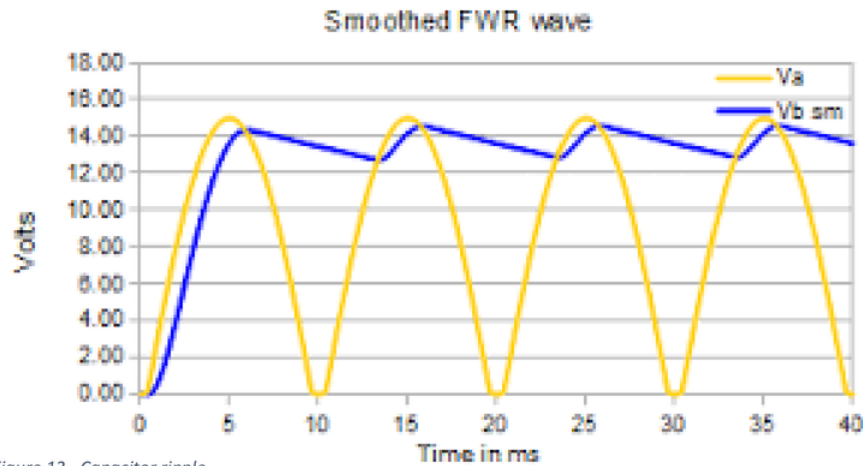


Figure 12 - Capacitor ripple

The effect can be seen by examining the voltage waveforms before and after smoothing, where even though the highest value has fallen a bit the lowest value is no longer 0V but approx. 12V taking the overall average up significantly.

The size of the ripple can be calculated by assuming a saw tooth shape i.e. $V_{rms} = V_{pp}/2\sqrt{3} = V_p/3.46$. The ripple amount depends on the load current, frequency and capacitance. Higher load currents will increase the size of the ripple. It also depends on the internal resistance of the transformer and rectifier where more resistance gives more smoothing but degrades load regulation. Ripple current needs consideration ($\geq 1A$ load) in that storage and release of charge results in AC current flow, which in turn causes heating thus, derate the component for higher ambient temperatures and higher reliability.

Basic design calculations follow a process of :-

A suitable transformer rated for continuous current required

A bridge rectifier capable of passing a peak current twice this rated current and a reverse voltage rating of more than $3 \cdot V_{rms}$

A suitable smoothing capacitor can now be chosen; there are in depth calculations shown in section 3.2, based on practical processes and graphical data in the form of Schade curves, although tolerances on filter capacitors are large and so accuracy is not critical. (Darren Ashby. Bonnie Baker. Ian Hickman. Walt Kester. Robert Pease. Tim Williams. Bob Zeidman., 2008)

2.3 Rectifiers and Transformers

The transformer alters the mains to a more suitable value of AC and the rectifier removes the negative half and provides only positive voltages. Due to diodes being cheap and readily available the bridge design is common.

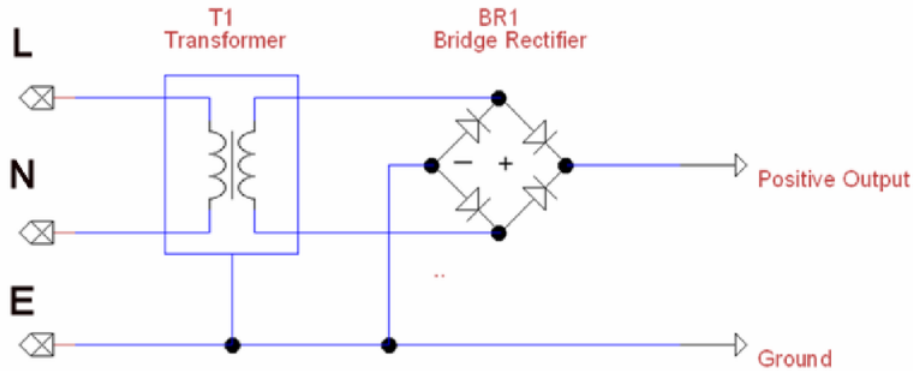


Figure 13 - Rectifier and Transformer

Rectifier: A silicon diode in forward bias has a 0.7V drop, generally between 2-3V is the accepted range for this configuration. Average diode current along with peak values need to be determined. PIV and surge current also figure in the design where $I_{\text{surge}} = I_s V_m / (R_s + \text{ESR})$ thus is dependent on filter capacitor ESR. See sections 3.2 and 3.3 for details.

Transformer: Losses occur in the windings of a transformer, which are dependent on loading, meaning off load voltages are higher. Secondary winding voltage, current and resistance calculations must be undertaken allowing for determination of the VA rating, which links with the demands for the output of the PSU. In depth design calculations are in section 3.4

3. Design method, choices and calculations

3.1 Regulator Design

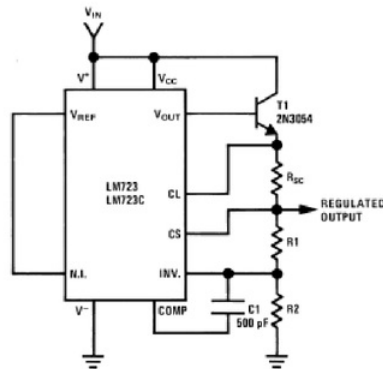
LM723C design

In order to satisfy the criteria for the PSU a circuit design was required and some simple parameters needed to be calculated.

From table 2 in data sheet calculations of the values of external components where undertaken.

Table 2. Formulae for Intermediate Output Voltages

Outputs from +2 to +7 volts (Figure 4 Figure 19 Figure 20 Figure 21 Figure 24 Figure 27)	Outputs from +4 to +250 volts (Figure 22)	Current Limiting
$V_{OUT} = \left(V_{REF} \times \frac{R_2}{R_1 + R_2} \right)$	$V_{OUT} = \left(\frac{V_{REF}}{2} \times \frac{R_2 - R_1}{R_1} \right); R_3 = R_4$	$I_{LIMIT} = \frac{V_{SENSE}}{R_{SC}}$
Outputs from +7 to +37 volts (Figure 17 Figure 19 Figure 20 Figure 21 Figure 24 Figure 27)	Outputs from -6 to -250 volts (Figure 18 Figure 23 Figure 25)	Foldback Current Limiting
$V_{OUT} = \left(V_{REF} \times \frac{R_1 + R_2}{R_2} \right)$	$V_{OUT} = \left(\frac{V_{REF}}{2} \times \frac{R_1 + R_2}{R_1} \right); R_3 = R_4$	$I_{KNEE} = \left(\frac{V_{OUT} R_3}{R_{SC} R_4} + \frac{V_{SENSE} (R_3 + R_4)}{R_{SC} R_4} \right)$ $I_{SHORT\ CKT} = \left(\frac{V_{SENSE}}{R_{SC}} \times \frac{R_3 + R_4}{R_4} \right)$



Typical Performance

Regulated Output Voltage	+15V
Line Regulation ($\Delta V_{IN} = 3V$)	1.5 mV
Load Regulation ($\Delta I_L = 1A$)	15 mV

Figure 19. Positive Voltage Regulator (External NPN Pass Transistor)

Figure 14 - Extract from LM723C datasheet

To obtain an output between +7 and +37 V use given equation and take values for R1 and R2 from table 1 page 8 of data sheet (see below). Vref is also taken from data sheet and can be found in the electrical characteristics on page 15 to be 7.15V for LM723C.

Table 1. Resistor Values (kΩ) for Standard Output Voltage

Positive Output Voltage	Applicable Figures	Fixed Output ±5%		Output Adjustable ±10% ⁽¹⁾			Negative Output Voltage	Applicable Figures	Fixed Output ±5%		5% Output Adjustable ±10%		
		See ⁽²⁾	R1	R2	R1	P1			R2	R1	R2	R1	P1
+3.0	Figure 4, Figure 19, Figure 21, Figure 24, Figure 27 (Figure 19)	4.12	3.01	1.8	0.5	1.2	+100	Figure 22	3.57	102	2.2	10	91
+3.6	Figure 4, Figure 19, Figure 21, Figure 24, Figure 27 (Figure 19)	3.57	3.65	1.5	0.5	1.5	+250	Figure 22	3.57	255	2.2	10	240
+5.0	Figure 4, Figure 19, Figure 21, Figure 24, Figure 27 (Figure 19)	2.15	4.99	0.75	0.5	2.2	-6 ⁽³⁾	Figure 18, (Figure 25)	3.57	2.43	1.2	0.5	0.75
+8.0	Figure 4, Figure 19, Figure 21, Figure 24, Figure 27 (Figure 19)	1.15	6.04	0.5	0.5	2.7	-9	Figure 18, Figure 25	3.48	5.36	1.2	0.5	2.0
+9.0	Figure 17, Figure 19, (Figure 18, Figure 21, Figure 24, Figure 27)	1.87	7.15	0.75	1.0	2.7	-12	Figure 18, Figure 25	3.57	8.45	1.2	0.5	3.3
+12	Figure 17, Figure 19, (Figure 19, Figure 21, Figure 24, Figure 27)	4.87	7.15	2.0	1.0	3.0	-15	Figure 18, Figure 25	3.65	11.5	1.2	0.5	4.3
+15	Figure 17, Figure 19, (Figure 18, Figure 21, Figure 24, Figure 27)	7.87	7.15	3.3	1.0	3.0	-28	Figure 18, Figure 25	3.57	24.3	1.2	0.5	10
+28	Figure 17, Figure 19, (Figure 19, Figure 21, Figure 24, Figure 27)	21.0	7.15	5.6	1.0	2.0	-45	Figure 23	3.57	41.2	2.2	10	33
+45	Figure 22	3.57	48.7	2.2	10	39	-100	Figure 23	3.57	97.6	2.2	10	91
+75	Figure 22	3.57	78.7	2.2	10	68	-250	Figure 23	3.57	249	2.2	10	240

(1) Replace R1/R2 in figures with divider shown in Figure 28.

(2) Figures in parentheses may be used if R1/R2 divider is placed on opposite input of error amp.

(3) V⁺ and V_{OC} must be connected to a +3V or greater supply.

Figure 15 - Electrical Characteristics LM723C

$$V_{out} = (V_{ref} * (R1+R2)/R2) = (7.15 * (7.87+7.15)/7.15) = 15.02V$$

R_{sc} is a resistor between the current limit and current sense terminals. R_{sc} needs to reach 0.6V at 1A so that internal transistors will switch down V_{out}.

$$R_{sc} = 0.6/I_{sc} = 0.6/1 = 0.6 \text{ ohm}, 1W$$

Current Limiting (P4 datasheet R_{sc} = 10 ohm) and current limit is 65 milliamps, V_{sense}/R_{sc} = 0.66/10 = 66 this can be seen in graph on page 22 where the load regulation is tested.

This value is only an indicator and the value of 0.6ohm was chosen as this brings the knee of the load graph back to approx. 100 ohm and limits the current to 1A short circuit which is a close to the customer specification of rated current and a better option for the output.

Finding a minimum value for V_{in} – looking at the Electrical Characteristics on the datasheet page 4 it can be seen that :-

ELECTRICAL CHARACTERISTICS⁽¹⁾⁽²⁾⁽³⁾⁽⁴⁾ (continued)

Parameter	Conditions	LM723			LM723C			Units
		Min	Typ	Max	Min	Typ	Max	
Average Temperature Coefficient of Output Voltage ⁽⁵⁾	$-55^{\circ}\text{C} \leq T_A \leq +125^{\circ}\text{C}$		0.002	0.015				%/°C
	$0^{\circ}\text{C} \leq T_A \leq +70^{\circ}\text{C}$					0.003	0.015	%/°C
Short Circuit Current Limit	$R_{SC} = 10\Omega, V_{OUT} = 0$		65			65		mA
Reference Voltage		6.95	7.15	7.35	6.80	7.15	7.50	V
Output Noise Voltage	$BW = 100 \text{ Hz to } 10 \text{ kHz}, C_{REF} = 0$		86			86		μVrms
	$BW = 100 \text{ Hz to } 10 \text{ kHz}, C_{REF} = 5 \mu\text{F}$		2.5			2.5		μVrms
Long Term Stability			0.05			0.05		%/1000 hrs
Standby Current Drain	$I_L = 0, V_{IN} = 30\text{V}$		1.7	3.5		1.7	4.0	mA
Input Voltage Range		9.5		40	9.5		40	V
Output Voltage Range		2.0		37	2.0		37	V
Input-Output Voltage Differential		3.0		38	3.0		38	V
θ_{JA}	PDIP					105		°C/W
θ_{JA}	CDIP		150					°C/W
θ_{JA}	H10C Board Mount in Still Air		165			165		°C/W
θ_{JA}	H10C Board Mount in 400 LF/Min Air Flow		66			66		°C/W
θ_{JC}			22			22		°C/W

(5) For metal can applications where V_Z is required, an external 6.2V zener diode should be connected in series with V_{OUT} .

Figure 16 - Electrical characteristics continued LM723C

$$9.5\text{V} \leq V_{in} \leq 40\text{V} \quad \text{and} \quad (V_{in} - V_{out}) \geq 3\text{V}$$

From these values for V_{in} - V_{out} defined on the datasheet and consideration of the base-emitter junction drops of T1 and R_{sc} these must be added to the circuit and also to the minimum value of V_{in} - V_{out} and so the equation becomes:

$$(V_{in} - V_{out}) = [V_{in} - (V_{out} + 2\phi)] \geq 3\text{V} \quad \text{so } V_{in} \geq V_{out} + 2\phi + 3 = 15 + 1.2 + 3 = 19.2\text{V}$$

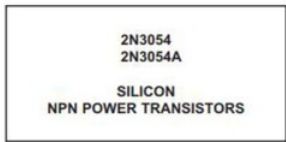
$$\text{Where } \phi = V_{BE \text{ ON}} (0.6\text{V})$$

Thus satisfying the minimum V_{in} of 9.5V.

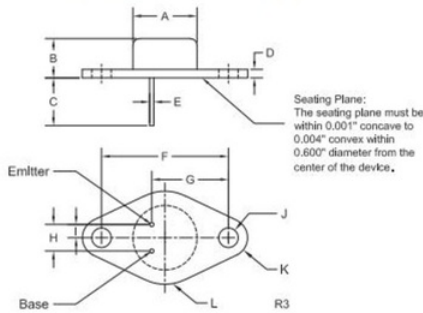
Selection of the series pass element Q1 must have the following characteristics

2N3054A	Required	Component Spec
$V_{CE0} \geq V_{min}$	24V	55V
$I_{C(MAX)} \geq I_{SC}$	1A	4A
$h_{fe} \geq \frac{I_{SC}}{I_O} @ V_{CE} = V_{in} - V_o - \phi$	Not applicable - Regulator adjusts I in order to maintain constant V	25 @ $V_{ce}=4\text{V}, I_c = 500\text{mA}$
$P_D \text{ max} \geq V_{in} * I_{SC}$	15W	75W
θ_{JC}	determined from heat management calculations	2.33
Safe Operating Area (SOA) so that it allows for $V_{CE} = V_{in} @ I_c = I_{sc}$	$V_{ce} = 20\text{V} @ I_c = 16\text{mA}$ (measured)	$V_{ce}=4\text{V}, I_c = 500\text{mA}$

The bypass transistor 2N3054A - package type TO-66, device is a silicon NPN transistor mounted in a hermetically sealed metal case, designed for general purpose amplification and switching. It has a power dissipation of 75W, storage junction temperature of -65 to +200 °C and a thermal resistance of 2.33 °C/W. An extract from the data sheet showing package dimensions is given here (also URL in references) and the thermal equation and heatsink design are found in section 3.5.



TO-66 CASE - MECHANICAL OUTLINE



MARKING:
FULL PART NUMBER

SYMBOL	INCHES		MILLIMETERS	
	MIN	MAX	MIN	MAX
A (DIA)	0.470	0.500	11.94	12.70
B	0.250	0.340	6.35	8.64
C	0.360	-	9.14	-
D	0.050	0.075	1.27	1.91
E (DIA)	0.028	0.034	0.71	0.86
F	0.956	0.964	24.28	24.48
G	0.570	0.590	14.48	14.99
H	0.190	0.210	4.83	5.33
I	0.093	0.107	2.36	2.72
J (DIA)	0.142	0.152	3.61	3.86
K (RAD)		0.141		3.58
L (RAD)		0.345		8.76

TO-66 (REV-R3)

Figure 17 - 2N3054A package type

3.2 Capacitor Design

Design by a practical procedure based on graphical data in the form of Schade curves remains the best option and the following curves give the required information for full-wave rectifier circuits. Bear in mind that the rectifier forward drop is significant for low voltage supplies e.g. 1V on a 12V supply and the dynamic resistance, which compared with the transformer secondary resistance and reflected primary resistance is negligible.

Definitions are as follows:

$V_{C(DC)}$ = the required full load average dc output voltage of the capacitor input filter

$V_{Ripple(pp)}$ = the maximum no load pp ripple voltage

V_M = the maximum no load output voltage

I_0 = the full load filter output current

f = the input ac line frequency

R_s = total series resistance

Referring to the regulator and for a simpler design $V_{in} + \frac{1}{2} \text{Ripple} + 10\% = V_c$ and so is taken as 24V average with 5Vpp ripple at full load. This assures that it is always above the required regulator minimum of 19.2V i.e. it has another 2.5V (half the ripple) added plus a 10% headroom margin, making $19.2 + 2.5 + 10\% = 23.87V$ i.e. 24V

Output ripple can now be determined and from page 3 of the regulator datasheet, ripple rejection ratio is given as -74dB and so with an input ripple of 5Vpp the output ripple requirement of 1mVpp is met.

For voltage ratios the gain in dB is given by $(dB) = 20 \log V_{out}/V_{in}$

i.e. $\text{Ripple In} = \text{Ripple Out} / (10^{-74/20}) = 0.001 / (0.199 \times 10^{-3}) = 5.012V$

As a rule of thumb V_M is taken as $V_c + 50\% = 24 + 12 = 36V$

From the spec $I_0 = 1A$ and $f = 50Hz$

Now from fig 8.5 the ripple factor (%) can be determined $r_f = \frac{V_{ripple(pp)}}{2\sqrt{2} V_{C(dc)}} \times 100\%$

So $r_f = 5 / (2 \times 1.414 \times 24) \times 100 = 7.27\%$

Figure 8-5. Root-Mean-Square Ripple Voltage for Capacitor-Input Circuits

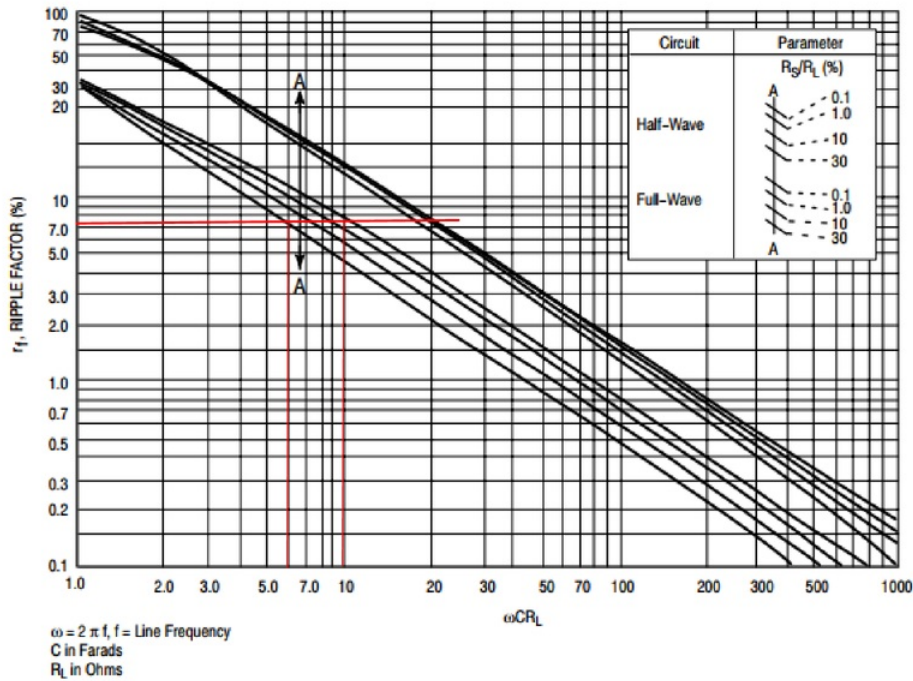


Figure 18 - RMS ripple voltage for Capacitor input

Looking at the graph above this value for ripple factor, r_f gives a range for ωCR_L of 6 to 10, therefore, a value of 8 was chosen.

This value can be used in conjunction with fig 8.3 to find the percentage value for the ratio of R_S/R_L using $V_{C(DC)}$ see below, where $V_C/V_M = 24/36 * 100 = 66\%$

Figure 8–3. Relation of Applied Alternating Peak Voltage to Direct Output Voltage in Full-Wave Capacitor-Input Circuits

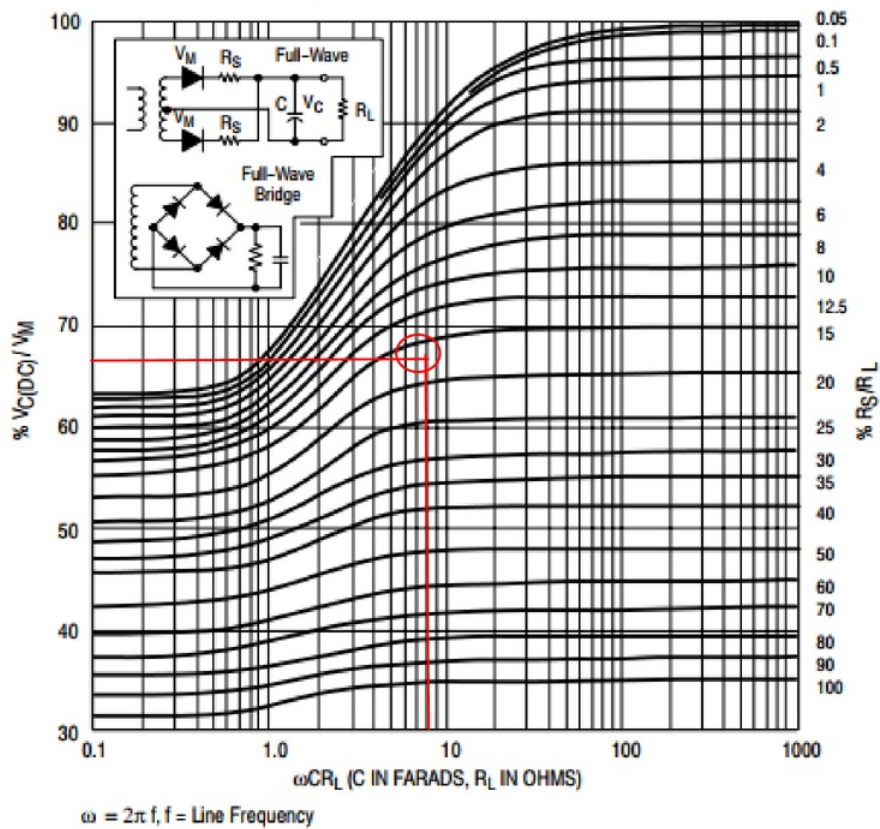


Figure 19 - AC Peak Voltage vs DC output

The nearest curve to the cross-over is 15% (R_S/R_L) and so by calculation a value for R_S is found from $0.15 \cdot R_L$ or $0.15 \cdot (V_{C(DC)}/I_0) = 0.15 \cdot (24/1) = 3.6\Omega = R_S$

This value R_S is used later for surge current, $I_{surge} = V_m/(R_S + ESR)$ it is the way the bridge diodes are modelled as a switch source and resistor, this is considered further in the conclusion.

By determination $C = \omega CR_L / 2\pi f (V_{C(DC)}/I_0)$ where $(V_{C(DC)}/I_0) = R_L$

And so $C = 8/(2\pi \cdot 50 \cdot 24) = 1061\mu F$

Using this information a suitable electrolytic can be chosen, considering things like, cost, size, etc.

The most important aspects of the specification are:

- Working voltage (must not be exceeded for periods of time to avoid failure)
- Working temperature (best to choose 105° rated as opposed to 85° rated thus increasing life in service)

- Capacitance (value deduced from design method)
- Tolerance (given as a percentage value and will impact cost)
- Polarity (electrolytic capacitors)
- ESR (this can affect performance and ideally should be zero, an increased value can increase the operating temp significantly)
- Ripple (deduced from design method)
- Leakage (can occur through dielectric)
- Size (larger ones are easier to cool and have bigger dielectric volume)

Rapid electronics do a Würth ATUL 1200uF 20% 50VDC 7.5mm Radial Alum. Electrolytic Capacitor, which fits the design specification.

Würth ATUL 1200µF 20% 50VDC 7.5mm Radial Alum. Electrolytic Capacitor 16x31.5



Image Representative of range.

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Product Details	Technical Details	Data Sheets	Questions (0)	Reviews (0)
A 1200µF 50V DC 20% radial aluminium electrolytic capacitor from the Würth ATUL range. Pitch is 7.5mm and case size is ø 16 x 31.5mm. • Recommended soldering: Wave • Operating temperature +105°C • Minimised ESR and long life • Load life: 4000 - 10,000 h @ +105°C				

Figure 20 - Capacitor selection

The data sheet can be found in the references, an extract is placed here.

D1 Electrical Properties:

Properties	Test conditions		Value	Unit	Tol.
Capacitance	0.25V; 120Hz	C	1200	µF	± 20%
Rated voltage		U _R	50	V (DC)	max.
Leakage current	after 2 min.	I _{Leak}	600	µA	max.
Dissipation factor	120 Hz	DF	10	%	typ.
Ripple current	100kHz @105°C	I _{ripple}	2870	mA	max.
Impedance	100kHz @20°C	Z	0.03	Ω	max.
Impedance	100kHz @-10°C	Z	0.066	Ω	max.

Figure 21 - Capacitor electrical properties

This capacitor has negligible ESR.

3.3 Rectifier Design

The rectifier ratings must now be specified and these are determined as follows:

Average current per diode $I_{F(av)} = I_o/2$ for full-wave rectification

$$\text{So } I_{F(av)} = 1/2 = 0.5A$$

RMS and Peak repetitive rectifier ratings can be determined from the following graph

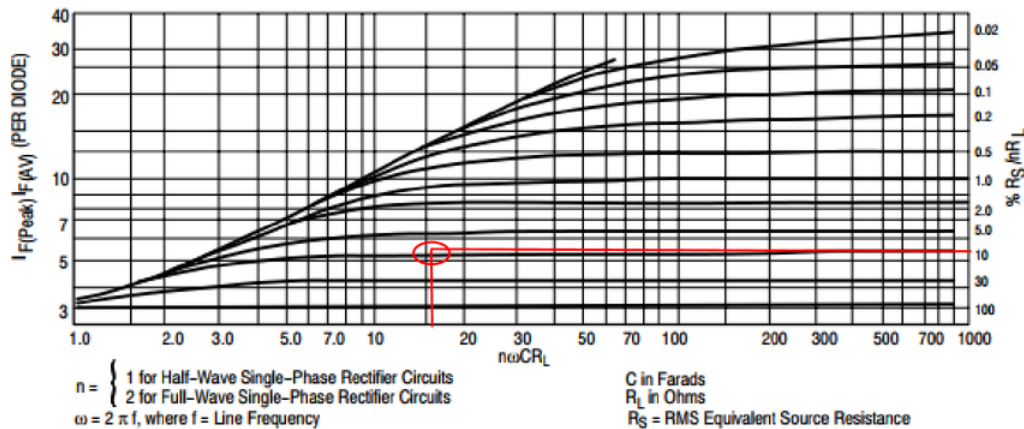


Figure 22 - RMS and Peak-to-Av Diode Current

The peak current can be found using the above graph.

This is determined by first finding $R_S/2R_L$ and since this value was previously determined to be 15% then half of this gives 7.5%

The x-axis value $n\omega CR_L$ is simply $\omega CR_L * 2$ (as $n=2$) i.e. $2*8 = 16$

By placing these values on the above graph it can be seen that $I_{F(peak)} = 5.2 * I_{F(av)} = 5.2 * 0.5 = 2.6A$

Next determine the Peak Inverse Voltage (PIV) which for full wave rectification is equal to V_m i.e. 36V add to this a 50% safety margin to cover line transients i.e. $36+18 = 54V$

Check data sheet for compliance with this $I_{F(peak)}$ value and the PIV making sure neither are exceeded when the bridge rectifier type is chosen.

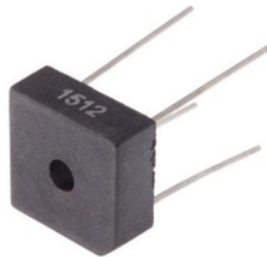
It is also noted that for a short period after switch on there is an increased value of current drawn during the time capacitors charge up, called a surge current, this must also be taken into account.

$$\text{Maximum surge current } I_{\text{surge}} = V_m / (R_S + \text{ESR}) = 54 / (3.6 + 0) = 15A$$

Having the specifications for the rectifier a suitable component can be chosen by using the search facility on RS.

Vishay VS-KBPC1005, Bridge Rectifier, 3A 50V, 4-Pin
D 72

RS Stock No: **817-2891**
Brand: Vishay
Mfr Part No: **VS-KBPC1005**



115 in stock for FREE next working day delivery

£1.862
Price Each (in a Pack of 5)

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5 - 45	£1.862	£9.31
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Quantity: Units Add to basket

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*Price indicative

Packaging Options: [?](#)

☒ Standard Pack
 ☐ Production Pack

Technical Reference

- RoHS Certificate of Compliance
- KBPC1, KBPC6 Series, Single Phase Rectifier Bridge, 3A, 50V
- Statement of conformity
- Schematic Symbol & PCB Footprint

Figure 23 - Bridge Rectifier Selection

The main specification considerations are 3A peak average forward current, 50V peak reverse repetitive voltage, a high surge current at 55A peak non-repetitive forward surge current. The data sheet can be found in the references.

3.4 Transformer Design

Transformer specifications include:

V_s = secondary RMS voltage, given by $V_s = \{V_m + (n) 1.0\} / \sqrt{2}$ and $n = 2$ for full-wave bridge
i.e. $V_s = \{36+2\} / 1.414 = 27V$

R_s = total resistance of secondary and any external resistors equal to R_s found previously from the capacitor design to be 3.6Ω .

I_s = secondary RMS current given for a full-wave bridge as $I_s = \sqrt{2} I_{rms} = 1.414 * 1 = 1.414A$

Where I_{rms} is the rectifier current 1A found earlier

Transformer VA rating = $V_s I_{rms} (\sqrt{2}) = 27 * 1 * 1.414 = 37.8 = 38VA$

The above design process does not consider line voltage variations or component tolerances. In fact, these are worth taking into account when designing the input supply and typically, they are line voltage +10 to -15% and filter capacitors +75 to -10%.

Specifications for this transformer narrowed down the choice to a 30V, 1.66A, 50VA toroidal transformer.

RKT 5015 :: Toroidal transformer, 50 VA, 2 x 15 V, 2 x 1.66 A



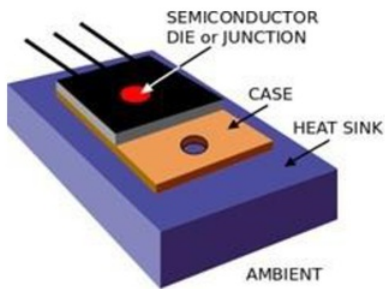
Figure 24 - Transformer selection

Data sheet is contained in reference list.

Most readily available PCB mounted types are limited to a turns ratio of 10:1 giving 24V on the secondary winding. To avoid manufacturing a bespoke one, this toroidal type from Farnell has a 30V secondary voltage (when secondaries are series connected) and sufficient current output, in fact its VA exceeds that calculated. But for the correct output voltage this type suits the requirements well and its size and weight (0.65kg) fit with the mounting requirements of the rig.

3.5 Heat Management Design

When considering the safe operation of a semi-conductor device it is essential that its junction temperature is kept below the maximum specified value taken from the data sheet.



It is clear from fig 25 what the subscripts in the equation refer to i.e.

J for junction

C for case

S for sink

A for ambient

Figure 25 - Thermal boundaries

The operating junction temperature is found from the thermal equation:

$$T_J = T_A + P_D \Theta_{JA}$$

Where: T_J = junction temperature ($^{\circ}\text{C}$)

T_A = ambient air temperature ($^{\circ}\text{C}$)

P_D = power dissipated by device (W)

Θ_{JA} = thermal resistance from junction-to-ambient air ($^{\circ}\text{C}/\text{W}$)

And this value is a sum of the thermal resistances as given below:

$$\Theta_{JA} = \Theta_{JC} + \Theta_{CS} + \Theta_{SA}$$

Where: Θ_{JC} = junction to case thermal resistance ($^{\circ}\text{C}/\text{W}$) this depends on device package type

Θ_{CS} = case to heatsink thermal resistance ($^{\circ}\text{C}/\text{W}$) this depends on type of interface used

Θ_{SA} = heatsink to ambient thermal resistance ($^{\circ}\text{C}/\text{W}$) this is a property of the heatsink

This only applies where an external heatsink is employed. Otherwise $\Theta_{JA} = \Theta_{JC} = 2.33$ as given on datasheet (fig 26).

2N3054
2N3054A

**SILICON
NPN POWER TRANSISTORS**



TO-66 CASE

Central
Semiconductor Corp.

www.centralsemi.com

DESCRIPTION:

The CENTRAL SEMICONDUCTOR 2N3054, 2N3054A devices are silicon NPN power transistors manufactured by the epitaxial base process, mounted in a hermetically sealed metal case, designed for general purpose amplifier and switching applications.

MARKING: FULL PART NUMBER

MAXIMUM RATINGS: ($T_C=25^\circ\text{C}$)

Collector-Base Voltage	
Collector-Emitter Voltage	
Collector-Emitter Voltage	
Collector-Emitter Voltage	
Emitter-Base Voltage	
Continuous Collector Current	
Continuous Base Current	
Power Dissipation (2N3054)	
Power Dissipation (2N3054A)	
Operating and Storage Junction Temperature	
Thermal Resistance (2N3054)	
Thermal Resistance (2N3054A)	

SYMBOL		UNITS
V_{CBO}	90	V
V_{CEV}	90	V
V_{CER}	60	V
V_{CEO}	55	V
V_{EBO}	7.0	V
I_C	4.0	A
I_B	2.0	A
P_D	25	W
P_D	75	W
T_J, T_{stg}	-65 to +200	$^\circ\text{C}$
θ_{JC}	7.0	$^\circ\text{C/W}$
θ_{JC}	2.33	$^\circ\text{C/W}$

ELECTRICAL CHARACTERISTICS: ($T_C=25^\circ\text{C}$ unless otherwise noted)

SYMBOL	TEST CONDITIONS	MIN	MAX	UNITS
I_{CEV}	$V_{CE}=90\text{V}, V_{EB}=1.5\text{V}$		1.0	mA
I_{CEV}	$V_{CE}=90\text{V}, V_{EB}=1.5\text{V}, T_C=150^\circ\text{C}$		6.0	mA
I_{CEO}	$V_{CE}=30\text{V}$		500	μA
I_{EBO}	$V_{EB}=7.0\text{V}$		1.0	mA
BV_{CEO}	$I_C=100\text{mA}$	55		V
BV_{CER}	$I_C=100\text{mA}, R_{BE}=100\Omega$	60		V
$V_{CE(SAT)}$	$I_C=500\text{mA}, I_B=50\text{mA}$		1.0	V
$V_{CE(SAT)}$	$I_C=3.0\text{A}, I_B=1.0\text{A}$		6.0	V
$V_{BE(ON)}$	$V_{CE}=4.0\text{V}, I_C=500\text{mA}$		1.7	V
h_{FE}	$V_{CE}=4.0\text{V}, I_C=500\text{mA}$	25	150	
h_{FE}	$V_{CE}=4.0\text{V}, I_C=3.0\text{A}$	5.0		
h_{fe}	$V_{CE}=4.0\text{V}, I_C=100\text{mA}, f=1.0\text{kHz}$	25	180	
f_T	$V_{CE}=10\text{V}, I_C=200\text{mA}, f=1.0\text{MHz}$	3.0		MHz
f_{hfe}	$V_{CE}=4.0\text{V}, I_C=100\text{mA}$	30		kHz

36V

Figure 26 - 2N3054A data sheet extract

First, determine whether a heatsink is required by finding the maximum allowable T_A for an unheatsinked 2N3054. T_J is taken as 115°C (data sheet range -65 to $+200$ but due to thermal sensitivity it is better to choose a lower value) the max continuous power dissipation is found from the power law i.e. $P_D = IV = 1 \times 15 = 15\text{W}$ these output voltage and current values are average and not peak values.

$$T_J = T_A + P_D \theta_{JA} \text{ re-arrange}$$

$$T_A = T_J - P_D \theta_{JA} = 115 - 15(2.33) = +80.05^\circ\text{C} \text{ this is maximum tolerable without heatsink}$$

Typical insulator thermal resistance (θ_{CS})

CASE	METAL-TO-METAL		USING AN INSULATOR	
	dry	H/S compound	H/S compound	Type
TO-3	0.2°C/W	0.1°C/W	0.36°C/W	3 mil mica
TO-3	0.2°C/W	0.1°C/W	0.28°C/W	Anodized Aluminum
TO-66	1.5°C/W	0.5°C/W	0.9°C/W	2 mil mica
TO-220	1.2°C/W	1.0°C/W	1.6°C/W	2 mil mica

Figure 27 - Junction thermal characteristics

For the package type examination of the above table gives θ_{CS} By substituting for θ_{JA} into the thermal equation and re-arranging gives an equation for θ_{SA}

$$T_J = T_A + P_D (\theta_{JC} + \theta_{CS} + \theta_{SA})$$

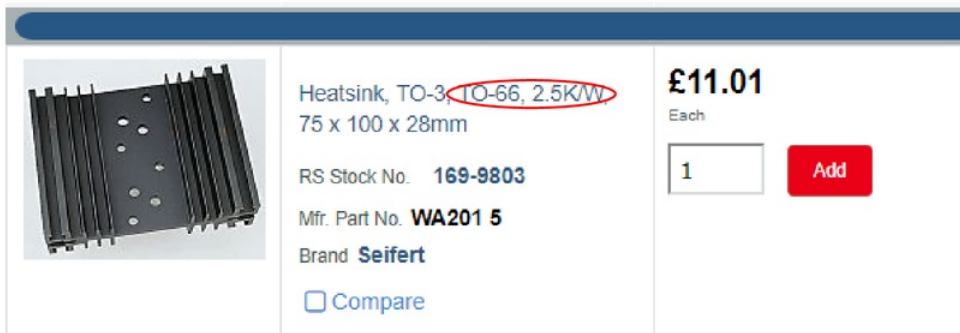
$$\frac{T_J - T_A}{P_D} = \theta_{JC} + \theta_{CS} + \theta_{SA}$$

$$\theta_{SA} = \frac{T_J - T_A}{P_D} - \theta_{CS} - \theta_{JC} = (115 - 20) / 15 - 1.5 - 2.33 = 2.5^\circ\text{C/W}$$

The average ambient temperature in the location of the instrument is 20° and for metal to metal junction θ_{CS} is given as 1.5°C/W for this package type.

The heatsink for this package can now be determined with a thermal resistance of 2.5°C/W

For the package type specified the correct heatsink was found using the search facility on RS, the data sheet is referenced and an image from RS is shown below.



Heatsink, TO-3, TO-66, 2.5K/W
75 x 100 x 28mm

RS Stock No. 169-9803
Mfr. Part No. WA201 5
Brand Seifert

£11.01
Each

1 Add

Compare

Figure 28 - Heatsink selected

4. Practical Testing and Improvement

This section documents the tests of the design on multisim at each stage, working backwards starting at the regulator, with data gathered compared with that expected from theory.

4.1 Regulator

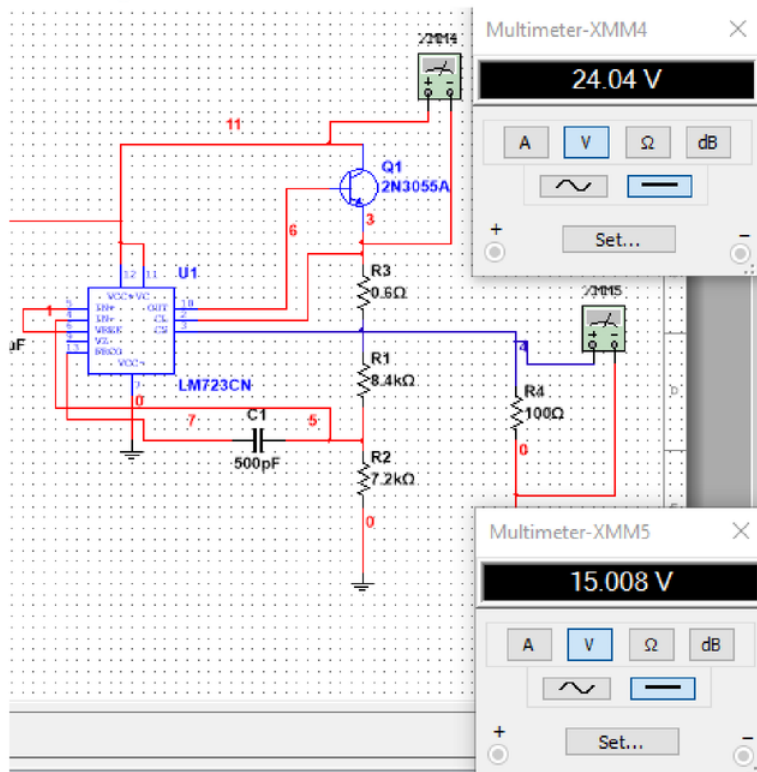


Figure 29 - Regulator testing

Line Regulation – DC sweep

First graph shows Vin varying between 15 to 20 volts, above 19.2 volts a steady output of 15 V is achieved

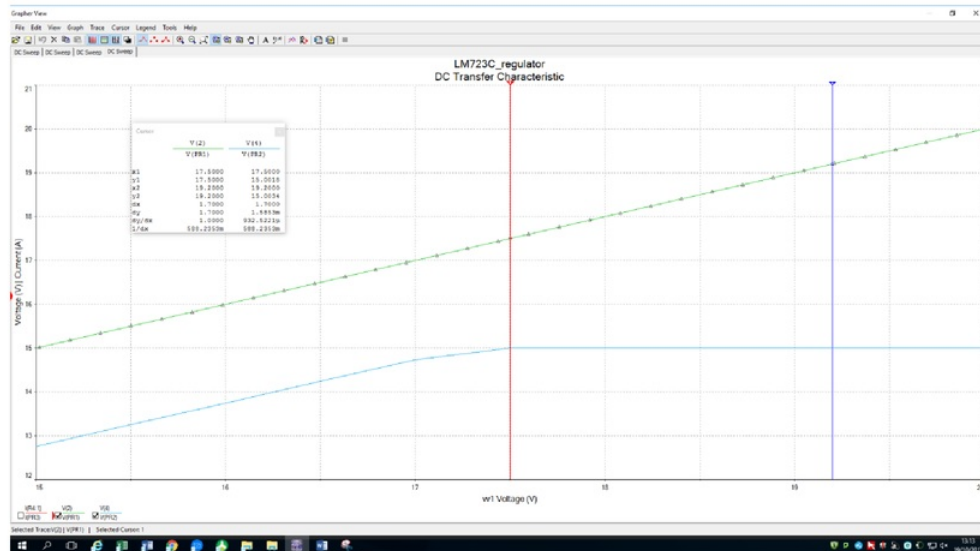


Figure 30 - Line regulation 15-20V

	V (2)	V (4)
	V (PR1)	V (PR2)
x1	17.5000	17.5000
y1	17.5000	15.0018
x2	19.2000	19.2000
y2	19.2000	15.0034
dx	1.7000	1.7000
dy	1.7000	1.5853m
dy/dx	1.0000	932.5221μ
1/dx	588.2353m	588.2353m

Figure 31 - Line regulation 15-20V results

The output on PR2 shows that when the input PR1 is above approx. 17.5 V then the desirable flat response of 15V is accomplished, below this threshold the output is less than the required value. The 19.2V value arrived at in the design is the minimum input voltage to the regulator deduced in the calculations in section 3 and accounts for device limits and input-output differential from the data sheet, at this value the output on PR2 is 15.0034V.

Second graph shows a higher range up to 1500V, the output does not start to significantly increase until approx. 1300V and can be seen to be 19.57V at 1400V input this demonstrates the regulator will perform at high values of input.

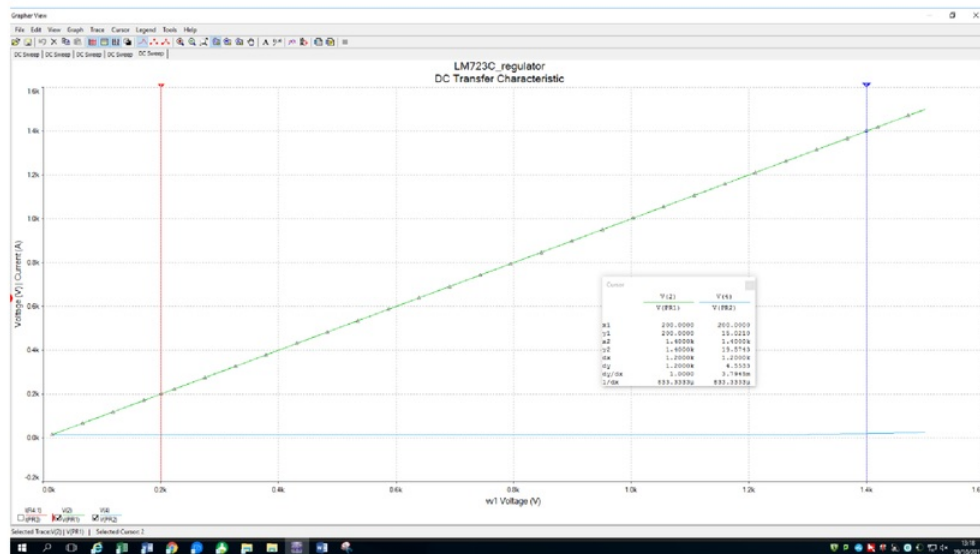


Figure 32 - Line regulation to 1.5kV

	V (2)	V (4)
	V (PR1)	V (PR2)
x1	200.0000	200.0000
y1	200.0000	15.0210
x2	1.4000k	1.4000k
y2	1.4000k	19.5743
dx	1.2000k	1.2000k
dy	1.2000k	4.5533
dy/dx	1.0000	3.7945m
1/dx	833.3333μ	833.3333μ

Figure 33 - Line regulation to 1.5kV results

Also we see that at 200V on the input to the regulator we are still at 15.02V at the output.

Load regulation – Parameter sweep

Parameter sweep

Resistor varied from 1 to 500 ohm in steps of 125 ohm, from 250 ohm obtain 15V, with current decreasing as load increases, short circuit current can be seen to be max at approx. 60 milliamps. This test was with R_{sc} at 10 ohm, (see page 17 for explanation)

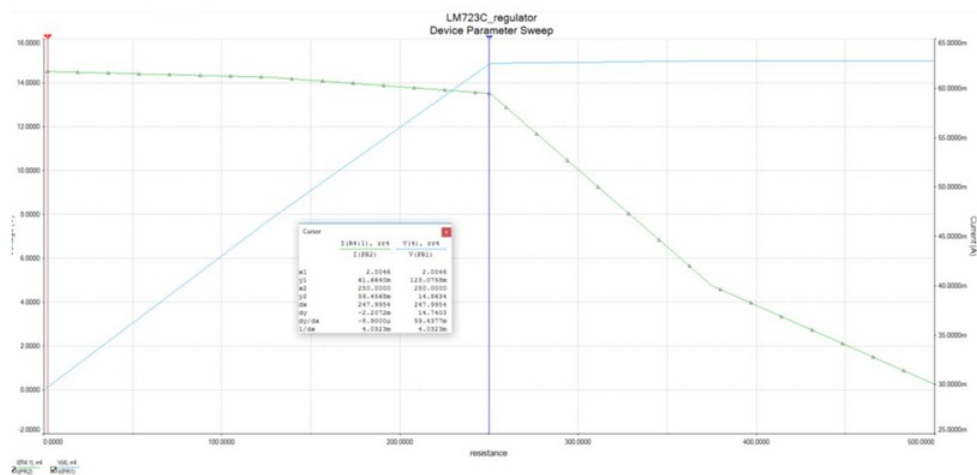


Figure 34 - Load regulation with R_{sc} 10 ohm

Cursor		
	$I(R4:1), \text{rr4}$	$V(4), \text{rr4}$
	$I(PR2)$	$V(PR1)$
x1	2.0046	2.0046
y1	61.6640m	123.0758m
x2	250.0000	250.0000
y2	59.4568m	14.8634
dx	247.9954	247.9954
dy	-2.2072m	14.7403
dy/dx	-8.9000u	59.4377m
1/dx	4.0323m	4.0323m

Figure 35 - Load regulation R_{sc} at 10 ohm results

In fig 36 it is shown that by changing the value of R_{sc} to the design of 0.6 ohm and not 10 ohm as per the datasheet the current is limited to 1A and the output stabilises at 15V after 100 ohm load resistance.

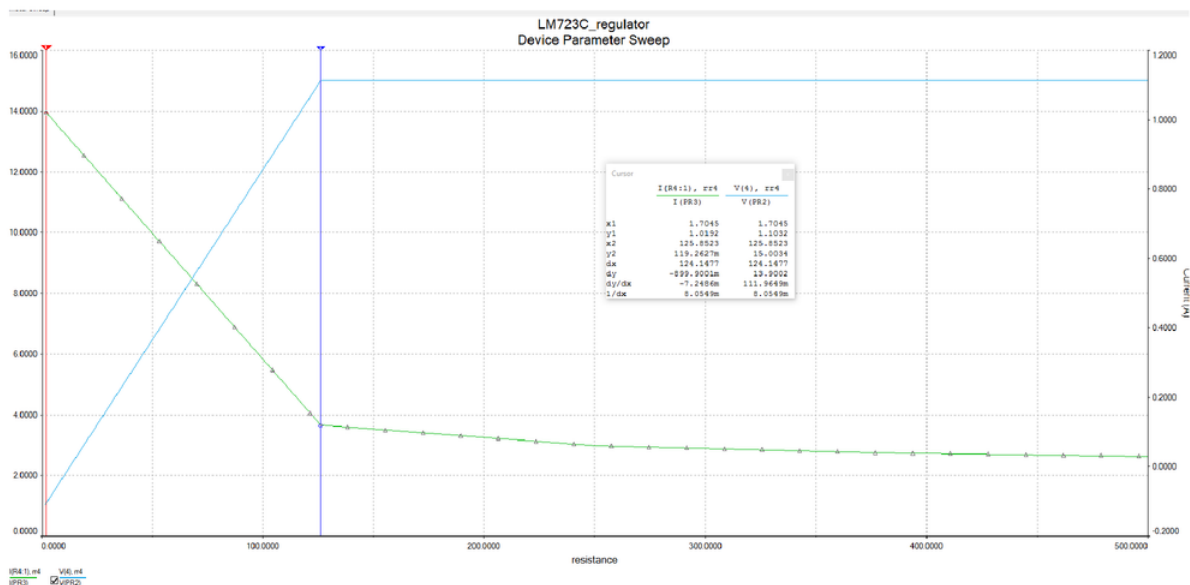


Figure 36 - Load regulation with Rsc at 0.6ohm

Cursor

	I (R4:1), rr4 I (PR3)	V(4), rr4 V (PR2)
x1	1.7045	1.7045
y1	1.0192	1.1032
x2	125.8523	125.8523
y2	119.2627m	15.0034
dx	124.1477	124.1477
dy	-899.9001m	13.9002
dy/dx	-7.2486m	111.9649m
1/dx	8.0549m	8.0549m

Cursor 1 shows the short circuit current at just over an amp and the voltage will be almost nothing due to the load being almost nothing.

The graph shows that as the load is increased the current drops as expected and the voltage stabilises, at 125 ohm a steady 15V output is obtained and the current can be seen to be 119 milliamps from cursor 2.

Figure 37 - Load regulation with Rsc at 0.6 ohm results

A ripple was simulated with a 2.5Vpk source and using an offset the minimum value of 19.2V exceeded i.e. $21.7 \pm 2.5V$ then the output gave a steady 15V as expected.



The output ripple was measured at 1mV i.e. $15.005 - 15.004 = 0.001\text{V}$ which is shown on the next screenshot. (Channel B)

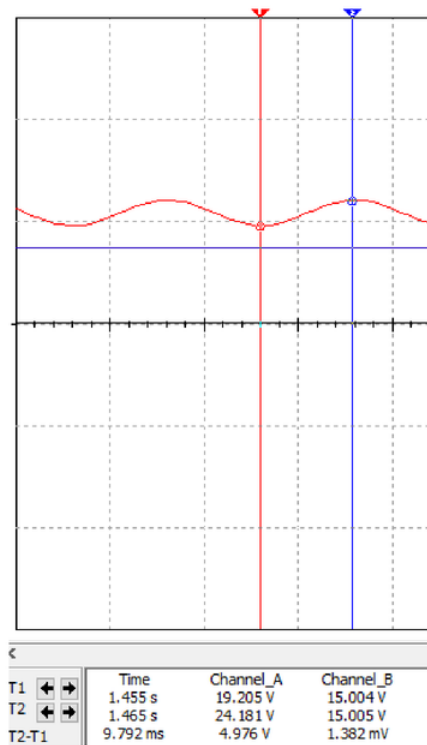


Figure 39 - Ripple removed

Channel A gives the 5Vpk-pk ripple which was injected ($24.18 - 19.20 = 4.98\text{V}$) which is twice the 2.5Vpk on the ripple source.

Fig 40 shows the effect by dropping the offset the output also drops and the curve shows sections, which are below the 15V required, this is due to V_{in} not staying above the minimum (19.12V deduced from the calculations)

4.2 Rectifier and Transformer

The completed circuit with rectifier and transformer can now be simulated. The voltages which were calculated are achieved at each stage as shown below.

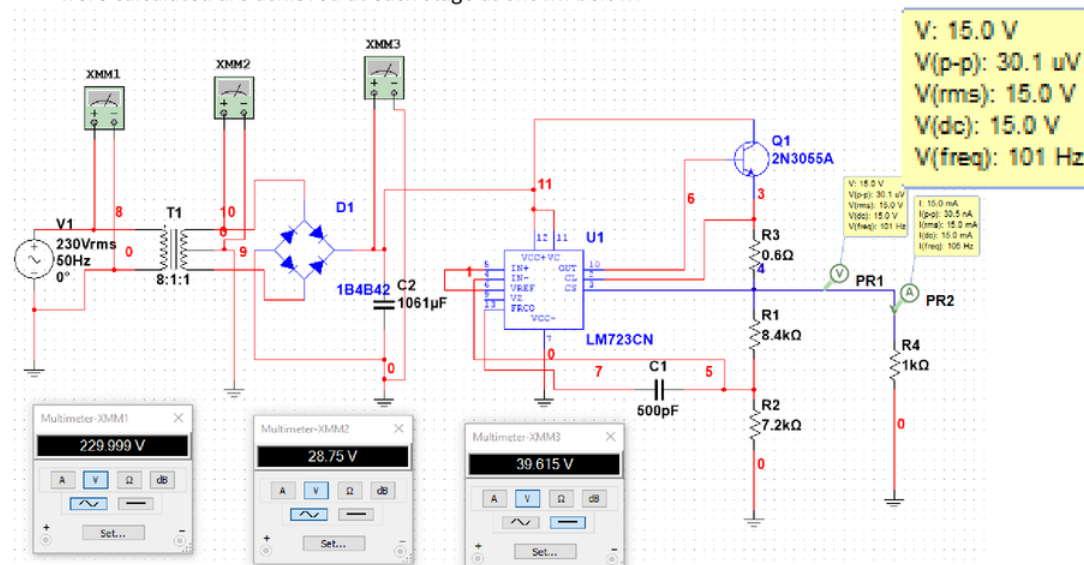


Figure 41 - Complete circuit test (1k)

Below is shown the transformer and rectifier waveforms. Input at 230*v2 and output at 28.75*v2 (allowing for small cursor placement errors) and the regulation without filtering to a value of 15Vdc.

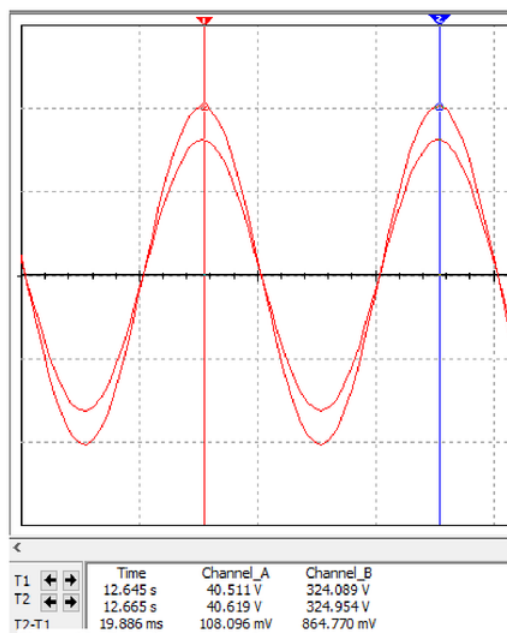


Figure 43 - Transformer waveforms

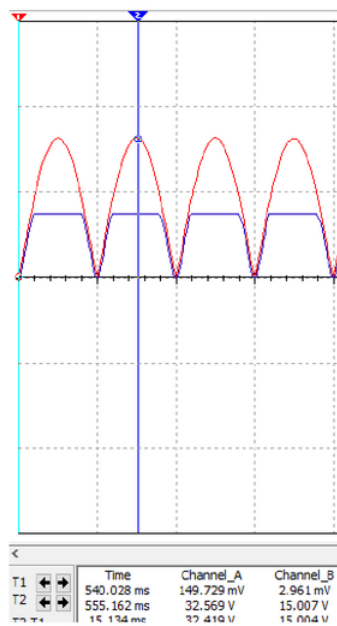


Figure 42 - Rectifier waveform

The transformer turns ratio adapted for the toroidal type found in the design specification and re-simulated giving the required 15V output under various load conditions.

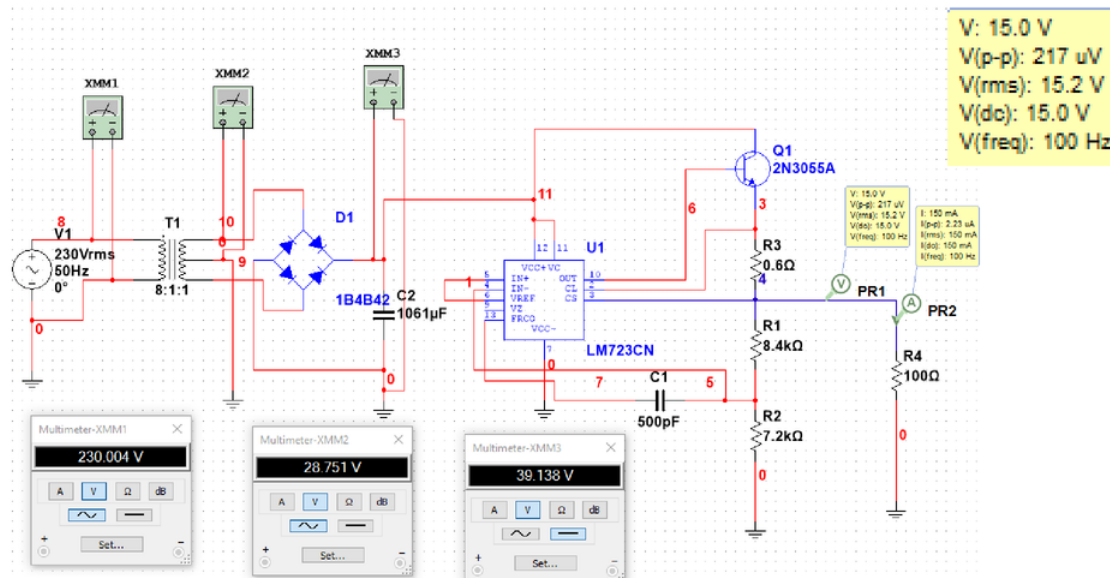


Figure 44 - Complete circuit test (100 ohm)

The short circuit current limit can be seen to be operating correctly at the rated current 1.02A when the load is reduced, this was seen in the load regulation analysis section 4.1

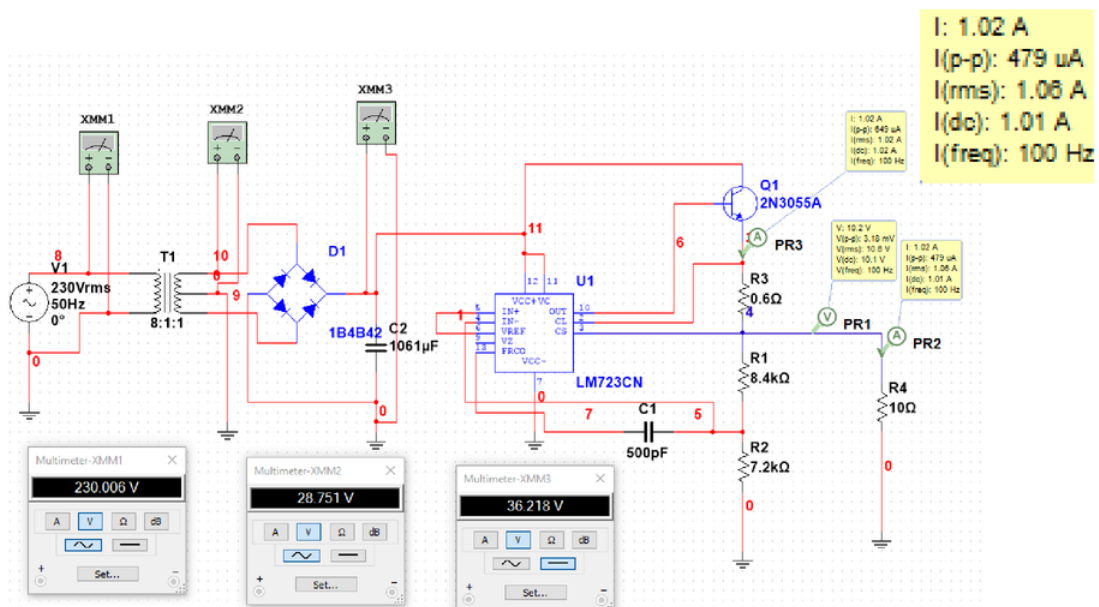


Figure 45 - Complete circuit test (10 ohm)

5. Conclusion

In conclusion, each stage of the design has been carefully calculated to produce minimum requirements for the following stage and thus guarantee the overall performance of the power supply. Evaluation of the practical and theoretical results is given in a series of comparison tables starting with the back end of the supply and working towards the input side.

Voltage Regulator LM723C	Required	Component Spec	Actual
Regulated Vout	15V	15V	15V
Rated Current	1A	Dependant on Rsc	1.02A
Input Voltage Range	-	9-40V	19.2-1300V
Input Voltage Differential (max)	Determined by capacitor ripple	5V	5V
Ripple output	1mVpk-pk	-74dB	1mVpk-pk
Efficiency	Not as efficient as a switching regulator as it needs to dissipate the difference between input and regulated voltage. However, the design has limited this differential and thus improved the efficiency.		

Improvement in the form of a switched mode power supply would give efficiency advantages as the pass transistor continuously switches from low-dissipation to full on/off states minimizing energy wastage. The customer specified use of a linear regulator as one of the design constraints.

By-pass Transistor 2N3054A	Required	Component Spec	Actual
$V_{CE0} \geq V_{min}$	24V	55V	24.04V
$I_{C(MAX)} \geq I_{SC}$	1A	4A	1.02A
$h_{fe} \geq \frac{I_{sc}}{I_o} @ V_{CE} = V_{in} - V_o - \phi$	Not applicable - Regulator adjusts I in order to maintain constant V	25 @ Vce=4V, Ic = 500mA	-
$P_D \max \geq V_{in} * I_{SC}$	15W	75W	10.5W at 10 ohm
θ_{JC}	From heat management calculations	2.33	2.33
Safe Operating Area (SOA) so that it allows for $V_{CE} = V_{in} @ I_c = I_{sc}$	Vce = 20V @ Ic = 16mA (measured)	Vce=4V, Ic = 500mA	Vce = 20V @ Ic = 16mA (measured)
Efficiency	In the active region power dissipation in the form of heat is high and results in a low efficiency between 30-50%. Heatsink is necessary.		

Wurth ATUL Capacitor	Required	Component Spec	Actual
C	1061uF	1200uF	1200uF
V_{RATED}	36V	50V	39V
Dissipation factor	7.27%	10%	-
I_o	1A	Determined by load	Determined by load
Impedance	low	0.03Ω	-

Efficiency	Aluminium Electrolytic capacitors offer the greatest volumetric efficiency due to dielectric layer thicknesses as low as 1µm.
------------	---

Rectifier KBPC1	Required	Component Spec	Actual
I _{F(AVG)}	0.5A	Determined by load	Determined by load
I _{F(PK)}	2.6A	3A	1.02A
PIV	54V	50-1000V	54V
I _{SURGE}	15A	50A	15A

Efficiency is the ratio of DC output power to AC input power this equates to the following for the full wave rectifier and so maximum available efficiency is 81.2%.

$$\frac{V_{dc}^2 / R_L}{V_{rms}^2 / R_L} = \frac{\left[\frac{2V_m}{\pi} \right]^2}{\left[\frac{V_m}{\sqrt{2}} \right]^2} = \frac{8}{\pi^2} = 0.812 = \underline{\underline{81.2\%}}$$

This is twice that available for half wave rectification. Also a full wave rectifier made from a centre tapped transformer and two power diodes will have reduced efficiency overall due to the extra requirement on the transformer output.

Toroidal Transformer	Required	Component Spec	Actual
V _s	27V	30V (2x15V in series)	28.7V
R _s	3.6Ω	0.64Ω (x2)	-
I _{s(rms)}	1A	1.66A	Determined by load
VA	38VA	50VA	Determined by load
Efficiency	Toroidal transformers are very efficient as they avoid corner magnetic leakage, the efficiency in the data sheet is 91%.		

Environmental considerations feature prominently in this design, the mounting plate for the instrumentation panel dictated the size and weight constraints, and the overall weight came in at under 0.8kg. By far the heaviest component (0.65kg) is the transformer its dimensions are 80mm diameter, 33mm height, the circuit board overall dimensions were 180mm x 140mm x 40mm.

The smoothing capacitor allows a large inrush current to develop which is approximately V_m/R_s and it charges with time constant τ = R_s C₁. Roughly speaking it will not damage the diode if V_m/R_s < I_{FSM} and τ < 10ms (50Hz). Making R_s large is advantageous to reduce I_{SURGE} and make rectifier and transformer ratings closer to the DC requirements of this supply.

The regulator IC has internal current limiting, thermal shut down and safe area protection, all this makes them robust devices and almost indestructible.

In conclusion results matched the customer specification and an efficient low cost solution was accomplished .

6. References

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EE-classes. (2012). *LM7805 datasheet*. Available: <http://ee-classes.usc.edu/ee459/library/datasheets/LM7805.pdf>. Last accessed 14 Oct 2017.

Texas Instruments. (2002-2016). *LM317 datasheet*. Available:
<http://www.ti.com/product/LM317/datasheet>. Last accessed 14 Oct 2017.

Design components

Regulator data sheet - LM723C

<http://www.ti.com/lit/ds/symlink/lm723.pdf>

Bypass transistor data sheet - 2N3054A

https://www.centralsemi.com/get_document.php?cmp=1&mergetype=pd&mergepath=pd&pdf_id=2n3054.PDF

Capacitor data sheet - Wurth ATUL 1200uF 50VDC electrolytic capacitor

<http://docs-europe.electrocomponents.com/webdocs/15d3/0900766b815d36f7.pdf>

Rectifier datasheet –Single Phase Rectifier Bridge 3A, 6A KBPC1, KBPC6 Series

<http://docs-europe.electrocomponents.com/webdocs/1300/0900766b81300a97.pdf>

Transformer data sheet

<http://cdn-reichelt.de/documents/datenblatt/C500/RKT5018.pdf>

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assignment 1

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

92/100

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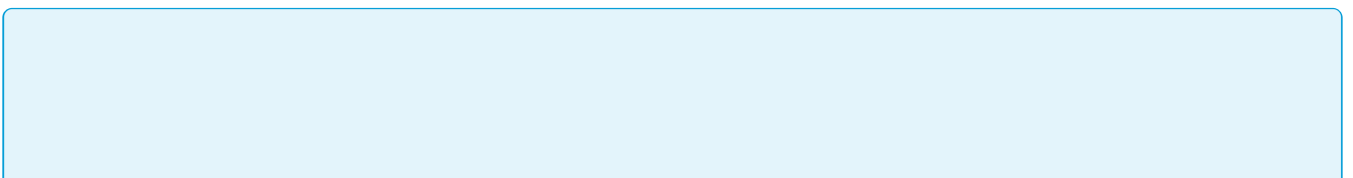
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GRADING FORM: CSG-RUBIC



RESEARCH-INFORMED LITERATURE



There was evidence of extensive further reading and research from highly credible and reliable sources. Your interpretation and understanding of the additional research was excellent and demonstrated a deep underlying appreciation of the subject. Your references were appropriate to the task and your reference list was of an appropriate length for this assignment.

9

KNOWLEDGE AND UNDERSTANDING



The knowledge and understanding of the subject demonstrated by this assignment was generally excellent. There were very few gaps in your knowledge of the basic principles and the higher level concepts were very well explained. Your explanation of the design process and calculations was also excellent and it did extend your knowledge well beyond that contained in the course notes.

28

ANALYSIS



Your analysis of the task was excellent, both in class and as shown in this assignment. You have demonstrated very good analytical skills and your approach to the task was very logical. You carried out a detailed evaluation of the results and included an excellent conclusion relating your practical

18

results to accepted theory.

PRACTICAL APPLICATION AND DEP.



Your application of practical skills for this task was generally excellent. You used the resources available in MultiSim appropriately when designing the circuit and you used appropriate options for testing and evaluating the circuit performance. You managed to design a very efficient circuit that functioned well within the specification and achieved with very little assistance. Your results were very detailed, well presented and allowed for an excellent conclusion to be attempted.

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SKILLS FOR PROFESSIONAL PRAC.



In this assignment you have demonstrated skills in working individually and also collaboratively. Your written report was very well structured and written in a coherent and logical way. The report was presented in a professional manner using appropriate language and formatting, good diagrams in appropriate places, good sentence/paragraph structure and clear calculations

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