

1809800

by Iwan CostelloDowns

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Assignment: Regulated Power Supplies

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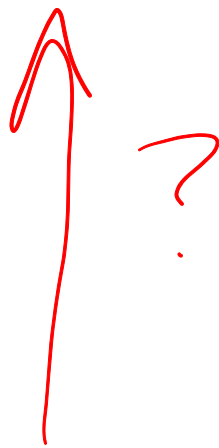
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- ① RESEARCH WAS MAINLY FOR COMPONENTS, SOME BACKGROUND INTO THE CONTEXT WAS NEEDED.
- ② DESIGN METHOD WAS EXPLAINED, BUT SCHEME CURVES WERE NOT ANNOTATED.
- ③ TESTING DIDN'T SHOW THE OUTPUT GRAPH FOR V_{OUT}/I_{OUT} AGAINST R_L - WHICH WAS THE MAIN TEST.
- ④ SOME VALID CONCLUSIONS.
- ⑤ ONLY 1 CHOICE FOR LOAD COMPONENT AND GENERALLY ALL FROM R_S .

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Design specification

The requirement of this task is to design a power supply based on a preexisting design specification for an industrial application, the application for this assignment is a power supply unit to a load cell controller used in an integrated paper mill mounted in an operator panel. The technical specifications demand an output of 24VDC with an operational current of 1.5A, due to the nature of the industry there are several environmental factors to consider.

Variable	Chosen Parameter
V _{AC} Input	240V
Input Frequency	50Hz
V _{DC} Output	24V
I _{DC} Output	1.5A
Temperature Rating	25 - 40C°
Ingress Protection (IP) Rating	IP66
Environmental Considerations	Heat, Dust and Pressurized Water

The supply will rectify mains 240V AC at 50Hz and output steady 24VDC for use in a load cell controller that uses a standard instrumentation current range of 4-20mA. Due to the hot and humid environment of the paper mill the panel will be exposed to pressurized water, as well as excessive amounts of paper dust as well as an ambient temperature of approx. 25-30C° with tolerance as the mill can reach temperatures into the 40C° range. Therefore, an ingress rating of 66 was chosen from Fig.1 as to totally protect against dust and any pressurized water.

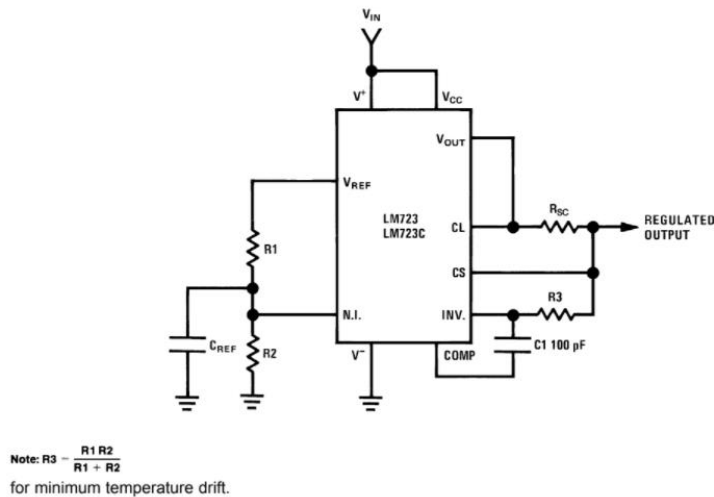
First Digit	Intrusion Protection	Second Digit	Moisture Protection
0	No protection.	0	No protection.
1	Protected against solid objects over 50mm, e.g. accidental touch by hands.	1	Protected against vertically falling drops of water, e.g. condensation.
2	Protected against solid objects over 12mm, e.g. fingers.	2	Protected against direct sprays of water up to 15 degrees from the vertical.
3	Protected against solid objects over 2.5mm, e.g. tools & wires.	3	Protected against direct sprays of water up to 60 degrees from the vertical.
4	Protected against solid objects over 1mm, e.g. wires & nails.	4	Protected against water splashed from all directions, limited ingress permitted.
5	Protected against dust limited ingress, no harmful deposits.	5	Protected against low pressure jets of water from all directions, limited ingress permitted.
6	Totally protected against dust.	6	Protected against strong jets of water, e.g. on ships deck, limited ingress permitted.

Fig.1 – IP Rating Chart - (Rainford Solutions, 2014)

Design Method Choices and Calculations

Choosing a Suitable Voltage Regulator

Typical Application



Typical Performance

Regulated Output Voltage	5V
Line Regulation ($\Delta V_{IN} = 3V$)	0.5mV
Load Regulation ($\Delta I_L = 50 \text{ mA}$)	1.5mV

Fig.2 – LM723C Voltage Regulator Chip - (Texas Instruments , 2013)

To easily satisfy the output criteria the regulator was designed first, despite being the back end of the system it is easier to establish a working regulator first then design a power supply due to the complexity of the regulator design. The regulator chip chosen is the LM723C, it has a suitable operating temperature suitable for the environment it will be placed in. The actual configuration of the design can be seen below in Fig.3, this configuration is an NPN current boost configuration.

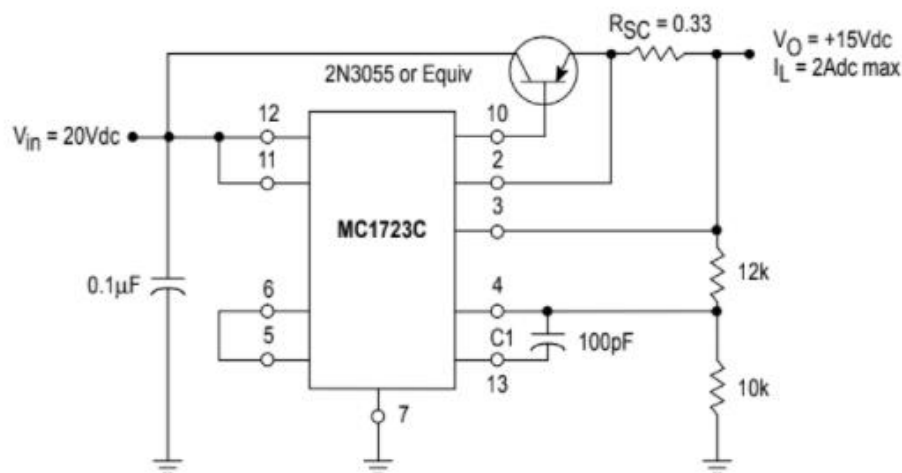


Fig.3 – Typical NPN Current Boost Connection - (Motorola, 1996)

There is an in-built current monitoring feature that monitors the voltage drop across R_{sc} as it increases proportional to output current, if said voltage drops exceeds 0.66V the transistor will cease to conduct due to an equal base-emitter voltage which holds output current. This prevents over current damage to the circuit. As seen from Fig.3 the default value for this is 0.33ohms. A reduction of this value increases the current flow. A Zener diode may be implemented into the design to prevent over voltage damage. Using the layout above the following simulation of the circuit was built as a first iteration in Fig.4.

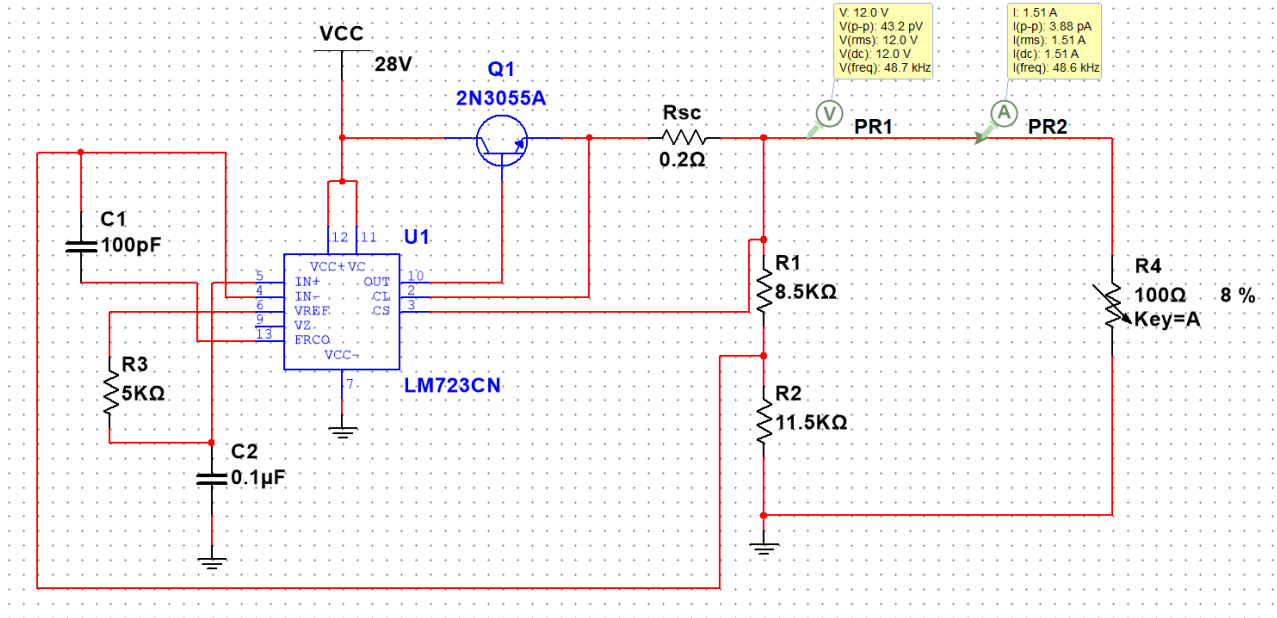


Fig.4 – Voltage Regulator 1st Iteration

To achieve the desired output the components must be calculated individually to give a refined 2nd iteration.

Voltage regulator component calculations

ELECTRICAL CHARACTERISTICS ($T_A = +25^\circ\text{C}$, $V_{in} = 12\text{ Vdc}$, $V_O = 5.0\text{ Vdc}$, $I_L = 1.0\text{ mAdc}$, $R_{SC} = 0$, $C_1 = 100\text{ pF}$, $C_{ref} = 0$ and divider impedance as seen by the error amplifier $\leq 10\text{ k}\Omega$ connected as shown in Figure 2, unless otherwise noted.)

Characteristics	Symbol	Min	Typ	Max	Unit
Input Voltage Range	V_I	9.5	–	40	Vdc
Output Voltage Range	V_O	2.0	–	37	Vdc
Input–Output Voltage Differential	$V_I - V_O$	3.0	–	38	Vdc
Reference Voltage	V_{ref}	6.80	7.15	7.50	Vdc
Standby Current Drain ($I_L = 0$, $V_{in} = 30\text{ V}$)	I_{IB}	–	2.3	4.0	mAdc
Output Noise Voltage ($f = 100\text{ Hz to } 10\text{ kHz}$) $C_{ref} = 0$ $C_{ref} = 5.0\text{ }\mu\text{F}$	V_n	– –	20 2.5	– –	$\mu\text{V(RMS)}$
Average Temperature Coefficient of Output Voltage ($T_{low} < T_A < T_{high}$)	TCV_O	–	0.003	0.015	$\%/^\circ\text{C}$
Line Regulation ($T_A = 25^\circ\text{C}$) $\left\{ \begin{array}{l} 12\text{ V} < V_{in} < 15\text{ V} \\ 12\text{ V} < V_{in} < 40\text{ V} \end{array} \right.$ ($T_{low} < T_A < T_{high}$) $12\text{ V} < V_{in} < 15\text{ V}$	Regline	– – –	0.01 0.1 –	0.1 0.5 0.3	$\% V_O$
Load Regulation ($1.0\text{ mA} < I_L < 50\text{ mA}$) $T_A = 25^\circ\text{C}$ $T_{low} < T_A < T_{high}$	Regload	– –	0.03 –	0.2 0.6	$\% V_O$
Ripple Rejection ($f = 50\text{ Hz to } 10\text{ kHz}$) $C_{ref} = 0$ $C_{ref} = 5.0\text{ }\mu\text{F}$	RR	– –	74 86	– –	dB
Short Circuit Current Limit ($R_{SC} = 10\text{ }\Omega$, $V_O = 0$)	I_{SC}	–	65	–	mAdc
Long Term Stability	$\Delta V_O / \Delta t$	–	0.1	–	$\%/1000\text{ Hr.}$

NOTE: T_{low} to $T_{high} = 0^\circ$ to $+70^\circ\text{C}$

Fig.5 – Voltage Regulator Datasheet Reference - (Motorola, 1996)

Using the datasheet as a reference, C_{ref} were set to $0.1\mu\text{F}$ to achieve minimal noise.

The output of the regulator comes from pin 4 and 10, the two resistors R_1 and R_2 act as a variable resistor and must balance. Using V_{ref} from the datasheet.

$$R_2 = \frac{V_{ref} \times (R_1 + R_2)}{V_{out}}$$

$$25000 = \frac{7.0 \times (R_1 + 25000)}{24}$$

$$R_2 = 0.2916 \times 25000 = 7291.6 \quad 7.3k$$

$$R_1 = R_2 - 7291.6 = 17.7k\Omega$$

To calculate R_{sc} the base emitter junction voltage drop is divided by the sensing current,

$$R_{sc} = \frac{0.66}{1.5} = 0.44\Omega$$

To find R3,

$$\begin{aligned}R3 &= R1 || R2 \\R3 &= 1770 || 7291 \\R3 &= 5.17k\Omega\end{aligned}$$

To determine the input voltage the transistor volt drops must be accounted for,

$$V_{in} \geq 24 + (2 \times 0.66) + 3 = 28.2V$$

Input stage component selection

To find the capacitor parameters.

A ripple rejection value of -74db was obtained from the datasheet.

$$\begin{aligned} \text{Ripple Rejection} &= \frac{\text{Ripple out}}{\text{Ripple in}} - 74\text{dB} \\ \text{Ripple Rejection} &= \frac{1\text{mV}}{\text{Ripple in}} - 74\text{dB} \\ \text{Ripple Rejection} &= 5.011\text{V} \end{aligned}$$

Halving this value gives us the peak-to-peak value of 2.5V.

Capacitor input value.

$$V_m = \left(V_{in} + \frac{1}{2} V_{in} \right) = 40\text{V}$$

Using the Schade curve in Fig.6 the rf value can be found to obtain ωCR_L .

$$rf = \frac{V_{\text{ripple}(p-p)}}{2\sqrt{2}V_c} \times 100$$

$$rf = \frac{25}{2\sqrt{2} \times 28.2} = 0.0313 \times 100 = 3.134\%$$

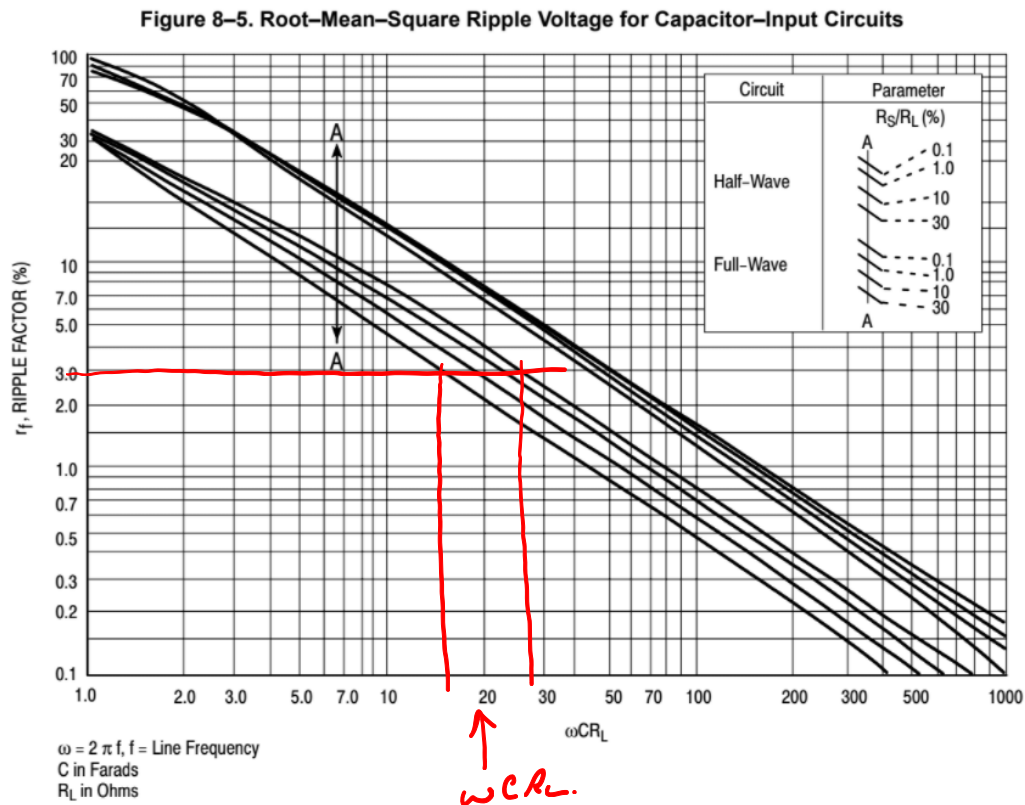
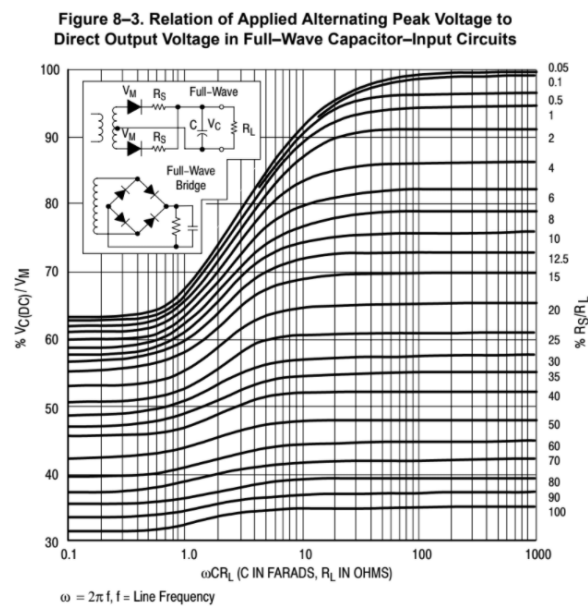


Fig.6 –Schade Curve RMS Voltage for Capacitor Input Circuits - (On Semiconductor, 2002)

Due to being a full wave rectifier the curve bandwidth is 15 to 202 at approximately 3.124% ripple factor. Therefore, the average value of 20 is taken for ωCR_L . Using this value in Fig.7 R_S/R_L can be found.



DIAGRAMS
 NEEDED
 ANNOTATION.

Fig.7 – Schade Curve of AC peak to DC peak Relationship for Full Wave Rectifier- (On Semiconductor, 2002)

$$\frac{V_c}{V_m}$$

$$\frac{28.2}{40} = 0.705 \times 100 = 70.5\%$$

Using the Schade Curve R_s/R_L can be found to be 15%

$$\frac{\omega C R_L}{2\pi f \left(\frac{V_c}{I_a} \right)}$$

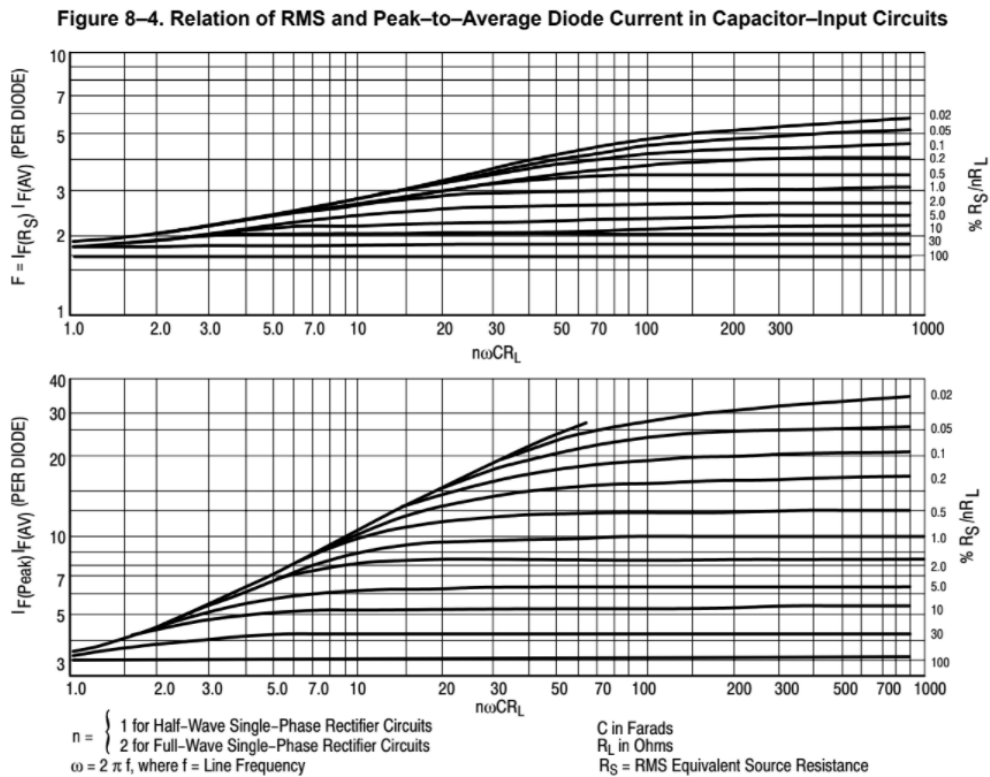
$$\frac{20}{2\pi \times 50 \left(\frac{28.2}{20} \right)} = 4.515 \text{ mF}$$

$$R_s = 0.15 \times R_L$$

$$R_s = 0.15 \times \left(\frac{28.2}{20} \right) = 2115 \Omega$$

2.12 ?

$\omega C R_L$ is doubled for a full wave rectifier, therefore $20 \times 2 = 40$.



ANNOTATE.

Fig.8 – Schade Curve of RMS to Peak to Average Diode Current in Capacitor Input Circuits. - (On Semiconductor, 2002)

Fig.8 allows the calculation of.

$$IF_{RMS} = 2.3$$

$$IF_{Peak} = 5.3 \times I_{avg} = 5.3A$$

$$I_{Surge} = \frac{mV}{R_s + ESR}$$

$$I_{Surge} = 40/2.115 = 18.9A$$

ESR considered negligible value. Therefore, Peak inverse voltage is.

$$PIV = V_m \times 2 \rightarrow 40 \times 2 = 80$$

A suitable bridge rectifier for this application would be the Vishay VS-KBPC101, it has a surge current of 55A and peak inverse voltage rating of 100V, an extra 20V is chosen for tolerance, it also adheres to our operational temperature parameters.

Attribute	Value
Bridge Type	Single Phase
Peak Average Forward Current	3A
Peak Reverse Repetitive Voltage	100V
Mounting Type	Through Hole
Package Type	D 46
Pin Count	4
Configuration	Single
Peak Non-Repetitive Forward Surge Current	55A
Maximum Operating Temperature	+150 °C
Minimum Operating Temperature	-40 °C
Peak Forward Voltage	1.1V
Peak Reverse Current	10µA
Length	16.7mm
Dimensions	16.7 x 16.7 x 6.35mm
Width	16.7mm
Height	6.35mm

Fig.9 - Vishay VS-KBPC101 Datasheet - (RS Components, 2022)

To calculate the transformer.

$$V_s = \frac{V_m + 2}{\sqrt{2}}$$

$$V_s = \frac{40 + 2}{\sqrt{2}}$$

$$V_s = 29.7V$$

Calculated Ratio.

$$Ratio = \frac{V_m + 240}{V_s} = \frac{8.08:1}{29.7}$$

$$VA \text{ Rating} = 2 \times V_s \times I_{rms}$$

$$VA \text{ Rating} = 2 \times 29.7 \times 23 = 136.62VA$$

A suitable transformer for this application would be the RS PRO 150VA to 24VAC Transformer. It has a power rating slightly higher than needed for tolerance purposes and outputs enough AC to be rectified.

Attribute	Value
Primary Voltage Rating	230V ac
Secondary Voltage Rating	24V ac
Power Rating	150VA
Number of Outputs	2
Mounting Type	Chassis
Length	100mm
Width	82mm
Depth	82mm
Dimensions	100 x 82 x 82mm
Fixing Hole Diameter	5.5 x 8.5mm
Weight	2kg
Minimum Operating Frequency	50Hz
Maximum Operating Frequency	60Hz

Fig.10 - RS PRO 150VA to 24VAC Transformer Datasheet - (RS Components, 2022)

Heatsink and thermal management

The calculation for a heatsinks performance is.

$$\theta JA = \theta JC + \theta CS + \theta SA$$

$$J = \text{Junction}$$

$$C = \text{Case}$$

$$S = \text{Heatsink}$$

$$A = \text{Atmosphere}$$

As seen earlier the chosen transistor is a 2N3055, using the datasheet form Fig.11 and Fig12 the heatsink needed to cool the component can be calculated.

THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction-to-Case	$R_{\theta JC}$	1.52	$^{\circ}\text{C/W}$

Fig.11 – 2N3055 Thermal Characteristics from Datasheet - (Motorola, 1995)

Case	θ_{cs}			
	Metal-to-Metal*		Using an Insulator*	
	Dry	With Heatsink Compound	With Heatsink Compound	Type
TO-204	0.5 $^{\circ}\text{C/W}$	0.1 $^{\circ}\text{C/W}$	0.36 $^{\circ}\text{C/W}$ 0.28 $^{\circ}\text{C/W}$	3 mil MICA Anodized Aluminum
TO-220	1.2 $^{\circ}\text{C/W}$	1.0 $^{\circ}\text{C/W}$	1.6 $^{\circ}\text{C/W}$	2 mil MICA

*Typical values; heatsink surface should be free of oxidation, paint, and anodization

Fig.12 – TO -204 Case Characteristics with Heatsink Compound from Datasheet - (On Semiconductor, 2002)

Thermal resistance for JC is 1.52.

$$TO - 204 \text{ Case With heatsink compound } \theta CS = 0.36$$

Rearranging

$$T_J = T_A + P_D \theta JA$$

$$\theta JA = \frac{T_J - T_A}{P_D}$$

T_A = Ambient temperature and P_D = Power dissipated can be ascertained from the specification.

$$P_D = (24V \times 1.5A) = 36W$$

$$\frac{200 - 30}{432} = 3.935$$

$$\frac{200 - 30}{432} = 3.935 - 0.28 - 152 = 2.135^{\circ}\text{C}/\text{W}$$

A heatsink suitable for this application would be the RS Pro Heatsink TO-3 as seen below in Fig.13 it has a thermal resistance of 2C/W which is desirable as it is below the calculated.

Attribute	Value
Length	46.4mm
Width	46.4mm
Height	33.3mm
Dimensions	46.4 x 46.4 x 33.3mm
Thermal Resistance	2 (Forced) °C/W, 2 (Natural) °C/W
Mounting	Bolt On, Horizontal, Vertical
Colour	Black
Material	Aluminium
Package Type	TO-3
Series	RSAW294
Finish	Black Anodized

Fig.13 – TO -3 Heatsink Datasheet - (RS Components, 2022)

Analysis and Results

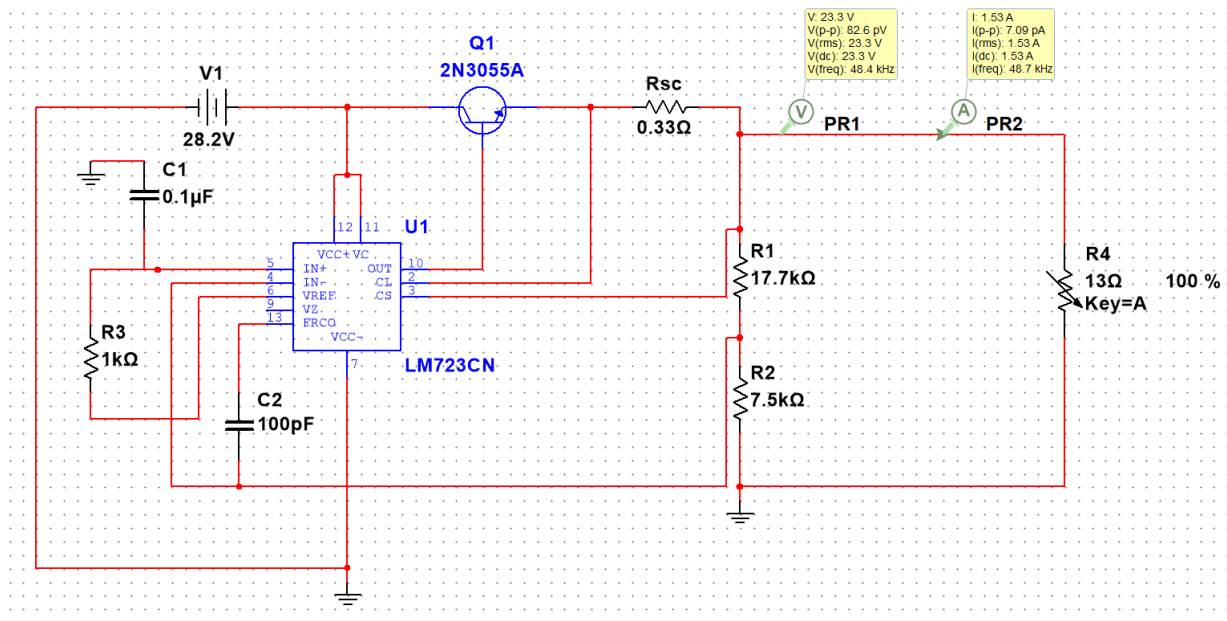


Fig.14 – Voltage Regulator 2nd Iteration

The final iteration of the circuit can be seen above in Fig.14, adding the DC voltage source to simulate the rectified input I was able to achieve an output voltage of 23.3VDC, and an output current of 1.53A. The current is certainly adequate however the voltage could be more accurate optimally speaking. Further tuning of the system may yield this result however this is the closest I could attain. Using the potentiometer see in Fig.14 the load value was able to be varied, the current stayed consistently above 20mA, the required signal voltage used in the load cell controller, this is more than an adequate performance of the system and can be said to have met the specification. Fig.15 shows the input stage simulation, because of the limitations of Multisim the whole circuit cannot be tested at once. Regardless we can observe the circuit working as intended by stepping down the AC supply into a manageable DC input, therefore it can be said to have met the specification.

*Results graph showing
V_{out} / I_{out} with R_L
shown as included.*

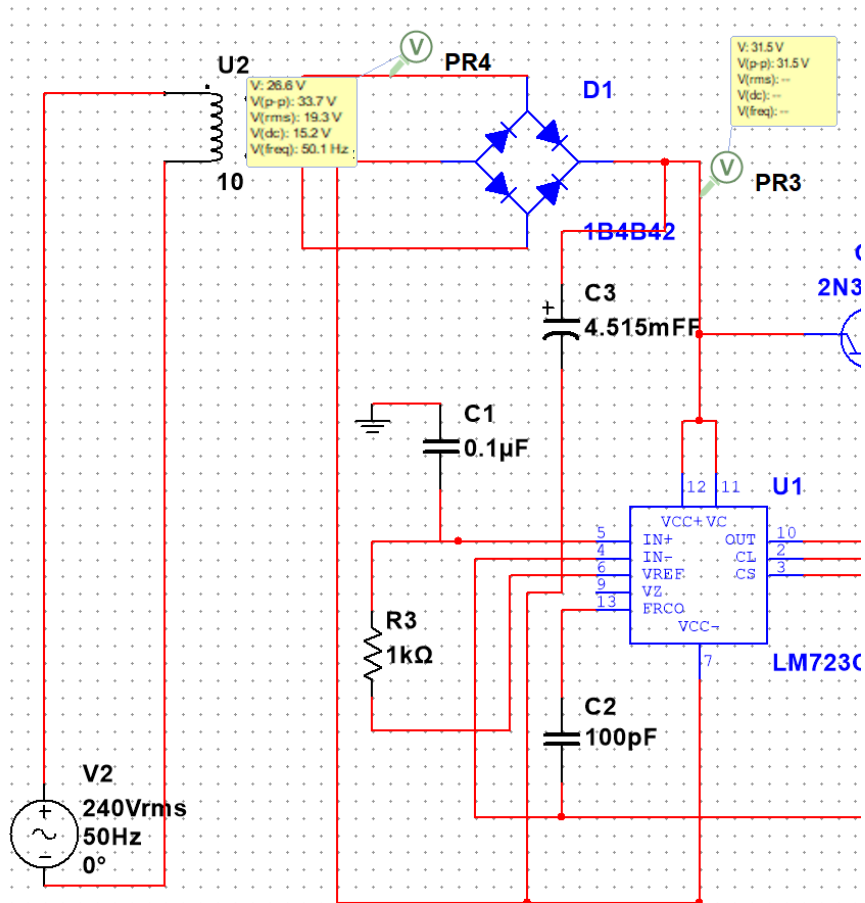


Fig.15 – Input Stage Simulation

Conclusion and Recommendations

Using the bottom-up approach, in accordance with the pre outlined specification the power supply unit for the load cell controller was successfully designed, built, and tested. Doing the design this way allowed me to design the system so that it met the specification outright and work backwards using approximate calculated values and then via tuning get the desired result. This is the advantage of this system over a top-down approach. Overall, the desired specifications were met or exceeded with tolerance except for the output voltage which was a little low. Something going on there.

The system was designed to be as safe as possible, with over current and over voltage precautions taken in the regulator side and the supply side, all components were selected from up-to-date websites from reputable sources, they were also selected with a limited tolerance in mind. A further recommendation would put a bleed LED into the regulator design to allow the system to de-energize when the supply is turned off. The chip is protected via transistor that sinks the full load current and bypasses the chip protecting it from currents exceeding 150mA. This method generates a lot of heat which perhaps the heatsink cannot manage. To improve upon these two transistors could be used to share the load. Overall if the circuit was built in real life better components could be used to improve shelf life, it would also be interesting to see the circuit built entirely physically to see how the whole unit performs under real life stresses and to evaluate the whole circuit as one which was unobtainable due to the nature of multisim. The smoothing capacitor is one large unit and perhaps could be remedied by using various smaller capacitors to utilize maximum space efficiency and to remove high frequency spikes emanating from the DC signal.

In conclusion, the overall assignment was a success in exploring the bottom-up approach to circuit design allowing a system of approximation based on desired results bolstered by eventual fine tuning of the circuit.

SOME VARIOUS CONCLUSIONS.

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FINAL GRADE

GENERAL COMMENTS

Instructor

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GRADING FORM: CSG-RUBIC

IWAN COSTELLODOWNS**60****RESEARCH-INFORMED LITERATURE**

There was some evidence of further reading and research and your interpretation and understanding of the additional research was satisfactory and demonstrated an underlying appreciation of the subject. Your references still rely on a small selection of mostly credible sources and you need to be more consistent with your referencing conventions e.g. citing diagrams as well as text.

5**KNOWLEDGE AND UNDERSTANDING**

The knowledge and understanding of the subject demonstrated by this assignment was reasonably detailed and mainly accurate. There were very few gaps in your knowledge of the basic concepts and your understanding of the higher level concepts was demonstrated to a limited degree - you could have explained in more detail how the circuit

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evolved. Further work – Your explanations need to be more detailed and written with a greater emphasis on critical evaluation rather than description.

ANALYSIS



Your explanation of the design process was good and the conclusions showed that you can interpret quantitative and qualitative data, although this was often descriptive. You could have evaluated the results and specified whether they concurred with theory suggesting reasons for any discrepancies. You have however demonstrated good analytical skills and your approach to the task was logical. Arguments made in the conclusions were mostly valid and demonstrated a good understanding of the topic. Further work – in your conclusion, you should relate the results to the original specification and to accepted theory.

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PRACTICAL APPLICATION AND DEP.



Your application of practical skills for this task was generally good. You used the resources available appropriately when designing the circuit and you used appropriate options for testing and evaluating the circuit performance. You managed to design an efficient circuit that functioned within the specification and achieved this by only asking for assistance when appropriate. Your results were comprehensive and allowed for a good conclusion to be attempted.

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SKILLS FOR PROFESSIONAL PRAC.



Your written report was reasonably well presented in terms of content and layout and was mostly structured in a coherent way, however you should endeavour to use the available word count more effectively in future.

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