EEE118: Electronic Devices and Circuits

Lecture VII

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Review

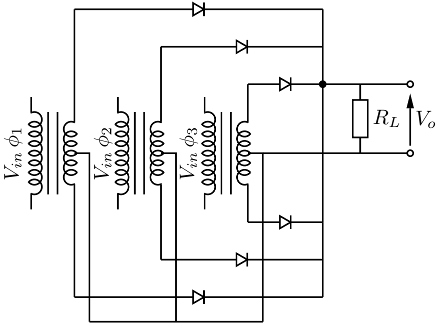
1. Introduced the idea of linear power supplies
2. Briefly discussed some differences between single phase and three phase supplies
3. Considered the half wave rectifier in detail
4. Used a peak detector circuit to smooth the output voltage of the peak detector
5. Developed a simple model to find a suitable capacitor value for a power supply filter
6. Considered full wave and bridge rectifiers as an extension to the half wave principle
7. Noted that in the full wave circuit the smoothing capacitor is replenished at double the line frequency
8. Observed that the output voltage polarity available is only a function of where the reference is placed

Outline

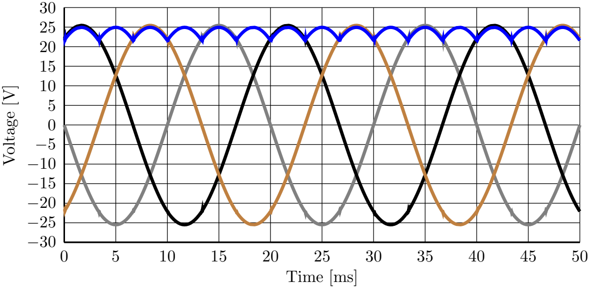
Three Phase Full Wave Rectifiers

- Most power systems that handle more than a few kW are three phase systems
- A three phase power system has three live conductors instead of the single live conductor in most domestic systems
- The three live conductors carry power at the same frequency, but are displaced in phase from one another by 120°.
- The main advantage of three phase is that power is continuously available and never drops to zero. Two phases are always have non-zero voltage at any time.
- The phase currents tend to cancel each other, summing to zero in the case of a linear balanced load. This makes it possible to eliminate or reduce the size of the neutral conductor

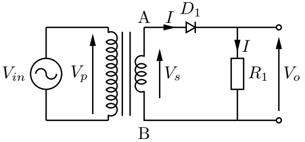
- All the phase conductors carry the same current and so can be the same size, for a balanced load.
- Power transfer into a linear balanced load is constant, which helps to reduce generator and motor vibrations.
- Three-phase systems can produce a magnetic field that rotates in a specified direction, which simplifies the design of some types of electric motor/generator.



- There is a large DC output voltage, $V_{DC} = 0.955\, V_{s_{pk}}$, in the un-smoothed output waveform.
- The peak to peak ripple voltage of the un-smoothed output waveform is 0.133 $V_{s_{pk}}$. This is compared to a value of $V_{s_{pk}}$ for single phase full wave and half wave rectifier circuits.



- The fundamental frequency of the ripple is six times the input frequency e.g. 300 Hz for 50 Hz input. This should be compared to twice the input frequency for single phase half wave and full wave rectifiers respectively.
- Because of this, the un-smoothed three phase output is significantly "better" than single phase.
- For many three phase applications it is therefore not necessary to use smoothing.
- Where smoothing is needed, it is easier to achieve than in single phase circuits because
  - The intrinsic ripple voltage is smaller 0.133 $V_{s_{pk}}$ *vs.* $V_{s_{pk}}$.
  - The ripple frequency is higher, so the time between replenishing the smoothing capacitor is reduced. Consequently, for a given ripple specification the smoothing capacitance can be a smaller value. High capacitance electrolytics are expensive especially when higher voltage specification is required e.g EVOX RIFA 6800 μF, 385 V, £84.80 + VAT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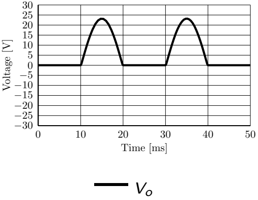
V_s
R_1
V_o
B


Voltage [V]
Time [ms]
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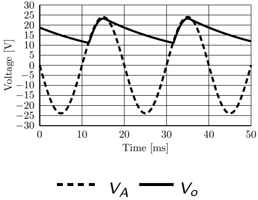
Voltage [V]
Time [ms]
V_A
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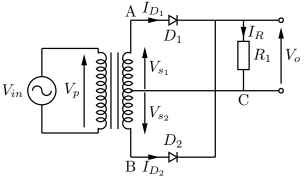
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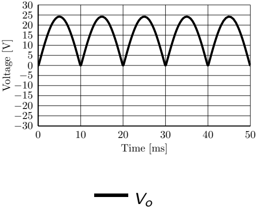
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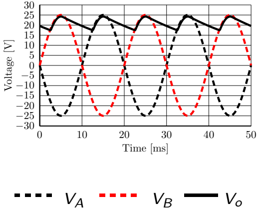
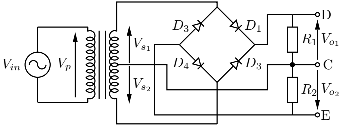
V_o


Voltage [V]
Time [ms]
V_A
V_B
V_o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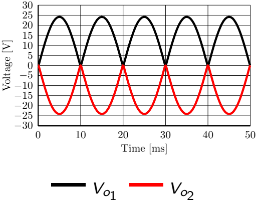
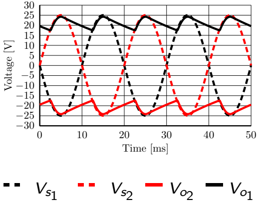

Voltage [V]
Time [ms]
V_{o_1}
V_{o_2}


Voltage [V]
Time [ms]
V_{s_1}
V_{s_2}
V_{o_2}
V_{o_1}

Stabilisation and Regulation of DC Power Supplies

- The output from a rectifier and smoothing circuit is not often of sufficient quality to supply an electronic circuit directly. (although exceptions do exist in e.g. power electronics / electrical machines).
- The effects of finite supply and transformer impedance make it difficult accurately to predict the DC component in the output waveform, and make the DC and ripple components of the power supply dependent on the load.
- The supply voltage can vary. Although we say a 240 V RMS supply in the UK the regulation states that this can have a large tolerance. The current regulation is that it should be 230 V $\pm 10\%$ (207 - 253 V). This just covers the same voltage range as continental Europe. The utility companies use this tolerance to manage the load and ensure the frequency specification is maintained.

- The ripple voltage can also be a problem, introducing noise (hum) into circuits. To have a very small ripple voltage requires high smoothing capacitance, which is expensive and bulky - often impractical.

To mitigate the short-comings of these circuits regulation and stabilisation are required.

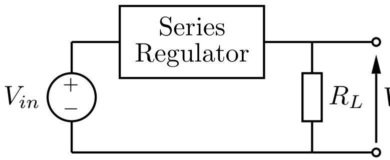
Stabilisation

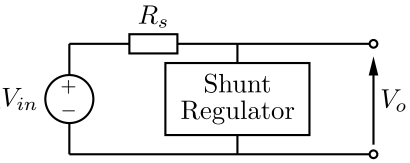
The process of making the output independent of changes in utility supply voltage.

Regulation

The process of making the output voltage independent of the load current.

Regulation and stabilisation are achieved simultaneously by circuits called regulator circuits of which there are two types series regulators and shunt regulators.





These types can be further subdivided depending on their principle of operation. In EEE118 only the Zener diode shunt linear regulator will be covered. See EEE340 or the EEE118 course books for a more general appraisal. In both series and shunt linear regulators the lowest value of the unregulated DC input voltage must be greater than the required output voltage by a defined margin which is dependant on the particulars of the circuit design. In prior times rectification, regulation and stabilisation was achieved by other methods [1,2,3].

[1] Smith, F. L. (editor), *Radiotron Designers Handbook*, RCA Victor, 4th edition, 1954, Chapters 30 – 34

[2] Terman, F. E., *Electronic and Radioenineering*, McGraw Hill, 4th edition, 1957, Chapter 20

[3] Williams E., *Thermionic Valve Circuits*, Sir Isaac Pitman & Sons, 4th edition, 1961, pp. 237 onwards

Series Regulator Operation

The series regulator restricts the flow of current from the input to the output in such a way as to maintain a constant V_o across the load.

Shunt Regulator Operation

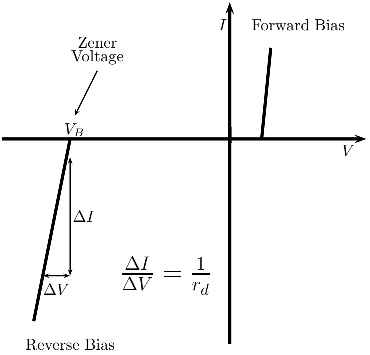
The shunt regulator restricts or increases its own current demand in such a way as to maintain a constant voltage across itself by dropping a varying voltage across R_s. Since the regulator is in parallel with the load, the load voltage is regulated as well.

To construct a shunt regulator an electronic device or component is required which can draw a varying current while dropping as, nearly as possible, a constant voltage. Essentially a current sink.

Zener Diode Linear Shunt Regulator

The simplest form of shunt regulator is constructed with a Zener diode. Where the Zener diode acts as a variable current sink. The Zener diode is a pn junction diode in which both N and P regions are highly doped. Their forward bias characteristics are similar to "normal" diodes but their reverse bias characteristics are engineered so that the diode will break down at a specified voltage. This breakdown behaviour is achieved by virtue of the high doping which gives rise to a large peak electric field when the diode is reverse biased. The high doping is also responsible for the very thin depletion width. Depending on the specified breakdown voltage the Zener diode will either breakdown by quantum mechanical tunnelling ($V_B < 4\ V$), by impact ionisation ($V_B > 6\ V$) or by both processes ($4\ V < V_B < 6\ V$).

The breakdown gives the Zener diode a very abrupt or "sharp" breakdown characteristic. When broken down a small increase in the applied voltage will yield a large increase in current.

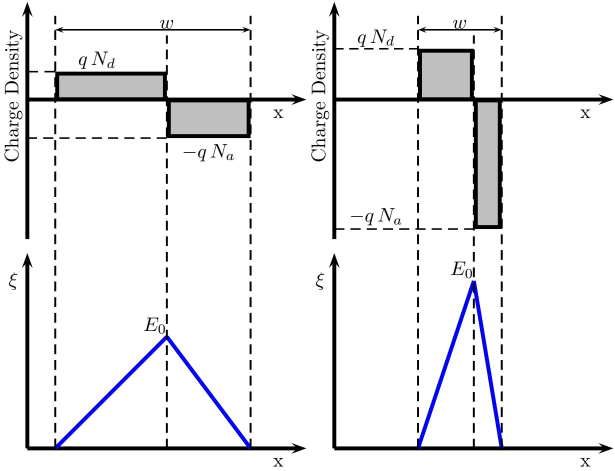


Note that it is assumed that the I-V curve in the breakdown region is linear. This is not very realistic, so generally the dynamic resistance, r_d is thought of as the tangent of the curve at a particular breakdown current.

Under normal Zener operation in a shunt regulator the dynamic resistance varies in order to conduct enough current through the diode so that the voltage across the load is held constant by dropping the rest of the supply voltage across R_s.

Zener Diodes - Impact ionisation

There are more zener diodes with $V_B > 6$ V than $V_B < 6$ V so the Zener effect, which is dominant in the lower voltage devices will be ignored for the moment. A pn diode is designed with a doping level in the P and N type material which will yield the "critical electric field" at a particular terminal voltage. Electric field is measured in V/m so what about the meters? It transpires that the wider the depletion region is the more voltage is required to reach the critical field. Consequently a Zener diode can be designed to break down at a particular voltage by controlling the doping density in the P and N regions. In Si the critical field is approximately 40 V/μm, but it is influenced somewhat by the doping densities. Some high voltage Zener diodes will have a pin structure where an lightly doped intrinsic region is sandwiched between the highly doped P and N regions. This acts to increase the depletion distance requiring a higher voltage to yield the critical electric field.



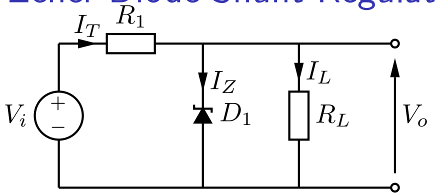
Two pn diodes one with lower doping density (left). Observe that the maximum field E_0, is lower at a given applied voltage in this case than in the higher doping density case (right).

Zener Diodes from a Circuit Perspective

- Since a Zener diode is normally used in reverse bias, it will be assumed that the the cathode will be positive w.r.t anode from now on.
- Zener diodes are only effective regulators if they are biased above their reverse breakdown voltage.
- Once the diode has broken down in a reverse direction, an increase in reverse bias ΔV will lead to an increase in reverse current ΔI
- The ratio of the *small change in V* against the *small change in I* is the dynamic or small signal[4] resistance of the reverse biased diode. It is variable and depends on the biasing conditions. It cannot be computed by dividing the breakdown voltage by the current. It is the change in V and the change in I over a small portion of the breakdown characteristic that is important. dv/di.

[4] small and large signals will be treated fully in semester two.

A Zener Diode Shunt Regulator Circuit



In this circuit V_i is the output from any of the rectifier circuits that have been discussed in this course.

- The output voltage V_o will be close to V_B provided the diode is biased above its breakdown voltage. If $V_{C-A} > V_B$ the current is always greater than zero.
- Assume the load current, I_L, is constant but V_i is variable - due to ripple or utility variations.
- A reduction in V_i of ΔV_i will cause a reduction in voltage across R_1 of ΔV_i and hence a reduction in the output voltage.
- However the falling output voltage acts to slightly switch off the Zener diode causing the Zener current, I_Z, to fall by just enough to prevent V_o changing.

- The reduction in the total current I_T due to the falling voltage drop across R_1 is compensated by a similar reduction in I_Z such that I_L (and therefore V_o) are unaffected.
- Similarly if V_i remains constant but I_L changes the increasing I_L tends to lower V_o. A small decrease in V_o tends to switch off the Zener diode slightly, reducing its current and alowing I_L to increase such that V_o remains unchanged.

Design Approach,

- Work out or choose, based on your knowledge of the load, the maximum load current, I_L.
- Choose a Zener diode based on the required output voltage V_o (e.g. BZX55C25 - 25 V)
- Use the diode's manufacturers data sheet to find the minimum current required for proper operation (smallest I_Z that still yields the correct breakdown voltage).

- Consider the conditions that are most likely to cause the regulator to switch off i.e. minimum input voltage and maximum load current; find a value for R_1. The maximum required load current and minimum required Zener current must be able to flow even when the input voltage is at a minimum.

$$\frac{V_{i_{min}} - V_o}{R_1} = I_{L_{max}} + I_{Z_{min}} \tag{1}$$

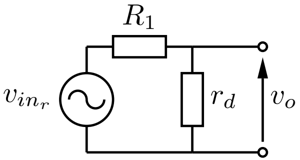
If the value of R_1 is larger than that given by (1), there would be insufficient current under the worst case of input voltage to satisfy the requirements of the load and the regulator. Therefore (1) represents the largest acceptable value of R_1. Of course if R_1 is made smaller than this value its power dissipation will be unnecessarily high.

- Calculate the worst case power dissipation in R_1. (hint: Max input voltage, full load current)
- Calculate the worst case power dissipation in the Zener diode (hint: Max input voltage, no load current). Check the Zener you chose is capable of dissipating the required power, if not select a higher power Zener diode.

Effect on the ripple,

- To calculate the effect of the Zener diode regulator on the ripple an equivalent circuit can be used which models the small changes in Zener resistance that occur to due small fluctuations in the input voltage (or load current).
- If the regulator has been well designed the diode will be broken down in the reverse direction. From the perspective of the ripple signal the diode can be thought of as a small signal (or dynamic) resistance which is equal to the inverse of the slope of the tangent of the breakdown characteristic at the operating point.

In the ripple equivalent circuit only the effect of the small ripple is considered, hence the input is AC. The DC has been neglected.



The output ripple voltage, v_o is obviously a potential division of the input ripple voltage v_{in_r} in the ratio of R_1 and the small signal (dynamic) resistance of the Zener diode. The load resistance (if it is connected) appears in parallel with the dynamic resistance of the Zener and the two may be paralleled using the usual formula. Hence the value of v_o calculated without the load is the worst case ripple voltage. If r_d is lower than R_1 (almost always true) there can be a significant reduction in output ripple. Limitations,

- The voltage is not adjustable.
- The Zener and R_1 may have high power dissipation.
- The dynamic resistance of the Zener is low it is not as low as transistor based linear regulators.

Review

- Covered the differences between three phase and single phase systems more fully.
- Concluded the section on linear power supplies with a review of the circuits.
- Introduced stabilisation and regulation of power supplies.
- Briefly noted the existence of series and shunt regulators
- Discussed the usefulness of the Zener diode as a shunt regulator
- Reviewed the principle of operation of Zener diodes (impact ionisation).
- Introduced the Zener diode shunt regulator circuit.
- Provided a method for designing the component values of the regulator.