AC to DC Power Supplies

Figure 1 Many AC to DC Supplies at work

Background

Virtually all electrical energy, worldwide, is transmitted as Alternating Current; in the U.S. the standard for homes is 120/240 Volts AC at 60Hz. Neighborhood transmission lines are usually several 10's of Kilovolts, and the large cross-country lines that you see on the metal towers are upwards of 500-750 Kilovolts. Virtually all electronic devices operate on Direct Current, ranging from less than 1V to perhaps a few hundreds of volts. (The amplifiers in Figure 1 are a great example of the latter.)

In this module we will take a look at some of the ways you can get from one voltage level to another safely, and convert AC to DC. In addition, we will look at methods to regulate voltages, and provide protection against short circuits.

This document is not intended to be an exhaustive design document, but rather an introduction to the concepts of approximations, and conservative design principles. It does not delve deeply into the limitations of real-world components, but rather presents an idealized theoretical approach, to give the reader some notions of the underlying processes. The math is approachable and a bare minimum of calculus is employed.

The Ubiquitous Transformer

The enabling technology for moving electrical energy, and efficiently converting between voltage levels is the transformer.

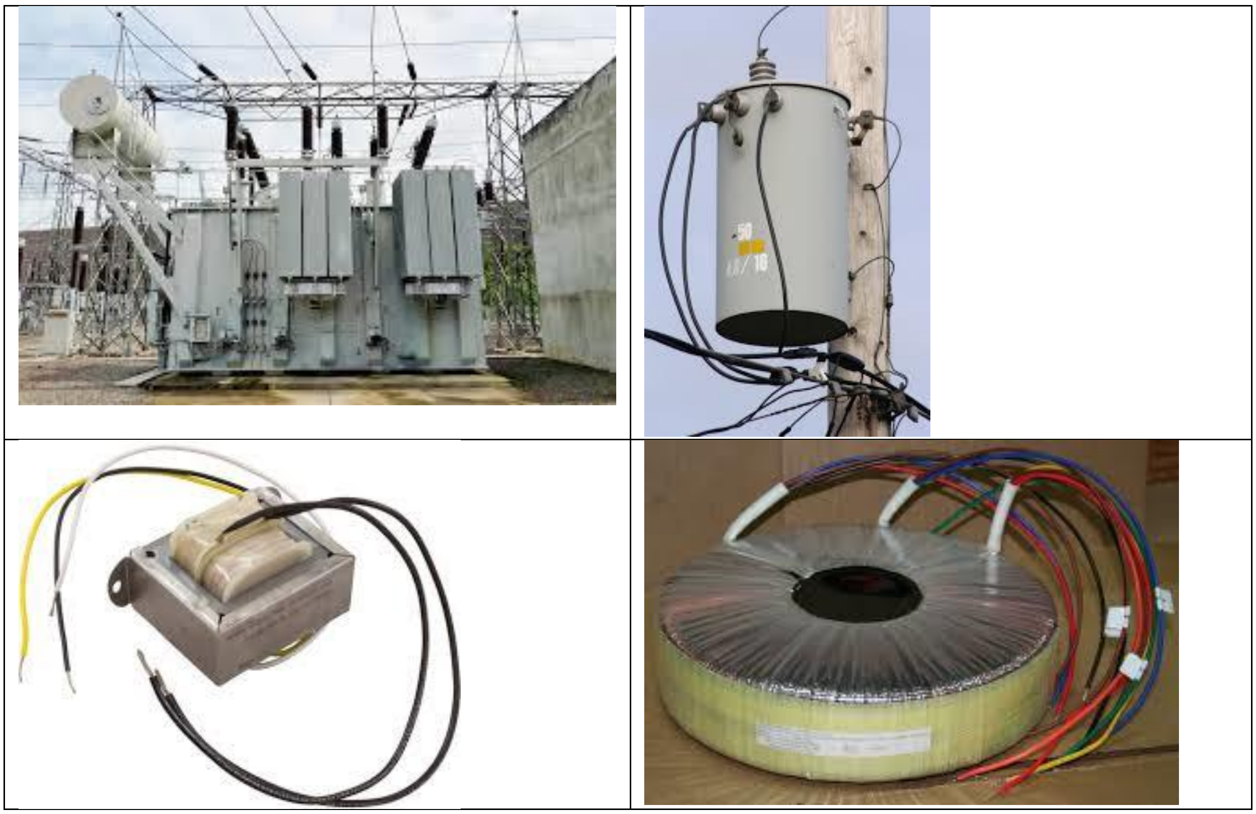

Figure 2 Various transformer styles

In Figure 2 we can see a number of sizes and styles of transformer. The upper left is one in an electrical substation that can handle several megawatts of power. The upper right is a common utility pole unit for powering a residence and is capable of about 50 KW. The lower left is a small instrument transformer and can handle several watts, and the lower right is one made in the shape of a toroid, and can handle several hundred watts.

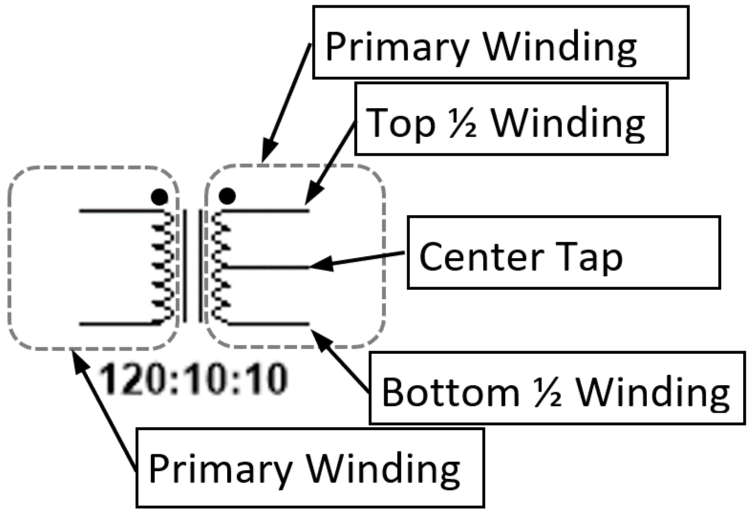

Figure 3 Transformer Circuit Symbol

A typical transformer symbol is shown in Figure 3. We can think of it as multiple coupled inductors mounted on a common magnetic core. A changing voltage on one inductor will create a changing magnetic flux in the core, that will induce a corresponding voltage on the other windings. The ratio of the voltages is, to a good degree of approximation, equal to the ratio of the turns on each winding. In the example above, we show a primary voltage of 120V, and 2 secondary voltages of 10V each with respect to the middle wire, which is usually referred to as a "center tap." In this case the top half of the winding will develop 10V with respect to the center tap, as will the bottom half, but they will be out of phase with each other. There are dots that indicate polarity. When current flows into the primary winding dotted end, it will flow out of the secondary winding dotted end. If the center tap is considered to be the reference, i.e. ground, then current flows into the non-dotted secondary end at the same time that it is flowing out of the dotted winding. Also, note that there is no difference, other than the number of turns, between primary and secondary. Either winding could function in either mode, with suitable applied voltages. The primary is the winding that has the excitation voltage applied.

Let's look at an application circuit, Figure 4. Note that with transformers, voltages are always specified in RMS (Root Mean Square) units, unless specifically noted otherwise. 120V RMS, (169.7V pk) is applied to the primary, and the two secondaries have 10V RMS each on the output, 180 degrees out of phase with each other. Example waveforms are shown in Figure 5.

It is important to realize that an ideal transformer has no losses; large ones in the 10 MW range are manufactured with efficiencies greater than 99%![1] (Smaller transformers in the range of 10 VA to several hundred VA will have some losses, albeit small ones.) For a first approximation, you can say that $Power_{input} \cong Power_{output}$. This means that while voltages are scaled by the ratio

[1] There is a manufacturer of transformers in the MVA range that purportedly has one that achieves 99.7% efficiency at full load. I have seen it manufactured and tested, and the numbers are believable.

of turns, currents are scaled by the inverse ratio of turns. Let's say that an excitation voltage, *V1*, is applied to a primary of *N1* turns, and we observe the conditions on a secondary with *N2* turns. We will measure the voltage at the secondary as *V2*. Similarly, the currents in the primary and secondary will be *I1* and *I2* respectively. It is important to note that in addition to translating voltage levels, that a transformer also adds isolation between the primary and secondary windings, i.e. there is not direct electrical connection – the coupling is entirely magnetic.

We can then say the following:

$$\frac{V1}{V2}=\frac{N1}{N2},\frac{I1}{I2}=\frac{N2}{N1} \tag{1.1}$$

Application of the transformer to an AC to DC power supply

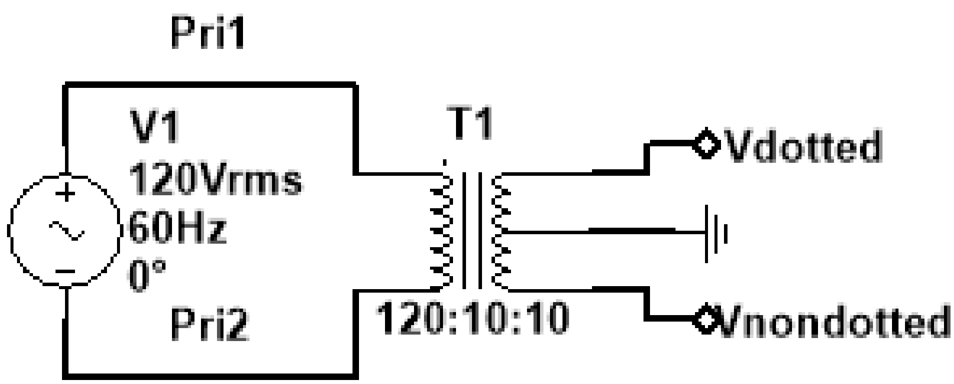

Figure 4 Transformer application circuit.

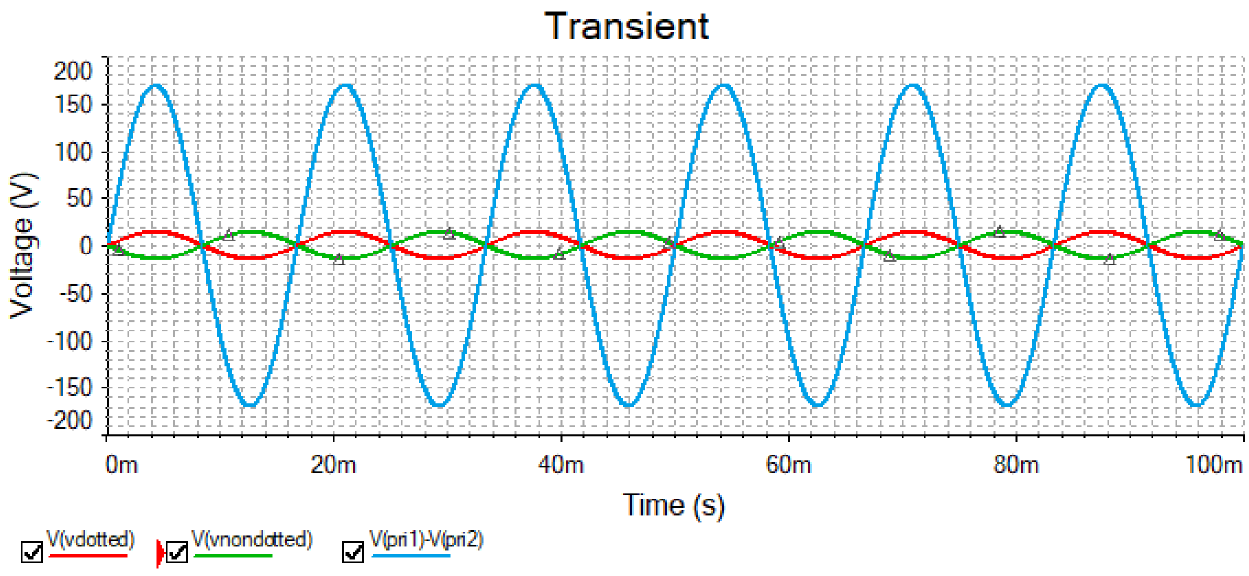

Figure 5 Transformer Waveforms

We now have a lower voltage A.C. waveform – still not too useful for powering our smartphones, but a step closer. We can employ a diode (rectifier) to isolate the positive voltage excursions as shown in Figure 6 and we will now get a waveform that never goes negative as shown in Figure 7.

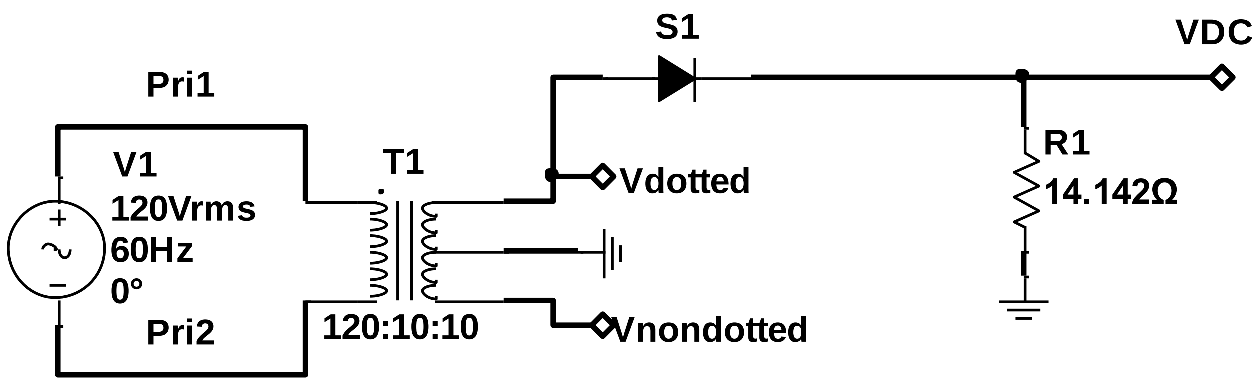

Figure 6 Rectifier and Load Added

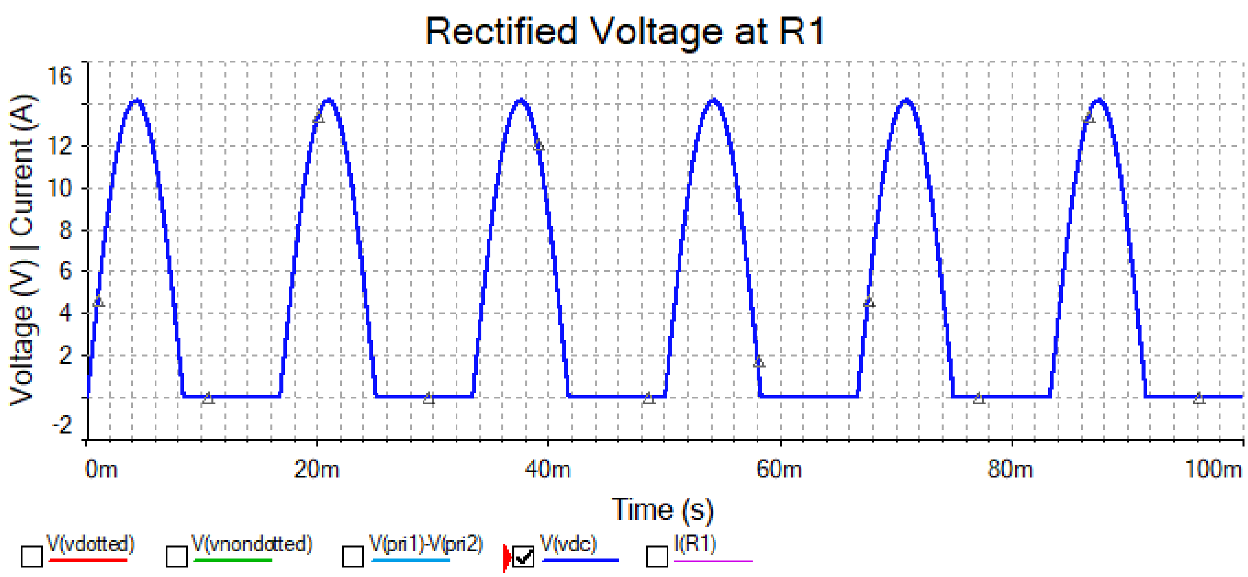

Figure 7 Rectified voltage at R1

Note that we are dealing with sinusoidal waveforms, and in that case (and that case only!) we can say the following:

$$Vpeak = VRMS \cdot \sqrt{2} \tag{1.2}$$

If we had an ideal diode for the rectifier, then that would also be the peaks of the waveforms for the rectified signal as well. However, ideal diodes are not readily available. [2] In power supply design we normally use the **C**onstant **F**orward **V**oltage **D**rop (*CFVD*) model, typically 0.7 to 0.8 Volts.[3] In this case we can say:

$$VPeak_{rectified} = \left(VRMS \cdot \sqrt{2}\right) - CFVD \tag{1.3}$$

At least this waveform has no negative excursions, but it is still not suitable for powering a small portable device; they really need a steady voltage. What can we do? We can see in Figure 7 that the diode is supplying energy to the resistor for a portion of each cycle, and from that we might conclude that we need something to store energy and deliver it to the resistor whenever the diode is not conducting. You have studied two fundamental devices that store energy: inductors and capacitors. Either could actually be used for this scenario, but capacitor supplies are more easily understood, and more widely used, so we will consider them for this document. We will add the capacitor as shown in Figure 8.

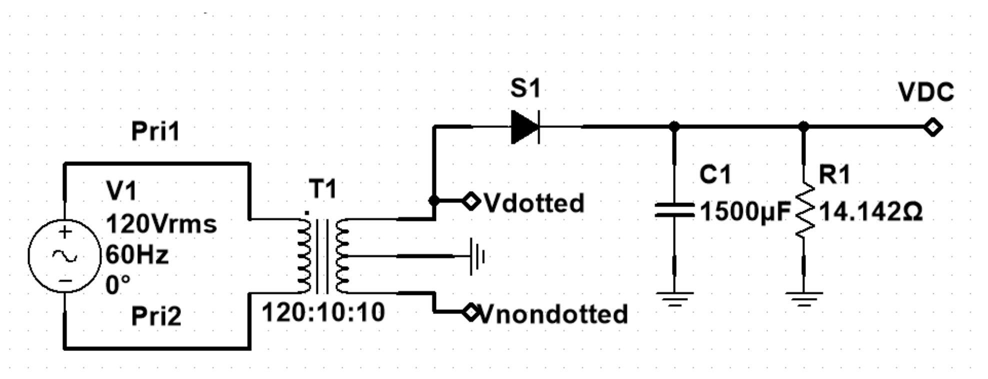

Figure 8 Added Capacitor

What does this buy us? Referring to Figure 9 we can see that the capacitor charges up to the peak value of the rectified voltage – we are using a *CFVD* of 0.7V – and then discharges into the load. We have clearly improved the situation, as the output voltage never goes to 0, but it is not perfectly

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[2] Theoretically a good approximation can be synthesized using MOSFETs and suitable control circuitry, but that is for another day.

[3] Manufacturer data sheets are a very useful for discovering this voltage. It does indeed vary with current, and for a conservative design, you should look at the voltage drop at the maximum instantaneous current expected, and use that for the CFVD value.

steady. For many applications, this situation is acceptable. Let's consider some variables, and start putting together a way to analyze and design circuits like this.

The time between charging peaks, *T*, is related to the line frequency. In this circuit the capacitor gets recharged once every AC cycle, which for the U.S. is 1/60 of a second.

$$T = \frac{1}{LineFrequency} \tag{1.4}$$

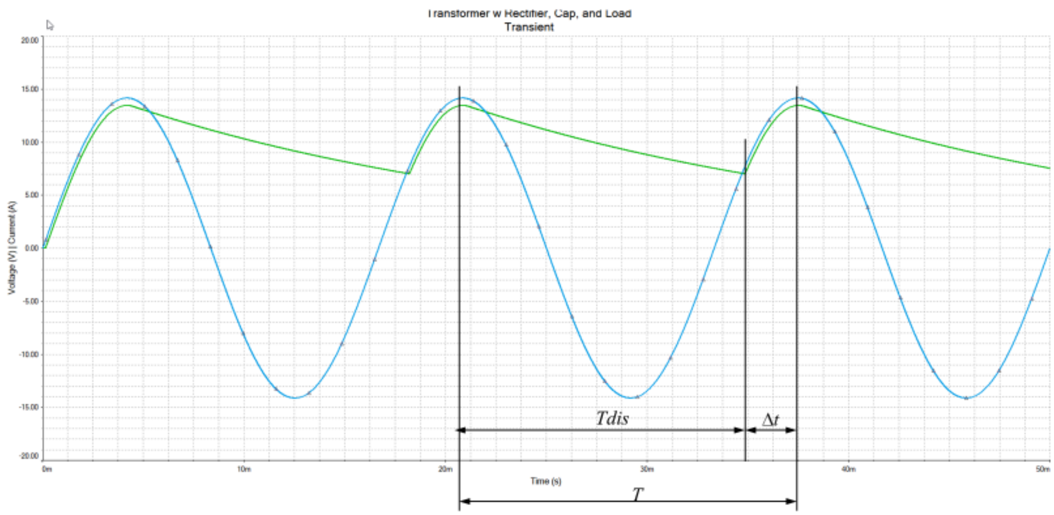

Figure 9 AC and DC waveforms

The length of the discharge is *Tdis*, and the total length of the recharge period is Δt .

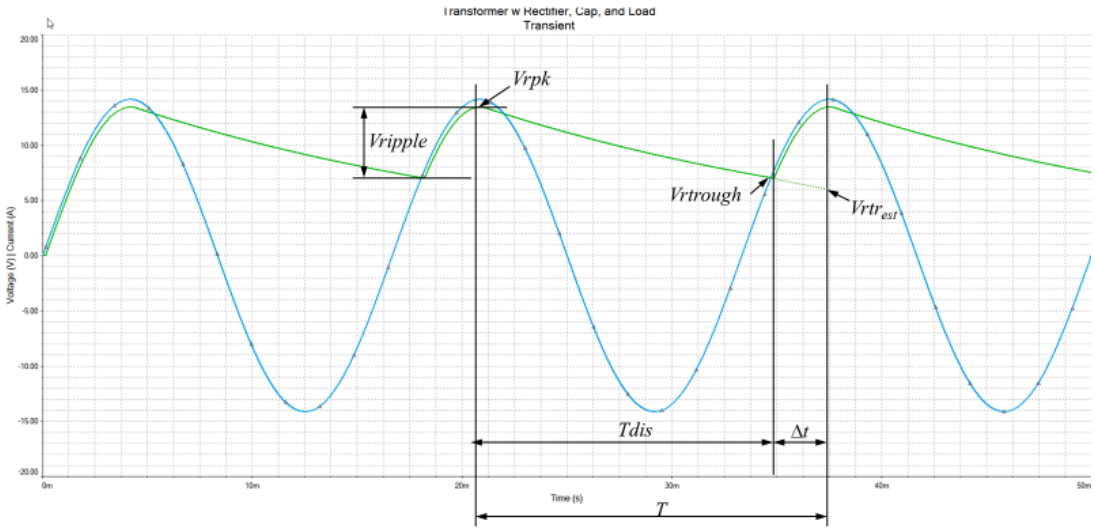

Figure 10 Ripple Voltages

Examining Figure 10, we can start to come up with some techniques for *estimating* the DC voltages. Why not an exact solution? The "exact" solution is actually very tedious, and frequently the most important variable is the ripple trough voltage, *Vrtrough*. Also, we will ultimately need to design one using standard size components, and that gives us a constraint on possible solutions. Finally, we may need to consider variations in line voltages and component tolerances. All of this points us to the notion that an "exact" solution may not be necessary, as long as we can come up with conservative estimates for the circuit values.[4] Note that in the US, the nominal line voltage is 120V, but carries a tolerance of $+/-10\%$, meaning that your line voltage could be as low as 108V or as much as 132V and still be considered "normal"

Equation (1.3) gives us the value for the peak voltage on the capacitor, and for a given line voltage, transformer, and diode, we are stuck with that. *C'est la vie*. Note that we can say by inspection of Figure 10 that $Vripple = Vrpk - Vrtrough$. What we need is a way to estimate the ripple trough voltage, just before the capacitor starts to recharge. Let's look at some approximations that will get us there. In a well designed power supply, we can say the following:

$$\Delta t \ll T, Tdis \simeq T \tag{1.5}$$

If that is the case then we can estimate *Vrtrough* as:

$$Vrtrough \simeq Vrtr_{est} \tag{1.6}$$

[4] Working with constraints and estimating values is an important general engineering principle!

Note that with this approximation, the actual measured value of *Vrtrough* will always be less than our estimated value and therefore this will be a conservative estimate. We now need to estimate the rate of discharge of the capacitor. Recall the following, from basic electrical theory:

$$Vcap = \frac{Q}{C}, \frac{dV_{Cap}}{dt} = \frac{dQ_{Cap}}{dt} \cdot \frac{1}{C} = \frac{I_{Cap}}{C} \tag{1.7}$$

(Note that I might play fast and loose with signs!)

Now we need a conservative estimate for the capacitor current during discharge. In a circuit with a resistance load, we know that the cap is following an exponential discharge and therefore the capacitor current is varying with time. However, if want a conservative estimate value for the capacitor current, we can simply assign the discharge current of the capacitor as:

$$I_{CAP} \simeq \frac{Vrpk}{Rload} \tag{1.8}$$

This estimates a value for the capacitor discharge current as being somewhat greater than it really is, but again this is conservative. This gets us to the following:

$$Vrtrough = Vrpk - \left(\frac{Vrpk}{Rload} \cdot \frac{1}{C} \cdot T \right) = Vrpk \cdot \left(1 - \frac{T}{Rload \cdot C} \right) \tag{1.9}$$

Current Waveforms

From a cursory examination of (1.9), we might conclude that in order to reduce the ripple voltage, we simply make the capacitor very large and we are through. However, TANSTAAFL[5] comes into play, and so we must also consider the current waveforms during the charge cycle, i.e. Δt . Referring to Figure 11, we can see that there is quite a ratio of the peak currents in the diode relative to the average load current in the resistor – ~ 9x!

[5] "There ain't no such thing as a free lunch" - This is widely associated with the science fiction writer Robert Heinlein. He used the term several times in his 1966 novel *The Moon is a Harsh Mistress*. In other words, in engineering everything has a cost, including performance metrics.

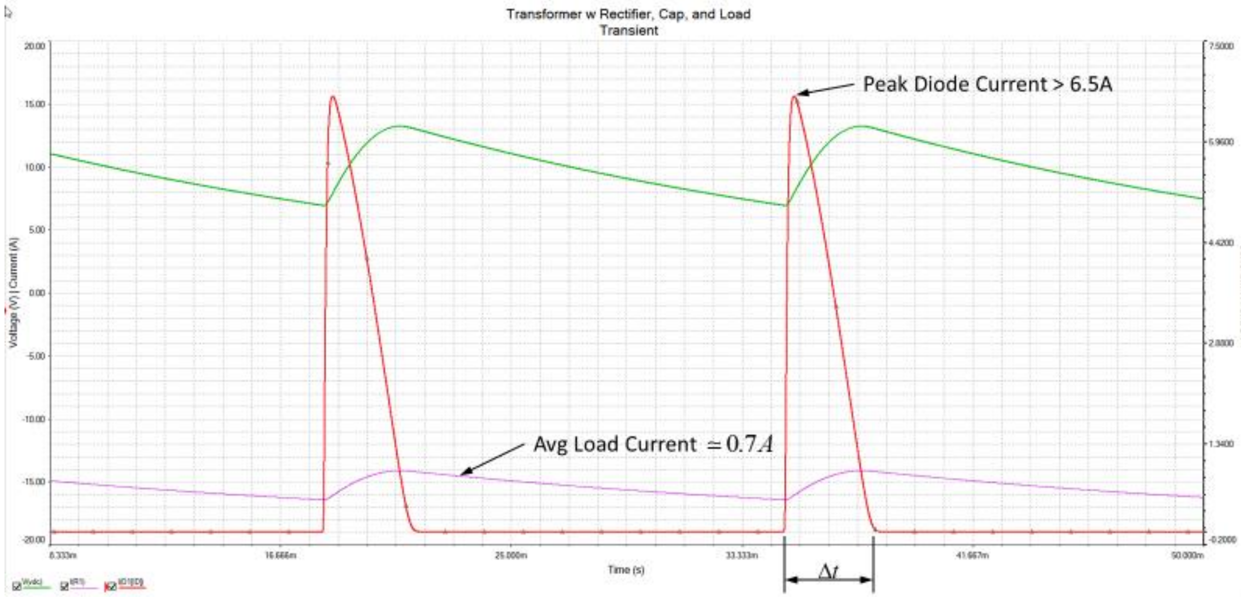

Figure 11 Current Waveforms in Diode and R Load

From basic charge balance, we can surmise that all of the charge delivered to the load over time *T*, must be supplied by the diode during the small "on time", Δt. In Figure 12, we have plotted the output voltage, and the peak diode currents for several values of capacitance. We can see that as the ripple voltage is decreased by increasing the capacitance, the peak diode currents rise sharply. Clearly there must be a relationship between the peak diode current, the ripple voltage, the capacitor value, and Δt. Also, note that the diode currents are approximately triangular in shape.

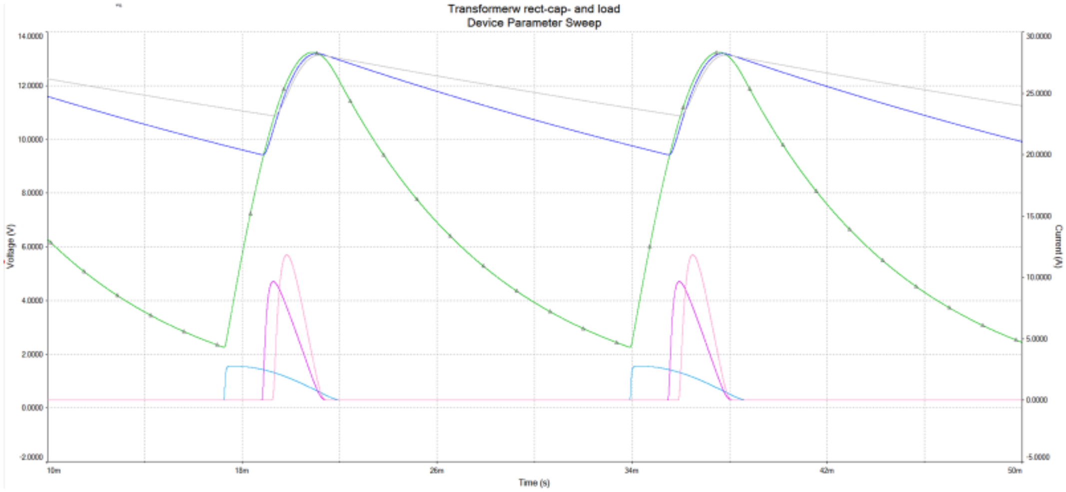

Figure 12 Peak Diode Currents and Load Voltage for increasing values of capacitance, C1

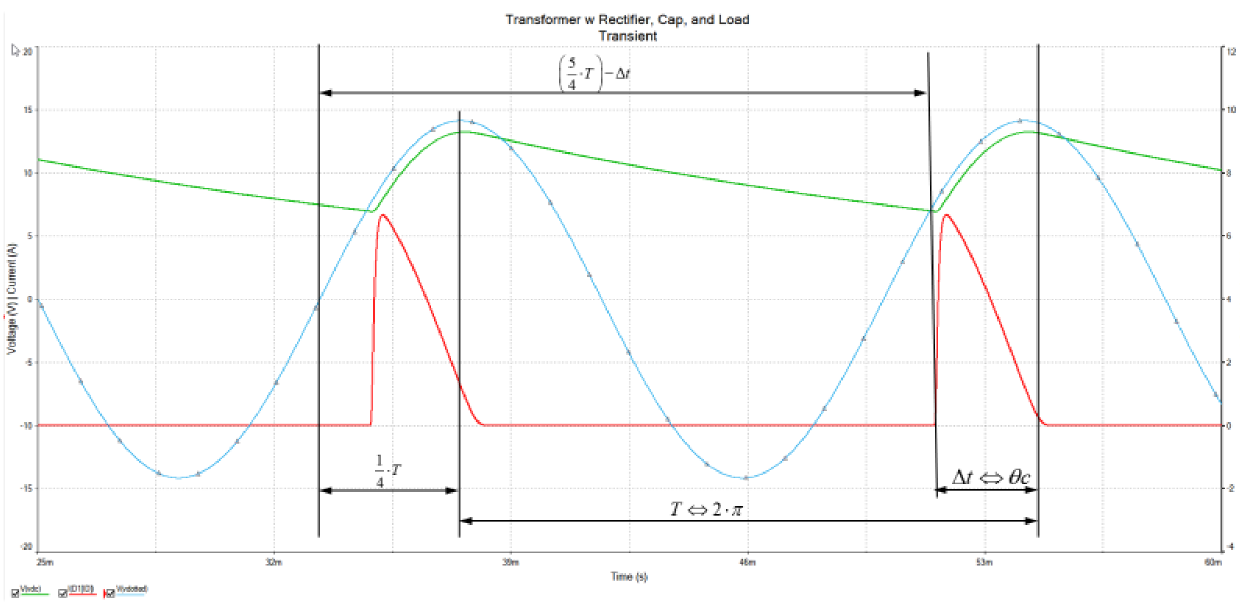

Figure 13 Time relationship & radian angles

Referring to Figure 13, we have defined some key time intervals, and expressed those in terms of radians. θc is the conduction angle in radians, corresponding to Δt .

Now some identities:

$$T \leftrightarrow 360^{o} \leftrightarrow 2\cdot\pi, \frac{\Delta t}{T} = \frac{\theta c}{2\cdot\pi} \tag{1.10}$$

Pushing on a bit further:

$$\Delta t = \frac{\theta c}{2\cdot\pi}\cdot T = \frac{\theta c}{2\cdot\pi}\cdot\frac{1}{f} = \frac{\theta c}{\omega}, where \rightarrow \omega = 2\cdot\pi\cdot f \tag{1.11}$$

If $f = 60HZ$ then $\omega = 377\,{}^{R}\!/_{S}$.

Putting this all together gives us the following – note the *VACpk* is *Vdotted* in our schematic above:

$$Vripple = Vrpk - Vrtrough = \left[VACpk - CFVD\right] - \left[VACpk\cdot\sin\left(2\cdot\pi\cdot f\left({}^{5}\!/_{4}\cdot T - \Delta t\right)\right) - CFVD\right] \tag{1.12}$$

That looks pretty intimidating but it can be reduced further with the aid of trig identities.[6]

$$Vripple = VACpk - VACpk\left(\sin\left({}^{5}\!/_{2}\cdot\pi - \theta c\right)\right) = VACpk - VACpk\cdot\cos\left(\theta c\right) \tag{1.13}$$

We are getting close, but we still need something more manageable to be useful. An excellent tool is the Taylor series.[7] For small θc the Taylor series for a cosine function is:

$$Taylor(\cos) = 1 - \frac{\theta c^{2}}{2!} + \frac{\theta c^{4}}{4!} - \ldots \tag{1.14}$$

Of course, the 3rd term is tiny compared to the first 2 so we can say:

$$Vripple = VACpk - VACpk\left(1 - \frac{\theta c^{2}}{2}\right) = VACpk\left(\frac{\theta c^{2}}{2}\right) \tag{1.15}$$

We can rearrange to solve for θc and Δt :

$$\theta c = \sqrt{\frac{2\cdot Vripple}{VACpk}}, \Delta t = \frac{1}{\omega}\sqrt{\frac{2\cdot Vripple}{VACpk}} \tag{1.16}$$

Since we can calculate *Vripple* from our charge and discharge equations, (1.9) we have a mechanism for computing the conduction angle and that allows us to finally use the charge balance relations to calculate the peak diode current.

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[6] I have a bit if a love-hate feeling about trig identities. It always seems that you need to know the answer to get the answer!

[7] This tool is supremely useful for linearizing trig or transcendental functions over a relatively small range. It is too bad that math classes typically just use it as a form of student torture.

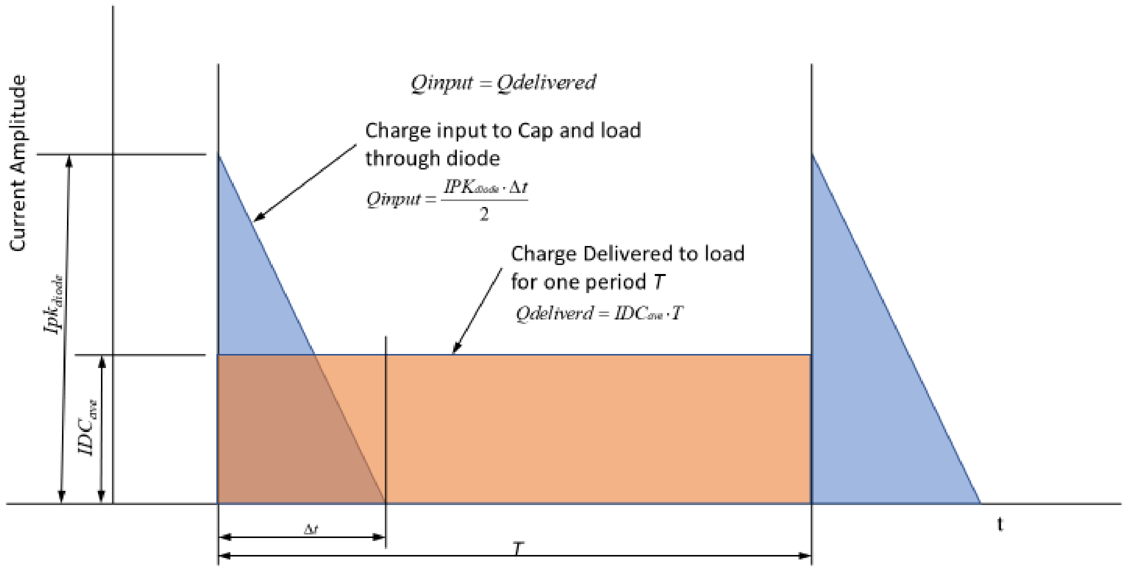

Figure 14 Timing relations for charge and current

From Figure 14 we can see the current and charge relations for 1 cycle, *T*. Over 1 cycle, the charge delivered to the load is represented by the orange rectangle. The charge input to the capacitor and load is modeled as the light blue triangle, which is very close to the waveshape of the observed signals. Charge balance requires that the input and delivered charges must be equal. This lets us develop the following relation:

$$\frac{Ipk_{diode} \cdot \Delta t}{2} = IDC_{average} \cdot T \quad (1.17)$$

Note that in this relationship, the charge *in* is modeled as a triangle, which is exceptionally easy to integrate! The charge *out* is modeled as a rectangle, which is even easier.[8] Also note the we can conservatively estimate $IDC_{average} \simeq \frac{Vrpk}{Rl}$

Let's do an example:

Specifications

- Transformer secondary 8.31V, RMS
- Rectifier CFVD 0.8V
- Capacitor 1000uF

[8] The above relations are derived from Jaeger and Blalock.

- Load resistor, Rl - 45Ω

Operating Conditions:

$$VACpk = 8.31 \cdot \sqrt{2} = 11.76V \ , \ Vrpk = 11.76 - 0.8 = 10.96V$$

We can conservatively estimate the load current : $ILoad_{est} = \frac{Vrpk}{RLoad} = \frac{10.96}{45} = 243mA$

Armed with this we can conservatively estimate the ripple voltage:

$$Vripple = \frac{10.96}{45} \cdot \frac{1}{1000uF} \cdot \frac{1}{60} = 4V \text{ , and } Vrtrough = 10.96 - 4 = 6.96V$$

We also have enough information to calculate the diode currents and the conduction interval, Δt .

$\theta c = \sqrt{\frac{2 \cdot 4}{11.76}} = 0.83R \Rightarrow 47.3^{o}$, $\Delta t = \frac{\theta c}{\omega} = \frac{0.83}{377} = 2.2mS$ Finally we can get the peak diode current using (1.17). $Ipk_{diode} = \frac{ILoad_{est} \cdot 2 \cdot T}{\Delta t} = \frac{243mA \cdot 2 \cdot \frac{1}{60}}{2.2mS} = 3.6A$!

Improvements and Modifications

There are some issues with AC to DC power supplies designed using this paradigm, and their application is usually only for small supplies with very limited output current. So what are the issues?

The first is the relatively high ratio of peak diode currents to average load currents. This places constraints on the diode selection, and transformer ratings. Since the current pulses are not sinusoidal, but triangular, this also causes harmonic distortion of the line currents; this is generally frowned upon by electric utilities. There is another subtle but serious problem – with a single diode rectifying the AC from the transformer, current is drawn during only one half of each complete cycle. This in turn means that there is a DC component of current drawn from the transformer and this can lead to a phenomenon referred to as "magnetic saturation" of the core material. This will cause the transformer to heat and in extreme cases can disturb the AC line.[9]

Fortunately, even with these simple supplies, we can ameliorate the situation somewhat. We could reduce the peak to average current ratio if we could recharge the capacitor more often. Also, it would be nice if we could draw current on both half-cycles of the AC waveform, which would eliminate DC components in the transformer. Here is a simple improvement:

[9] Transformers and other power grid components are considered in some detail elsewhere.

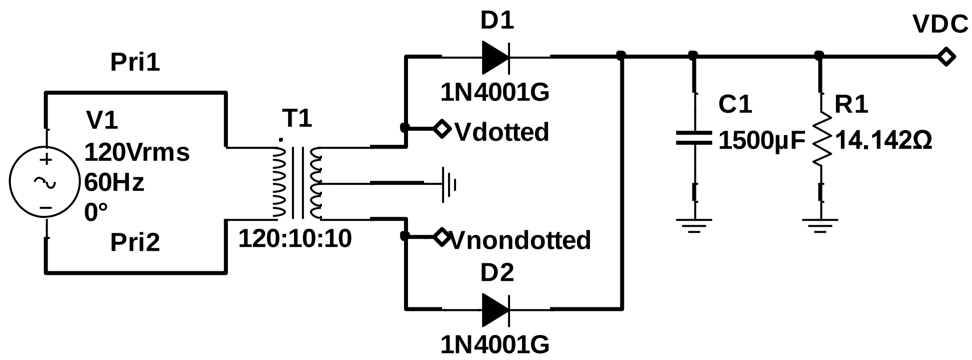

Figure 15 Full wave center-tapped power supply

We have added an additional rectifier to the *Vnondotted* phase coming from the transformer as shown in Figure 15. Since this phase is 180 degrees from the other one, diode *D2* can conduct when *D1* is off and vice-versa. This automatically doubles the number of times that the capacitor can be recharged for each complete AC cycle, and reduces ripple and peak currents accordingly. It also employs both half-cycles of the AC line and eliminates and DC component of the current signal. Let's see how it works:

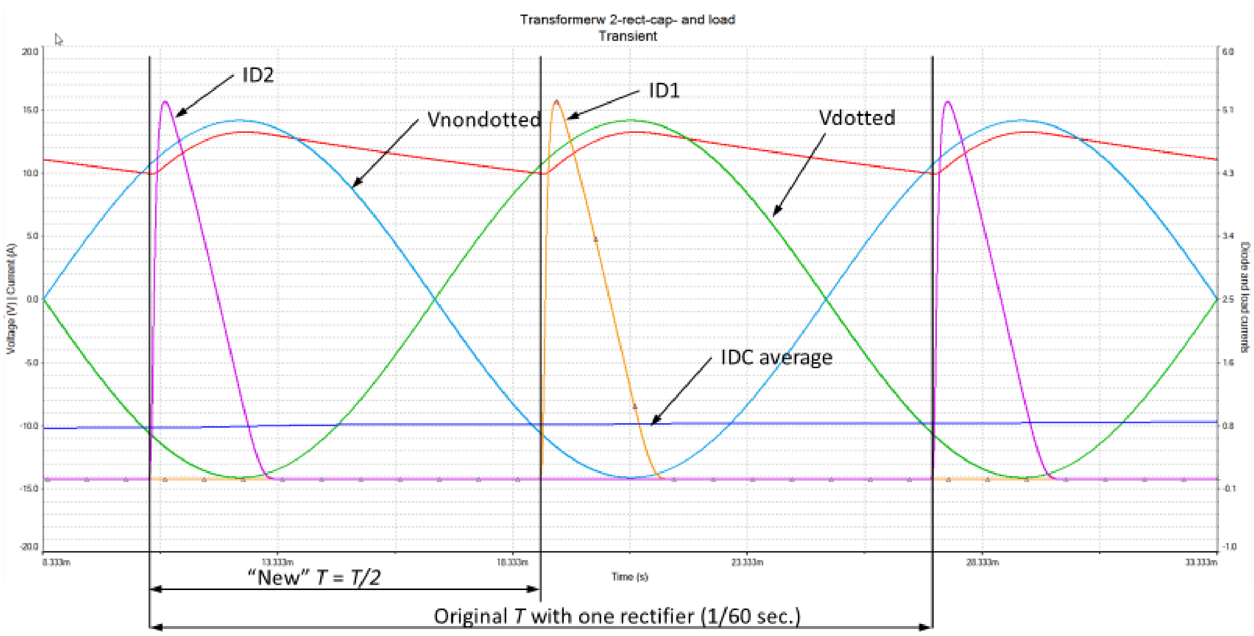

Figure 16 Current and Voltage waveforms - Full Wave center tapped

Referring to Figure 16, we can see that now we have 2 current pulses to recharge the capacitor in time *T*. We can use all of our previous calculations for ripple etc., just assuming a new value of *T* for the full-wave case as:

$$T_{fw} = \frac{T}{2} = \frac{1}{60 \cdot 2} = \frac{1}{120}\text{Sec} = 8.3333mS \tag{1.18}$$

Note that everything else stays the same for ripple and current calculation purposes. In the example above, note that the peak currents have gone down to slightly over 5 amps, and that the average load current is now slightly over 0.8 amps. Also the ripple trough is now 10 volts as compared to 7 volts for the single diode case of Figure 11. If we examine Figure 17 we can see that the currents in the transformer primary are symmetric, and of equal values in each polarity, indicating that there is no DC component in the transformer windings, and hence no saturation of the magnetic core material.

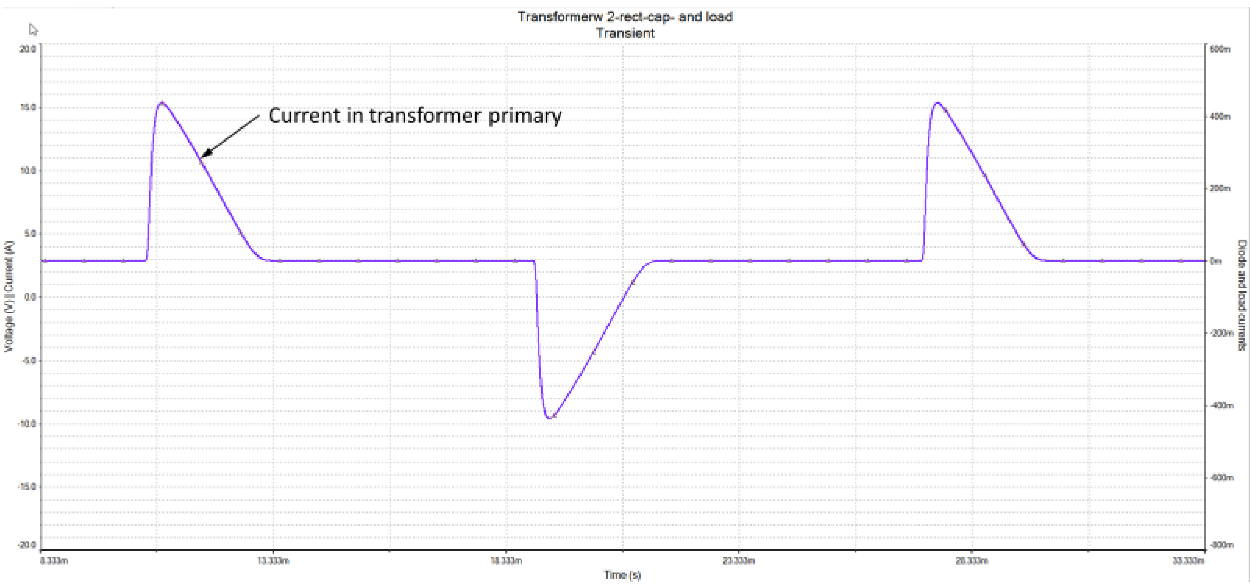

Figure 17 Transformer Currents

Voltage Regulation

Can we do even better? (Yes) We notice in all of our calculations so far that there is always some voltage ripple, and the cost of reducing that ripple is very high, especially when we consider the implications of very high diode currents. Fortunately, this is such a prevalent problem that IC manufacturers have come up with voltage regulator chips. These devices take a varying voltage at the input, and as long as a minimum specification for *Vrtrough* is met, they produce a constant regulated output voltage over a wide range of output currents and input voltages. Let's take a look at a conceptual diagram of what is in one:

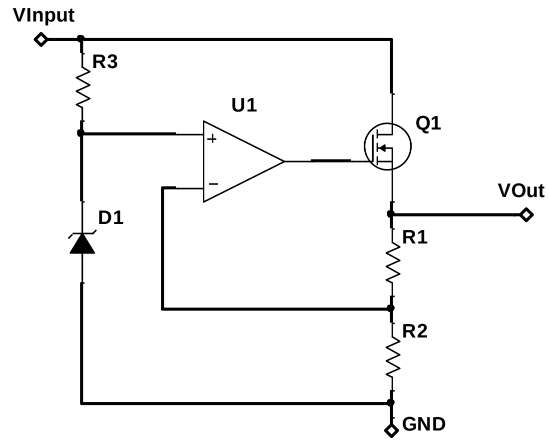

Figure 18 Conceptual Diagram of a 3 terminal voltage regulator

Note that there only 3 terminals, *VInput*, *VOut*, and *GND*. Ironically this class of regulator chip is referred to as a "3 terminal regulator". A great example is the LM78L05.[10] Conceptually, there is a "pass transistor", Q1, whose conduction is controlled by the voltage at the gate terminal. A fraction of the output voltage is taken from the voltage divider consisting of R1 and R2 and fed back to the inverting input of the opamp, U1. R3 and D1 form a voltage reference circuit that maintains a precision constant voltage over a wide range of inputs. D1 is a special diode referred to as a "reference diode" or a Zener, and is manufactured such that it maintains a constant voltage across it in the reverse breakdown region. All of these components are integrated into a single chip and most also include some form of short circuit and over temperature protection as an integral part of their construction.

There are some operating parameters and specifications that must be considered. The first is the rated output current. This is the maximum current the device can deliver, and usually the load current can be anything from 0 to this maximum value. If the load is greater than that value, the device's internal protection circuitry will engage and limit the output. For the device above the rated current is 100mA.

[10] An extremely common device See : https://www.digikey.com/product-detail/en/texas-instruments/LM78L05ACZ-NOPB/LM78L05ACZNS-NOPB-ND/6333

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7.5 Electrical Characteristics — LM78L05

Typical values apply for T_J = 25°C, Minimum and Maximum limits apply for the entire operating temperature range of the package(1)(2), I_O = 40 mA, C_I = 0.33 µF, C_O = 0.1 µF, V_{IN} = 10 V (unless otherwise noted).

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
V_O	Output voltage	T_J = 25°C	4.8	5	5.2	V
		V_{IN} = 7 V to 20 V, I_O = 1 mA to 40 mA(3)	4.75		5.25	
		I_O = 1 mA to 70 mA(3)	4.75		5.25	
ΔV_O	Line regulation	V_{IN} = 7 V to 20 V, T_J = 25°C		18	75	mV
		V_{IN} = 8 V to 20 V, T_J = 25°C		10	54	
	Load regulation	I_O = 1 mA to 100 mA, T_J = 25°C		20	60	
		I_O = 1 mA to 40 mA, T_J = 25°C		5	30	
I_Q	Quiescent current	T_J = 25°C		3	5	mA
ΔI_Q	Quiescent current change	V_{IN} = 8 V to 20 V			1	mA
		I_O = 1 mA to 40 mA			0.1	
V_n	Output noise voltage	f = 10 Hz to 100 kHz(4)		40		µV
$\Delta V_{IN}/\Delta V_O$	Ripple rejection	f = 120 Hz, V_{IN} = 8 V to 16 V, T_J = 25°C	47	62		dB
I_{PK}	Peak output current			140		mA
$\Delta V_O/\Delta T$	Average output voltage temperature coefficient	I_O = 5 mA		–0.65		mV/°C
$V_{IN(MIN)}$	Minimum value of input voltage required to maintain line regulation	T_J = 25°C		6.7	7	V

(1) For the operating ranges of each package, see *Absolute Maximum Ratings*.
(2) Limits are ensured by production testing or correlation techniques using standard Statistical Quality Control (SQC) methods.
(3) Power dissipation ≤ 0.75 W.
(4) Recommended minimum load capacitance of 0.01 µF to limit high-frequency noise.

Figure 19 Specifications for LM78L05 from TI (see footnote)

There are some other important specifications. From the perspective of designing a supply to work with device, you will need to consider that *Vin(min)* specification, highlighted in Figure 19. For a conservative design, this spec tells us that under worst case conditions, *Vrtrough* must be greater than 7V. You may also have to consider the maximum input voltage, which is specified above as 20V. The quiescent current flows out of the *GND* pin, and for our purposes we may assume that is small enough to be negligible. What this means for us, in a practical sense, is that the current relationships at the input and output may be described as:

$$Iinput \simeq IOut \tag{1.19}$$

Consider the case of a load that is drawing 100mA at 5V output from the regulator. This means that the current drawn from the capacitor is now a constant 100mA, regardless of the input voltage. This means that we no longer have to approximate *ICap* as in (1.8) – we already know what it is! Also, we are no longer approximating the discharge as a straight line – it really is a straight line.

Let’s look at a typical circuit:

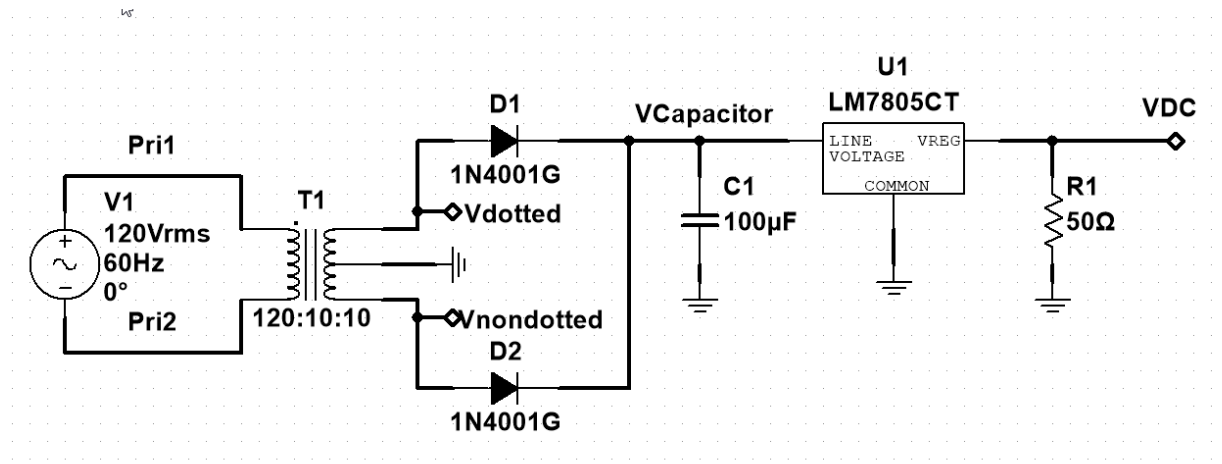

Figure 20 Typical 5V regulator circuit - delivering 100mA

We have employed a 7805 regulator, and have connected it to a load that will consume 100mA, as the output is constant. The input voltage to the regulator must be greater than 7V, so we have a really relaxed ripple voltage requirement. Furthermore, the capacitor may be greatly reduced which partially offsets the cost of the voltage regulator.

Referring to Figure 21 below, we can see that the waveform of the capacitor voltage is indeed a straight line, and is related to the constant output current. Also, with a very small capacitor, we have maintained a constant output voltage in the face of a very high input ripple voltage. Furthermore, the peak diode currents are now approximately 500mA, which is only a 5:1 ratio to the load current.

We need to also consider power dissipation in the regulator, and overall voltage conversion efficiency.

Since we are assuming that the input and out currents are equal, then we can think of the efficiency as:

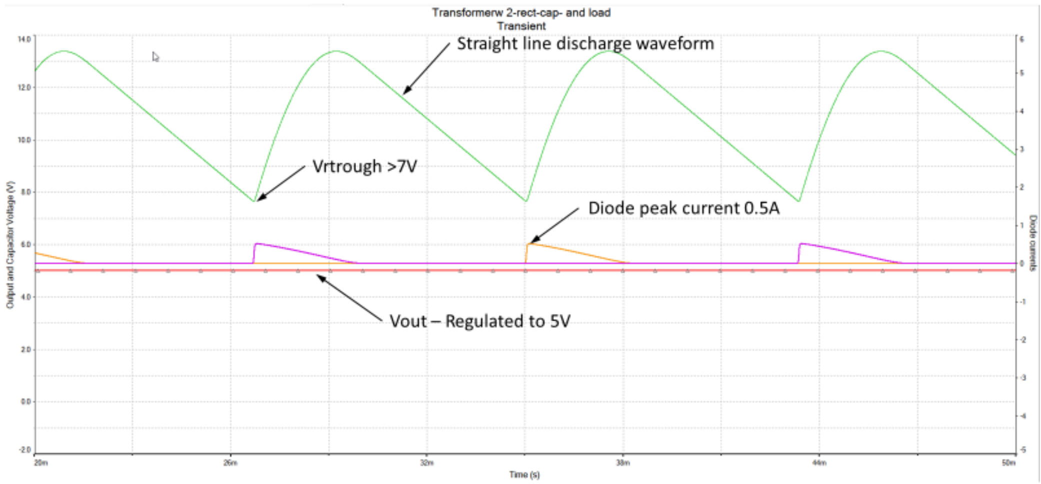

Figure 21 Voltage and Current Waveforms with Voltage Regulator

$$Efficiency = \frac{Pout}{Pin} = \frac{Vout \cdot Iout}{Vin \cdot Iout} = \frac{Vout}{Vin} \qquad \textbf{(1.20)}$$

We may need to consider the power rating of the device as well, i.e. how much power is dissipated in the regulator itself. This is especially important if you are contemplating a design that may require a heatsink.

$$PLoss = (Vin - Vout) \cdot Iout \qquad (1.21)$$

Note that *Vout* is defined by the regulator itself, but what is *Vin*? There are 2 reasonable scenarios. In the first you could calculate the RMS value of the DC input voltage, however you might need to consider how this would vary with load, as the ripple would vary with load. A more conservative approach is to assume that $Vin = Vrpk$.

There are a number of the other specifications that you may need to consider, however they tend to be more application specific. The most important for many day-to-day designs are the *Voltage Regulation* considerations, ΔVo, and the *Ripple Rejection*, $\frac{\Delta Vin}{\Delta Vo}$. Also, note that each manufacturer may express their specifications in a slightly manner, so careful reading of the spec sheet is a must!