A. Electronic Power Supplies

1. Low Voltage Unregulated Power Supplies

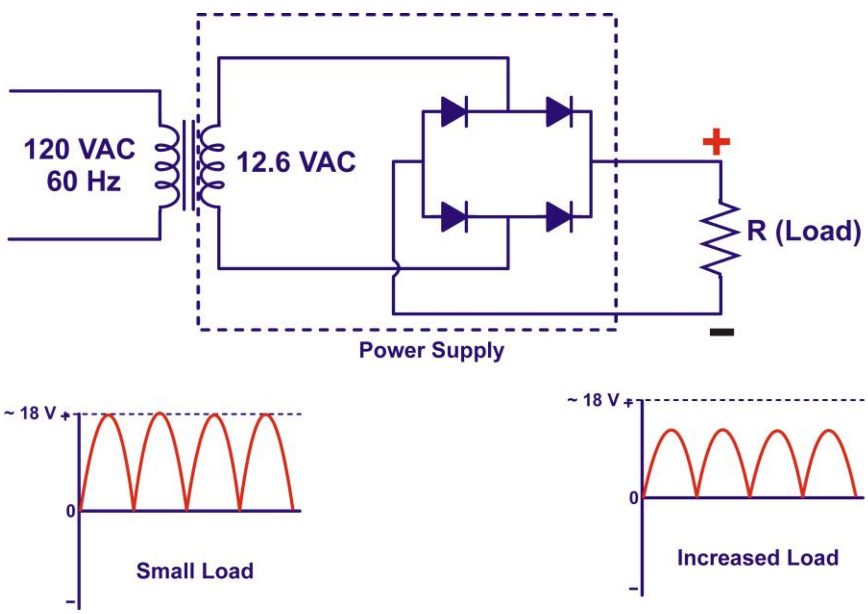

Figure 1, Power-Supplies-001 Basic Low Voltage Unregulated Power Supply

a. Refer to Figure "Power-Supplies-001". The source voltage is obtained from an AC line of 120 V. The transformer isolates and reduces the line voltage to 12.6 VAC. The four diodes form a full-wave rectifier.

b. The output voltage will vary, depending on the load. With a small load (load resistance higher than the internal resistance of the power supply), the output voltage will be around 18VDC. As the load resistance decreases below the internal resistance of the power supply, the output voltage will begin to drop. Notice the output has significant ripple (voltage increases and decrease similar to AC). It is possible that the load resistance can be so low that the components of the power supply will be damaged.

c. The effective operation of many circuits would be hampered by the ripple experienced in the simple power supply shown in Figure "Power-Supplies-001". To reduce the ripple, a filtering circuit is employed. The simplest is a single RC filter as shown in Figure "Power-Supplies-002".

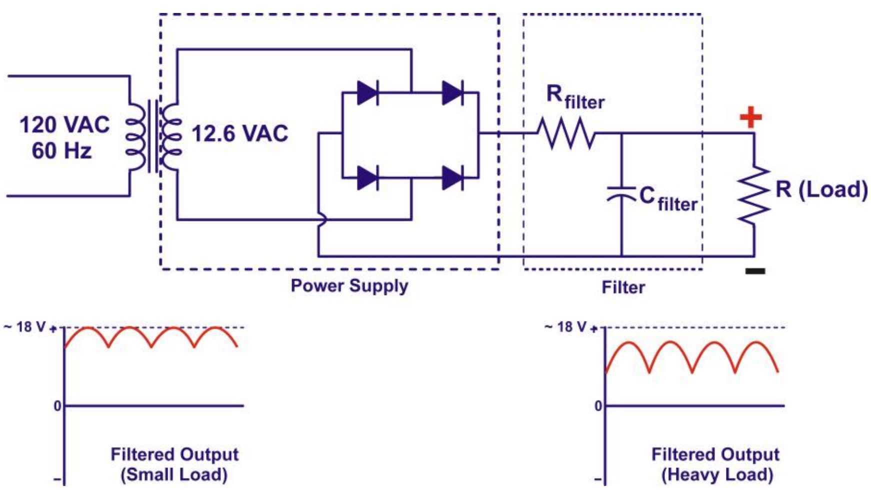

Figure 2, Power-Supplies-002 Basic Low Voltage Unregulated Filtered Power Supply

d. The value of R_{filter} is typically less than one tenth of the load resistance.

The value of C_{filter} will typically be in the hundreds of microfarads.

e. To reduce the ripple even further, a second RC network may be added as in Figure "Power-Supplies-003".

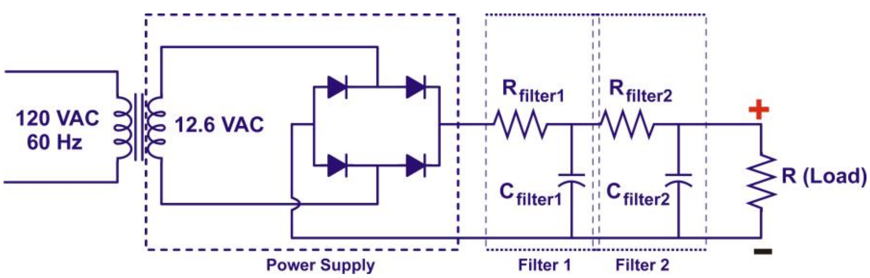

Figure 3, Power-Supplies-003 Basic Low Voltage Unregulated Double Filtered Power Supply

f. As many filter networks can be added as desired. However, each filter resistor added, increases the internal resistance of the power supply, thus reducing the voltage and current the supply is capable of delivering to the load.

g. Some circuits may be exposed to line noise and RF noise. The 12VDC system of an automobile typically has much noise. The supply to electronic devices for an automobile typically uses an inductor known as a choke to filter out such noise. The inductor acts like a high value resistor to the higher frequencies, yet a low (1 or 2 ohms or less) value resistor to the DC.

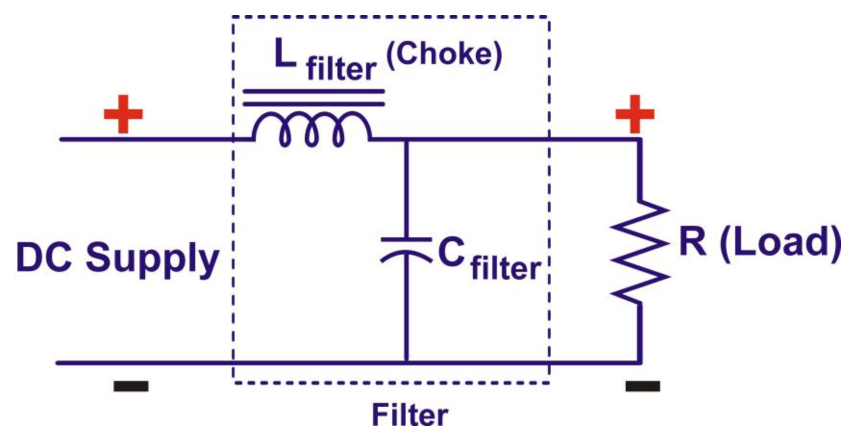

Figure 4, Power-Supplies-004 Choke and Capacitor Filter

2. Power Supply Regulation Circuits

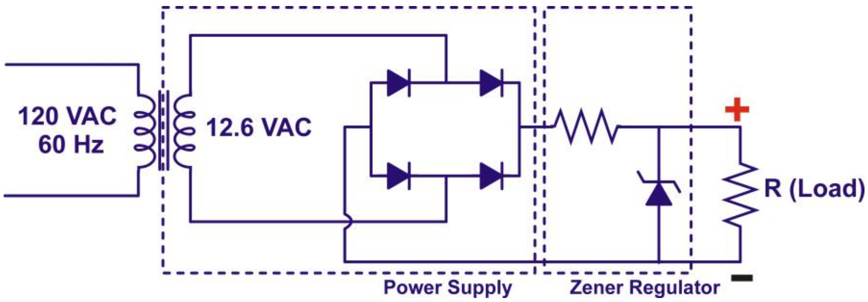

Figure 5, Power-Supplies-005 Zener Diode Voltage Regulated Power Supply

a. In the circuit of Figure "Power-Supplies-005", the voltage across the zener diode will remain constant regardless of how high the supply voltage is (within operating parameters of the diode). This in turn keeps the voltage across the load constant. The excess voltage is dropped across the resistor. If the supply voltage goes below the zener voltage, the diode can no longer regulate the voltage. It is possible to have a load resistance low enough to pull the voltage below the zener voltage. The power supply components must be sized for the load range.

b. Although this type of circuit works very well for some applications, it may not be stable enough for others. Some ripple will be seen by the load. It also has current limitations.

3. Zener Diode and Transistor Voltage Regulators

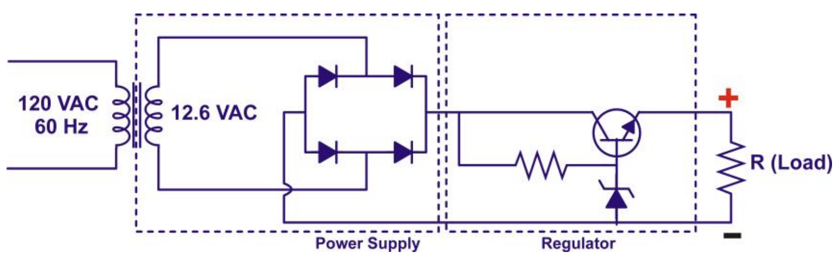

Figure 6, Power-Supplies-006 Zener Diode and Transistor Voltage Regulated Power Supply

a. In the circuit shown in Figure "Power-Supplies-006", the current capacity of the regulator is greatly increased by the use of the transistor. The base of the transistor is kept at a constant voltage by the zener diode. The base emitter junction drops about 0.5 to 0.7 volts. Therefore the voltage across the load will be about 0.5 to 0.7 volts higher than the zener voltage.

4. Integrated Circuit Voltage Regulator Circuits

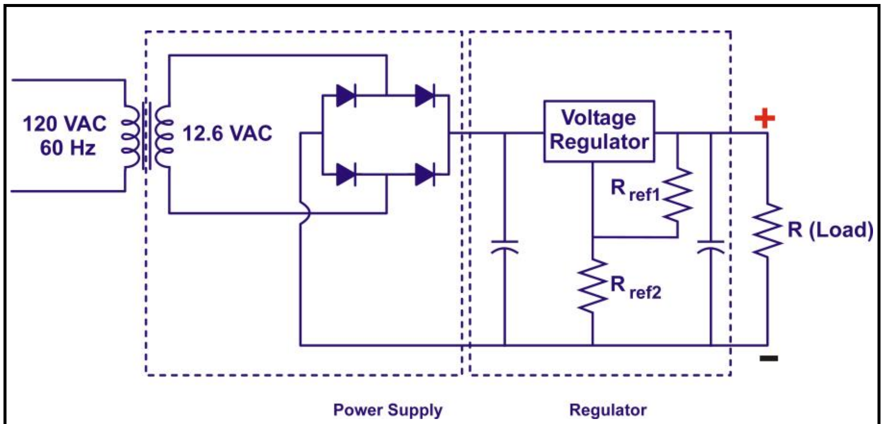

Figure 7, Power-Supplies-007 Three Terminal Semiconductor Voltage Regulated Power Supply

a. The circuit in Figure "Power-Supplies-007" provides a very stable output voltage at high currents. The current output is limited by the parameters of the Three-Terminal Voltage Regulator. The output voltage is set by the R_{ref1} and R_{ref2} voltage divider network. The lower the R_{ref2} value in comparison to the R_{ref1} value, the lower the output voltage.

b. The circuit in Figure "Power-Supplies-007" can be readily made into a variable output voltage regulated supply by simply making R_{ref2} variable as in Figure "Power-Supplies-008".

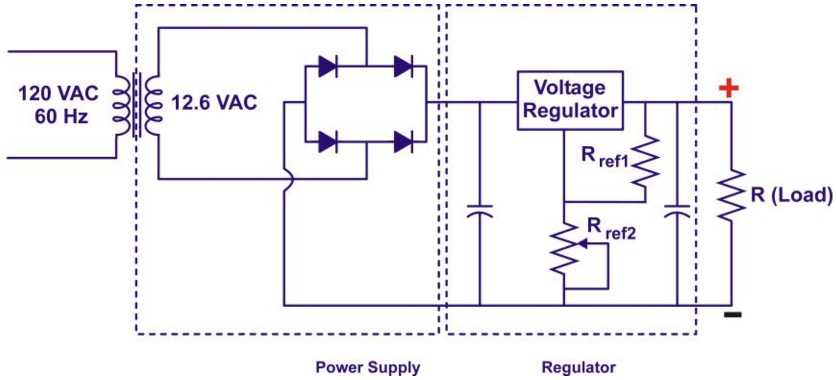

Figure 8, Power-Supplies-008 Three Terminal Semiconductor Variable Voltage Regulated Power Supply

5. High Voltage Power Supplies

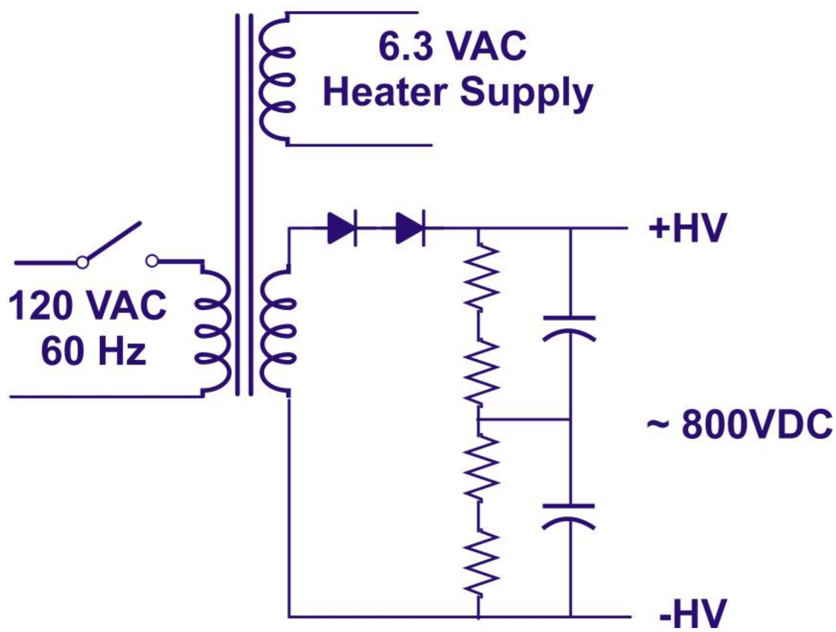

Figure 9, Power-Supplies-009 Simple Unregulated CRT High Voltage Power Supply

a. The circuit in Figure "Power-Supplies-009" supplies high (~800VDC) to a Cathode-Ray Tube (CRT). The CRT current demands very small and does not change (for all practical purposes). Therefore the ripple is negligible and the voltage level is very steady. Since the voltage is very steady, no voltage regulation is required. The low current drain also accounts for the need of only a half-wave rectifier. The dual in-line diodes are to split the high reverse voltage between the two diodes.

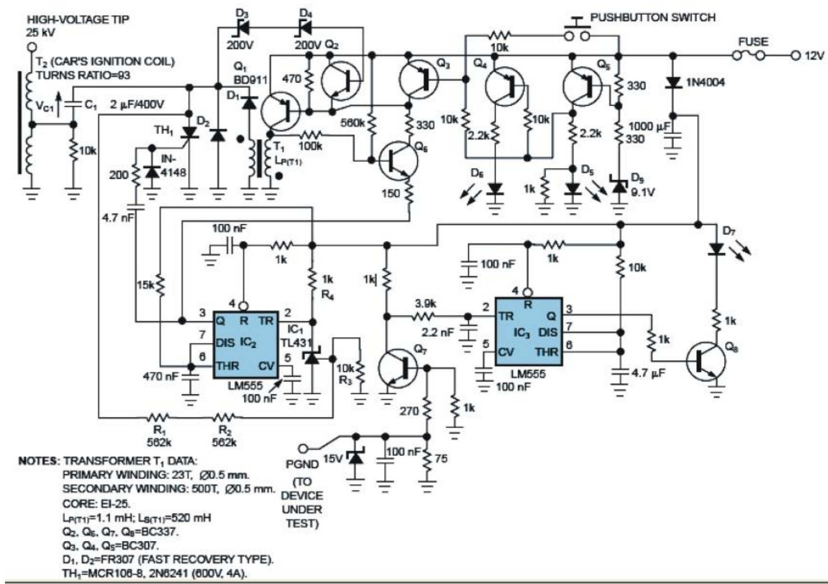

Figure 10, Power-Supplies-010 12VDC Supply to 25,000 Volt Power Supply Used To Test Electrical Insulation

b. Capacitive Discharge Ignition (CDI) System

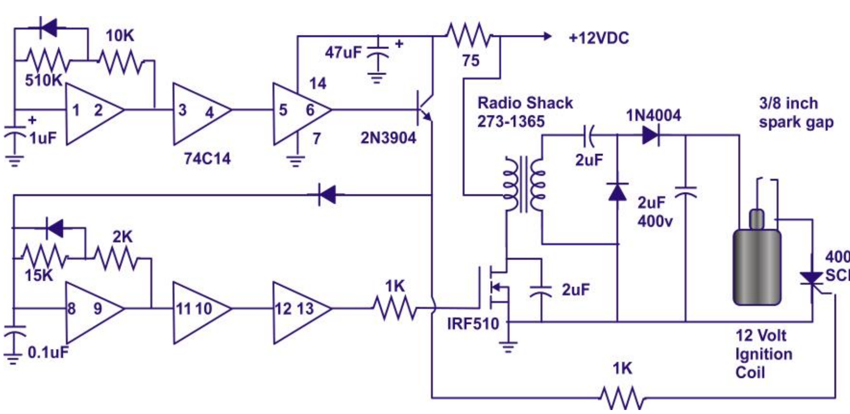

Figure 11, Power-Supplies-011 Capacitive Discharge Ignition System

c. The CDI circuit produces a spark from an ignition coil by discharging a capacitor across the primary of the coil. A 2µF capacitor is charged to about 340 volts and the discharge is controlled by an SCR. A Schmitt trigger oscillator (74C14) and MOSFET (IRF510) are used to drive the low voltage side of a small (120/12 volt) power transformer and a voltage doubler arrangement is used on the high voltage side to increase the capacitor voltage to about 340 volts. A similar Schmitt trigger oscillator is used to trigger the SCR about 4 times per second. The power supply is gated off during the discharge time so that the SCR will stop conducting and return to it's blocking state. The diode connected from the 3904 to pin 9 of the 74C14 causes the power supply oscillator to stop during discharge time. The circuit draws only about 200 milliamps from a 12 volt source and delivers almost twice the normal energy of a conventional ignition circuit. High voltage from the coil is about 10KV using a 3/8 inch spark gap at normal air temperature and pressure. Spark rate can be increased to possibly 10 Hertz without losing much spark intensity, but is limited by the low frequency power transformer and duty cycle of the oscillator. For faster spark rates, a higher frequency and lower impedance supply would be required. Note that the ignition coil is not grounded and presents a shock hazard on all of it's terminals. Use CAUTION when operating the circuit. An alternate method of connecting the coil is to ground the (-) terminal and relocate the capacitor between the cathode of the rectifier diode and the positive coil terminal. The SCR is then placed between ground and the +340 volt side of the capacitor. This reduces the shock hazard and is the usual configuration in automotive applications.

6. Inverters

a. Inverter circuits are used when a DC voltage higher than the DC supply voltage is needed or when there is a need to convert a DC supply voltage to an AC voltage. They also are used to isolate DC supplies from an AC line, especially when fairly high DC currents are needed. Inverters can supply the current needed without using large, heavy, and expensive transformers. Personal computer power supplies are inverters.

b. Switching power supplies offer higher efficiency than traditional linear power supplies. They can step-up, step-down, and invert. Some designs can isolate output voltage from the input.

c. A switching regulator is a circuit that uses a power switch, an inductor, and a diode to transfer energy from input to output. The power switch was the key to practical switching regulators. Prior to the invention of the Vertical Metal Oxide Semiconductor (VMOS) power switch, switching supplies were generally not practical. The inductor's main function is to limit the current slew rate through the power switch. This limits the otherwise high-peak current that would be limited by the switch resistance alone. The key advantage for using an inductor in switching regulators: when the inductor is used to drop voltage, it stores energy. This energy is can be expressed in Joules as a function of the current by: $E=1/2*L*I^2$.

d. A linear regulators uses a resistive voltage drop to regulate the voltage, losing energy (voltage drop times the current) in the form of heat. A switching regulator's inductor does have a voltage drop and an associated current but the current is 90 degrees out of phase with the voltage, so the energy is stored and can be recovered in the discharge phase of the switching cycle. This results in a much higher efficiency and much less heat.

e. The basic components of the switching circuit can be rearranged to form a step-down (buck), step-up (boost), or an inverter (flyback). These designs are shown in Figures "Power-Supplies-012" -A, -B, -C, -and -D respectively, where -C and -D are the same except for the transformer and the diode polarity. Feedback and control circuitry can be carefully nested around these circuits to regulate the energy transfer and maintain a constant output within normal operating conditions.

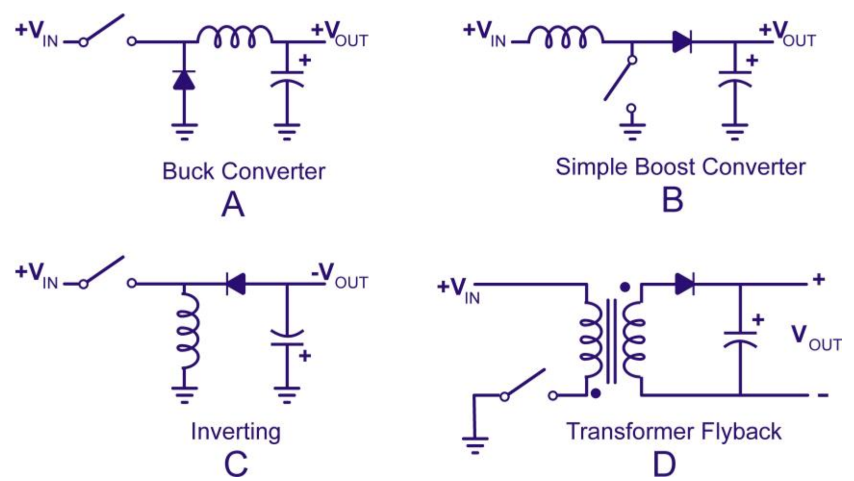

Figure 12, Power-Supplies-012 Convert Circuitry

f. **Why use Switching Regulators**? Switching regulators offer three main advantages compared to a linear regulators. First, switching efficiency can be much better than linear. Second, because less energy is lost in the transfer, smaller components and less thermal management is required. Third, the energy stored by switchers can be transformed to output voltages that can be greater than input (boost), negative (inverter), or can even be transferred through a transformer to provide electrical isolation with respect to the input (Figure "Power-Supplies-012" -D).

g. Given the advantages of switching regulators, one might wonder where would you use a linear regulator? Linears can provide lower noise and higher bandwidth; their simplicity can sometimes offer a less expensive solution.

h. There are, admittedly, disadvantages with switchers: they can be noisy and require energy management in the form of a control loop. Fortunately the solution to these control problems is found integrated in modern switching-mode controller chips.

i. **Charging Phase**: A basic boost configuration is depicted in Figure "Power-Supplies-013". Assuming that the switch has been open for a long time, the voltage across the capacitor is equal to the input voltage. When the switch closes, the input voltage, +VIN, is impressed across the inductor and the diode prevents the capacitor from discharging +VOUT to ground. Because the input voltage is DC, current through the inductor rises linearly with time at a rate proportional to the input voltage divided by the inductance.

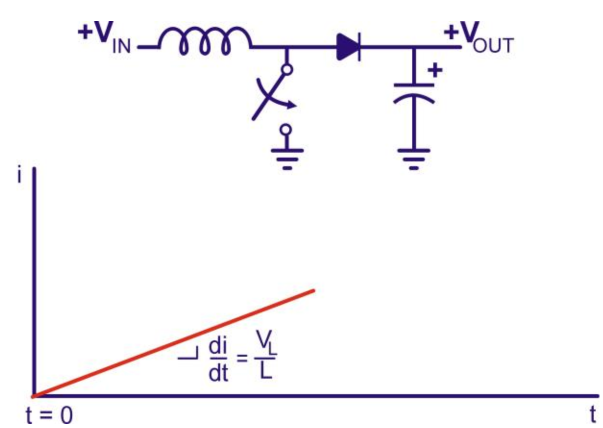

Figure 13, Power-Supplies-013 Boost Converter Charging Phase

j. **Discharge Phase**: Figure "Power-Supplies-014" shows the discharge phase. When the switch opens again, the inductor current continues to flow into the rectification diode to charge the output. As the output voltage rises, the slope of the current, di/dt, though the inductor reverses. The output voltage rises until equilibrium is reached or:

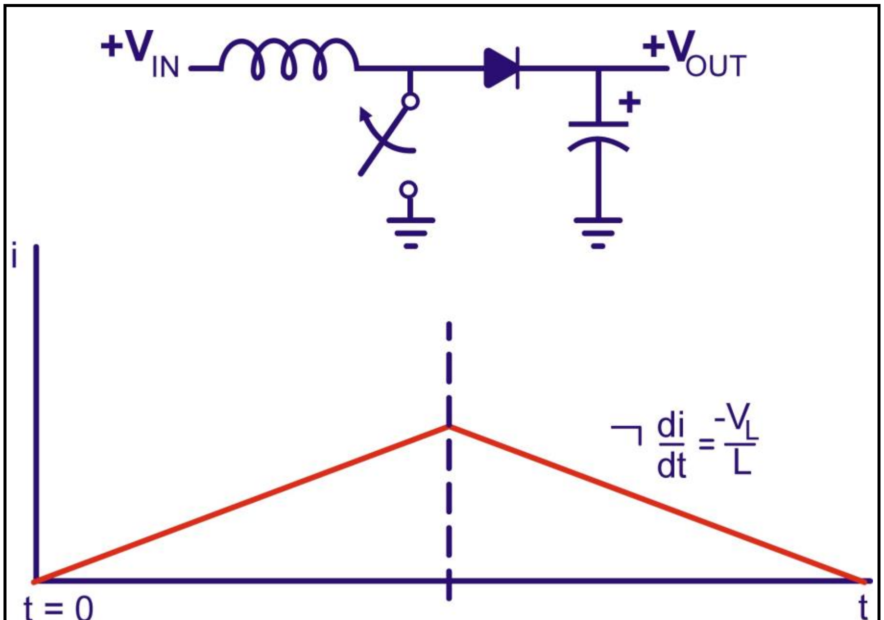

Figure 14, Power-Supplies-014 Boost Converter Discharge Phase

k. In a steady-state operating condition the average voltage across the inductor over the entire switching cycle is zero. This implies that the average current through the inductor is also in steady state. This is an important rule governing all inductor-based switching topologies. Taking this one step further, we can establish that for a given charge time, tON, and a given input voltage and with the circuit in equilibrium, there is a specific discharge time, tOFF, for an output voltage. Because the average inductor voltage in steady state must equal zero, we can calculate for the boost circuit:

l. $V_{IN} * T_{ON} = T_{OFF} * V_L$

m. and because:

n. $V_{OUT} = V_{IN} + V_L$

o. The relationship

p. $V_{OUT} = V_{IN} * (1 + t_{ON}/t_{Off})$ can be established. Using the relationship for duty cycle (D):

q. $t_{ON}/(t_{ON} + t_{Off}) = (D)$

r. Then for the boost circuit:

s. $V_{OUT} = V_{IN}/(1-D)$

t. Similar derivations can be had for the buck circuit:

u. $V_{OUT} = V_{IN} * D$

v. and for the inverter circuit (flyback):

w. $V_{OUT} = V_{IN} * D/(1-D)$

x. **Control Techniques**: From the derivations for the boost, buck, and inverter (flyback), it can be seen that changing the duty cycle controls the steady-state output with respect to the input voltage. This is a key concept governing all inductor-based switching circuits.

y. The most common control method, shown in Figure "Power-Supplies-015", is pulse-width modulation (PWM). This method takes a sample of the output voltage and subtracts this from a reference voltage to establish a small error signal (V_{ERROR}). This error signal compared to an oscillator ramp signal. The comparator outputs a digital output (PWM) that operates the power switch. When the circuit output voltage changes, V_{ERROR} also changes causing the comparator threshold to change. Consequently, the output pulse width (PWM) also changes. This duty cycle change then moves the output voltage to reduce to error signal to zero, thus completing the control loop.

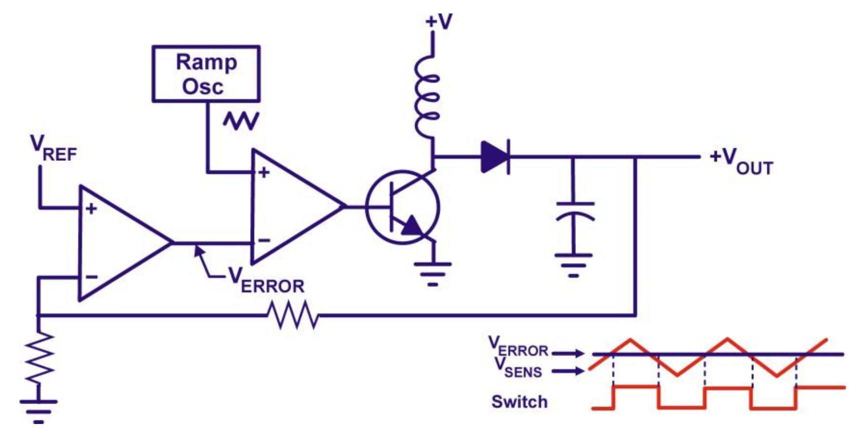

Figure 15, Power-Supplies-015 Varying Error Signal

z. Figure "Power-Supplies-016" shows a practical circuit using the boost topology formed with the MAX1932. This IC is an integrated controller with an onboard programmable digital-to-analog converter (DAC). The DAC sets the output voltage digitally through a serial link. R5 and R8 form a divider that meters the output voltage. R6 is effectively out of circuit when the DAC voltage is the same as the reference voltage (1.25V). This is because there is zero volts across R6 and so zero current. When the DAC output is zero (ground), R6 is effectively in parallel with R8. These two conditions correspond to the minimum and maximum output adjustment range of 40V and 90V, respectively.

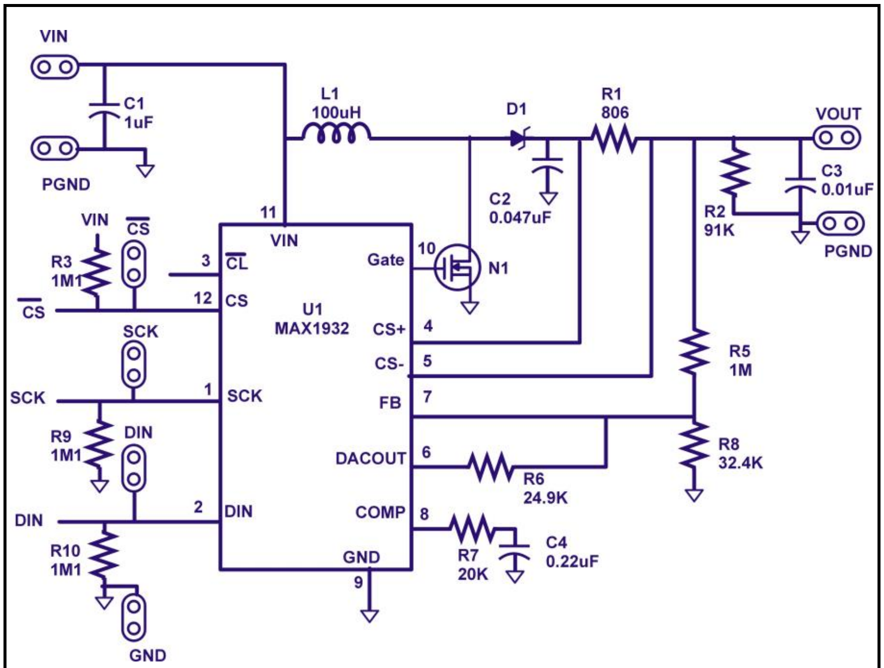

Figure 16, Power-Supplies-016 Integrated Boost Circuit

aa. Next, the divider signal is subtracted from the internal 1.25V reference and then amplified. This error signal is then output on pin 8 as a current source. This, in conjunction with the differential input pair, forms a transconductance amplifier. This arrangement is used because the output at the error amp is high impedance (current source) allowing the circuit's gain to be adjusted by changing R7 and C4. This provides the ability to trim the loop gain for acceptable stability margins. The error signal on pin 8 is then forwarded to the comparator and output to drive the power switch. R1 is a current-sense resistor that meters the output current. When the current is unacceptably high, the PWM circuit shuts down, thereby protecting the circuit.

bb. The type of switching (topology) in Figures "Power-Supplies-015 & 16" is classified as a voltage-mode controller (VMC) because the feedback regulates the output voltage. For analysis we can assume that if the loop gain is infinite, the output impedance for an ideal voltage source is zero.

Another commonly used type of control is current-mode control (CMC). This method regulates the output current and, with infinite loop gain, the output is a high-impedance source. In CMC, the current loop is nested with a slower voltage loop, as shown in Figure "Power-Supplies-017"; a ramp is generated by the slope of the inductor current and compared with the error signal. So, when the output voltage sags, the CMC supplies more current to the load. The advantage of CMC is its ability to manage the inductor current. In VMC the inductor current is not metered. This becomes a problem because the inductor, in conjunction with the output filter capacitor, forms a resonant tank that can ring and even cause oscillations.

cc. Current mode control senses the inductor current to correct for inconsistencies. Although difficult to accomplish, carefully selected compensation components can effectively cancel out this resonance in VCM.

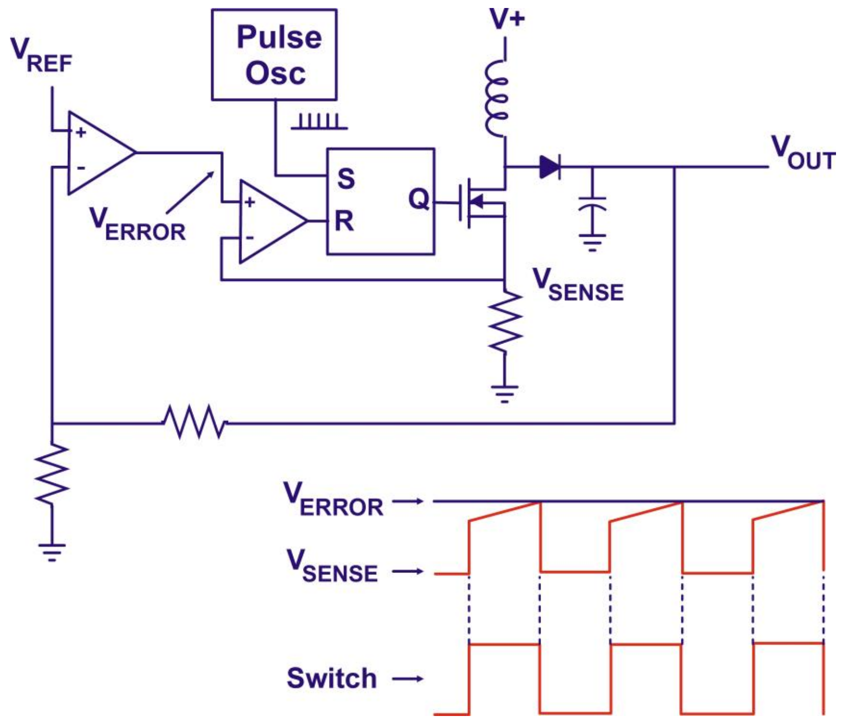

Figure 17, Power-Supplies-017 Current Mode Pulse Width Modulation

dd. The circuit in Figure "Power-Supplies-018" uses CMC with the MAX668 controller. This boost circuit is similar to Figures "Power-Supplies-015 & 16" except that R1 senses the inductor current for CMC. R1 and some internal comparators provide a current limit.

ee. R5 in conjunction with C9 filters the switching noise on the sense resistor to prevent false triggering of the current limit. The MAX668's internal current-limit threshold is fixed; changing the resistor, R1, adjusts the current-limit setting. The resistor, R2, sets the operating frequency. The MAX668 is a versatile integrated circuit that can provide a wide range of DC- DC conversions.

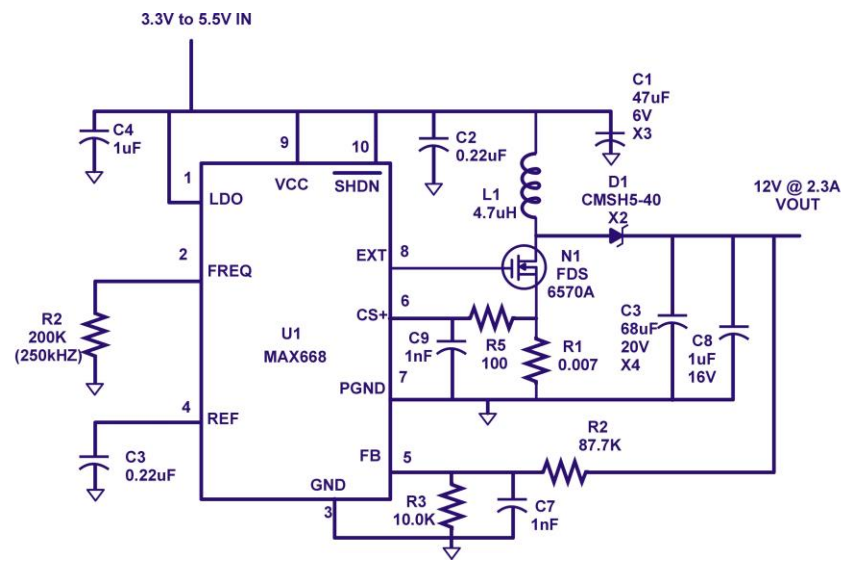

Figure 18, Power-Supplies-018 Current Controlled Boost Circuit

ff. Figure "Power-Supplies-019" shows a simplified version of a Quick-PWM architecture. To analyze this buck circuit, we start with the feedback signal below the regulating threshold defined by the reference. If there are no forward current faults, then the t_{ON} one-shot timer that calculates the on-time for DH is turned on immediately along with DH. This t_{ON} calculation is based on the output voltage divided by the input, which approximates the on-time required to maintain a fixed switching frequency defined by the constant K. Once the t_{ON} one-shot timer has expired, DH is turned off and DL is turned on. Then if the voltage is still below the regulating threshold, the DH immediately turns back on. This allows the inductor current to rapidly ramp up to meet the load requirements.

gg. Once equilibrium with the load has been met, the average inductor voltage must be zero. Therefore we calculate:

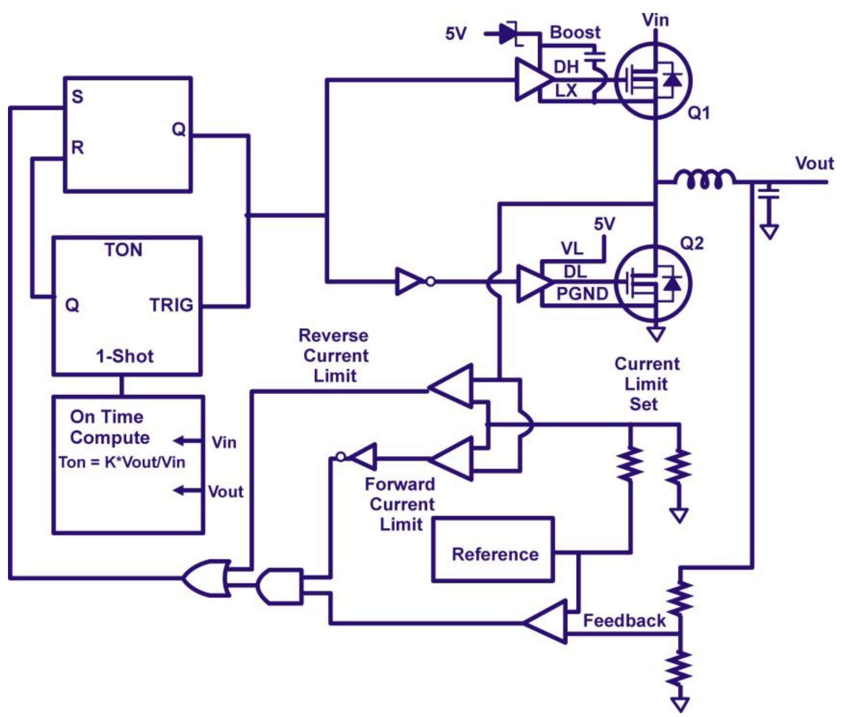

Figure 19, Power-Supplies-019 Block Diagram of Quick PWM Control (Maxim)

hh. $t_{ON} = (V_{IN} - V_{OUT}) = t_{OFF} * V_{OUT}$

ii. Rearrangin:

jj. $V_{OUT}/(V_{IN} - V_{OUT}) = t_{ON}/t_{OFF}$

kk. Adding 1 to both sides and collecting terms:

ll. $V_{OUT}/ V_{IN} = t_{ON}/(t_{ON} + t_{OFF})$

mm. Because the Duty Factor is D:

nn. $t_{ON}/(t_{ON} + t_{OFF}) = D$

oo. **For the Buck Circuit**: The Quick-PWM control method offers some advantages over PWM. Because Quick-PWM control generates a new cycle when the output voltage falls below the regulation threshold, heavy transients force the output to fall, immediately firing a new on-cycle. This result in a 100ns load-step response. It is also important to note that unlike the buck circuit in Figure "Power-Supplies-012", Figure "Power-Supplies-019", uses a MOSFET (Q2) instead of a diode for the discharge path. This reduces the losses associated with the diode drop, and the on-resistance of the MOSFET channel doubles as a current sense. Because output-voltage ripple is required to stimulate the circuit to switch, an output filter capacitor with some ESR is required to maintain stability. The Quick-PWM architecture can also respond quickly to line input changes by directly feeding the input voltage signal to the on-time calculator. Other methods must wait for the output voltage to sag or soar before action is taken, and this is often too late.

pp. A practical application of Quick-PWM is found in Figure "Power-Supplies-020". The MAX8632 is an integrated DDR memory power supply. Along with a Quick-PWM buck circuit (VDDQ), the MAX8632 integrates a high-speed linear regulator (VTT) to manage bus transients found in DDR memory systems. The linear regulator offers specific advantages over switchers because linears do not have an inductor to limit current slew-rate. This allows a very fast current slew rate to service load transients. Slower circuits would require large capacitors to provide load current until the power supply can ramp up the current to service the load.

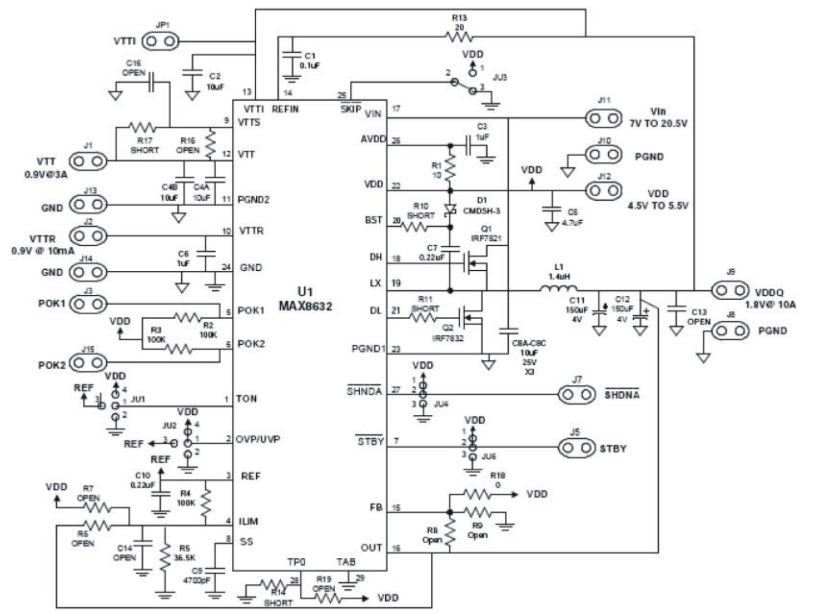

Figure 20, Power-Supplies-020 DDR Power Supply System (Maxim)

qq. **Efficiency**: One of the largest power-loss factors for switchers is the rectifying diode. The power dissipated is simply the forward voltage drop multiplied by the current going through it. The reverse recovery for silicon diodes can also create loss. These power losses reduce overall efficiency and require thermal management in the form of a heat sink or fan.

rr. To minimize this loss, switching regulators can use Schottky diodes that have a relatively low forward-voltage drop and good reverse recovery. For maximum efficiency, however, you can use a MOSFET switch in place of the diode. This is known as a 'synchronous rectifier' (see Figures "Power-Supplies-019,-020, & -021). The synchronous rectifier switch is open when the main switch is closed, and the same is true conversely. To prevent cross-conduction (both top and bottom switches are on simultaneously), the switching scheme must be break-before-make. Because of this, a diode is still required to conduct during the interval between the opening of the main switch and the closing of the synchronous-rectifier switch (dead time). When a MOSFET is used as a synchronous switch, the current normally flows in reverse (source to drain) and this allows the integrated body diode to conduct current during the dead time. When the synchronous rectifier switch closes, the current flows through the MOSFET channel. Because of the very low-channel resistance for power MOSFETs, the standard forward drop of the rectifying diode can be reduced to a few millivolts. Synchronous rectification can provide efficiencies well above 90%.

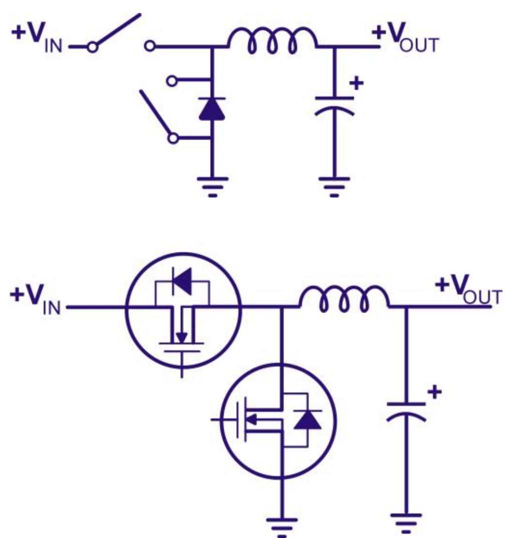

Figure 21, Power-Supplies-021 Synchronous Rectification For Buck Circuit

ss. **Skip Mode Improves Light Load Efficiency**: A feature offered in many modern switching controllers is skip mode. Skip mode allows the regulator to skip cycles when they are not needed, which greatly improves efficiency at light loads. For the standard buck circuit (Figure "Power-Supplies-012") with a rectifying diode, not initiating a new cycle simply allows the inductor current or inductor energy to discharge to zero. At this point the diode blocks any reverse-inductor current flow and the voltage across the inductor goes to zero. This is called 'discontinuous mode' and is shown in Figure "Power-Supplies-022". In skip mode, a new cycle is initiated when the output voltage drops below the regulating threshold. While in skip mode and discontinuous operation, the switching frequency is proportional to the load current. The situation with a synchronous rectifier is, unfortunately, somewhat more complicated. This is because the inductor current can reverse in the MOSFET switch if the gate is left on. The MAX8632 integrates a comparator that senses when the current through the inductor has reversed and opens the switch, allowing the MOSFET's body diode to block the reverse current.

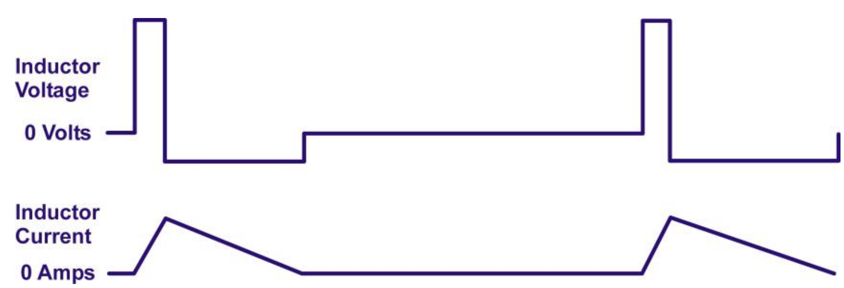

Figure 22, Power-Supplies-022 Discontinuous Mode Graphs

tt. Figure "Power-Supplies-023" shows that skip mode offers improved light-load efficiencies but at the expense of noise, because the switching frequency is not fixed. The forced-PWM control technique maintains a constant switching frequency, and varies the ratio of charge cycle to discharge cycle as the operating parameters vary. Because the switching frequency is fixed, the noise spectrum is relatively narrow, allowing simple lowpass or notch filter techniques to greatly reduce the peak-to-peak ripple voltage. Because the noise can be placed in a less sensitive frequency band, PWM is popular with telecom and other applications where noise interference is a concern.

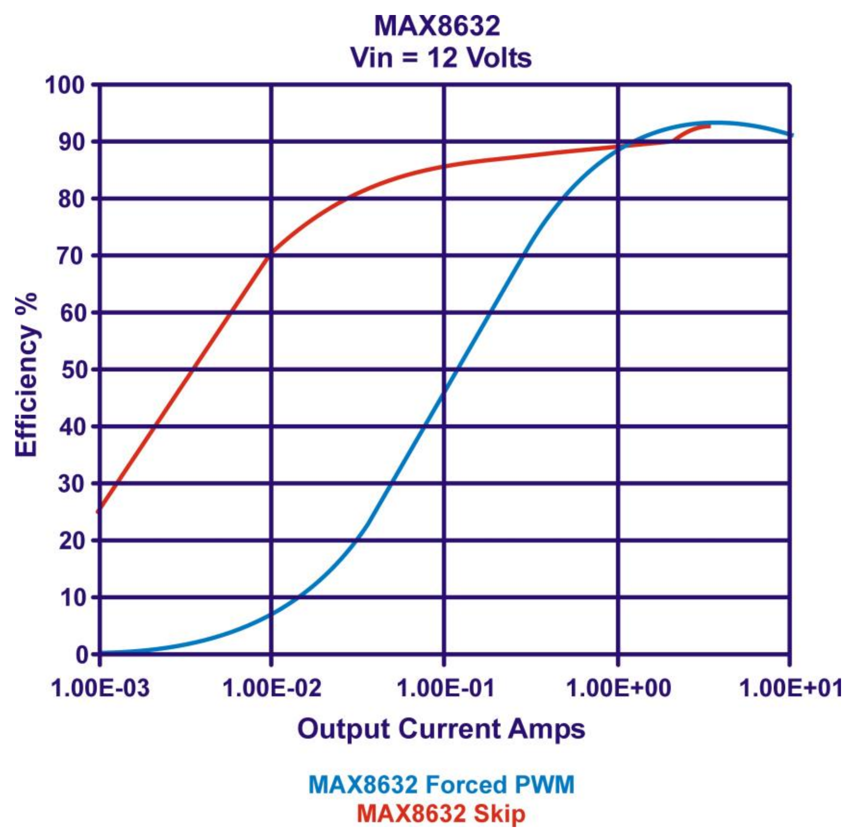

Figure 23, Power-Supplies-023 Efficiency Graphs

7. Vacuum Tube Power Supply

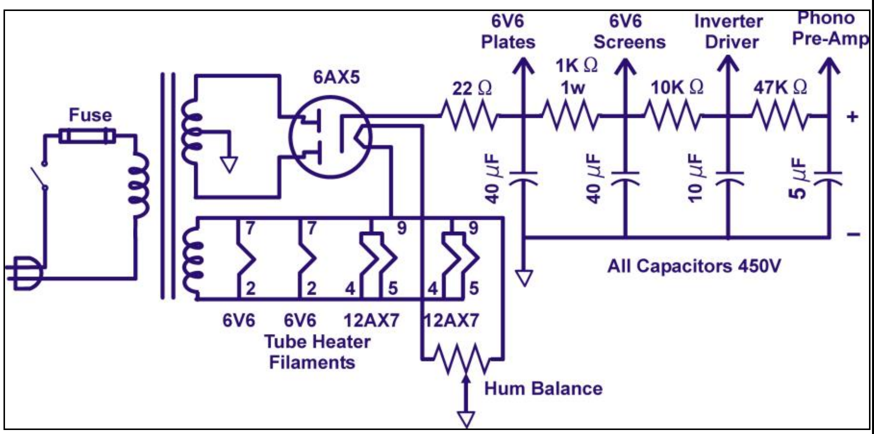

Figure 24, Power-Supplies-024 Vacuum Tube Amplifier Power Supply

a. Refer to the schematic diagram in Figure "Power-Supplies-024" throughout this description.

b. The transformer steps the line voltage up for B+ and down for heaters. This works by turns ratio. Let's say a given transformer has one secondary winding and it has 1/20 the number of turns on the secondary as on the primary. The voltage induced in the secondary will be (120 V) / 20 = 6 volts. If another transformer has 4 times as many turns on it's secondary as there are on it's primary the voltage will be 4 times 120 volts = 480 volts. The voltage a transformer will deliver is determined when it is manufactured and can't be changed.

c. The secondary at the bottom delivers 6.3 volts and for the particular tube lineup must have a current rating of at least 2.7 amps: 3 for a margin of safety. The hum balance control adjusts the voltages from each side of the heater winding to ground to be equal. Because they are equal in voltage and opposite in phase the magnetic and electric fields will tend to cancel each other out. This will considerably reduce the amount of hum in the amplifier's output.

d. The secondary at the top is the plate or B+ winding. It supplies a high voltage and the center tap (which is grounded) permits full wave rectification. The ground symbol often indicates nothing more than all of the points are connected together thus saving another line on a complex diagram.

e. When the top end of the winding goes positive the bottom end goes negative. The upper plate of the 6AX5 goes positive attracting electrons from the cathode. This causes a heavy electron current to flow between cathode and plate and the tube has a relatively low resistance. The lower, which is negative, plate repels the negatively charged electrons and no conduction takes place to this plate. When the next half cycle comes along the top plate will be negative and the lower one positive. The two plates take turns conducting current and conduction takes place over both halves of the cycle. If there were no capacitor the voltage would still fall to zero twice during each cycle as the input voltage passes through zero.

f. The 22 ohm resistor is a 1/4 watt unit and serves mainly as a fuse. It is omitted in many amplifiers but if you are building one I recommend its inclusion. A 1/4 watt resistor is only about 10 cents and a new rectifier tube can cost 3, 4, or 5 dollars. If a short develops the resistor will burn out saving the tube. The DC output voltage is given approximately by this equation.

g. Vdc = 1.4 x (Vac/2) - Rect Drop

h. Where Vdc is the DC output voltage across the first 40 microfarad capacitor, Vac is the voltage of the whole top secondary winding and Rect Drop can be determined by referring to the charts and graphs found in tube manuals. for this particular tube in this application the drop across the tube is approximately 140 volts. If the transformer has a 700 volt center tapped winding the output voltage will be 350 volts.

i. For example if the voltage of the upper winding is 430 volts the DC output voltage is Vdc = 1.4 x (500/2) - 140 = 210 volts.

j. The first capacitor charges up and holds the voltage up when it would otherwise drop to zero. There is some variation in the voltage as the capacitor is charged through the rectifier tube and discharges through the other tubes in the amplifier. The term for this variation is "ripple". The plates of the beam pentodes used in this, and most other amplifiers, are fairly immune to ripple in the plate voltage. Changing the voltage by 10 or 20 volts has a very small effect on the plate current. The voltage on the screen grid has a much larger effect. The 1 k ohm resistor and the second capacitor reduce the ripple voltage to much less than a volt.

k. The 10 k ohm resistor and the third capacitor reduce the ripple voltage to an even lower level but they perform a much more important function. That is to reduce variations in the DC voltage caused by low frequencies in the audio signal. These variations if fed to the earlier stages of the amplifier can act as signal and start low frequency oscillation sometimes called motor boating. The last resistor and capacitor serve the same function for the magnetic phono preamp. It is very sensitive to variations both line frequency ripple and variations from low frequency audio. These must be reduced to a few millivolts for the amplifier to work properly.