LECTURE 1

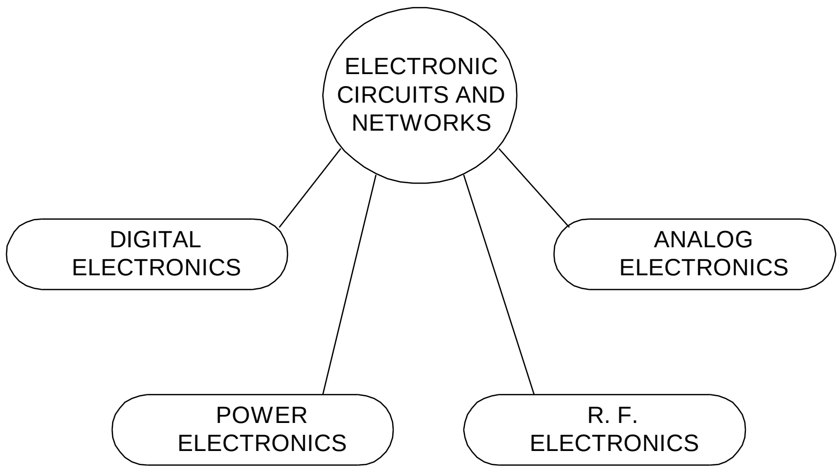
Overview of Power Electronics

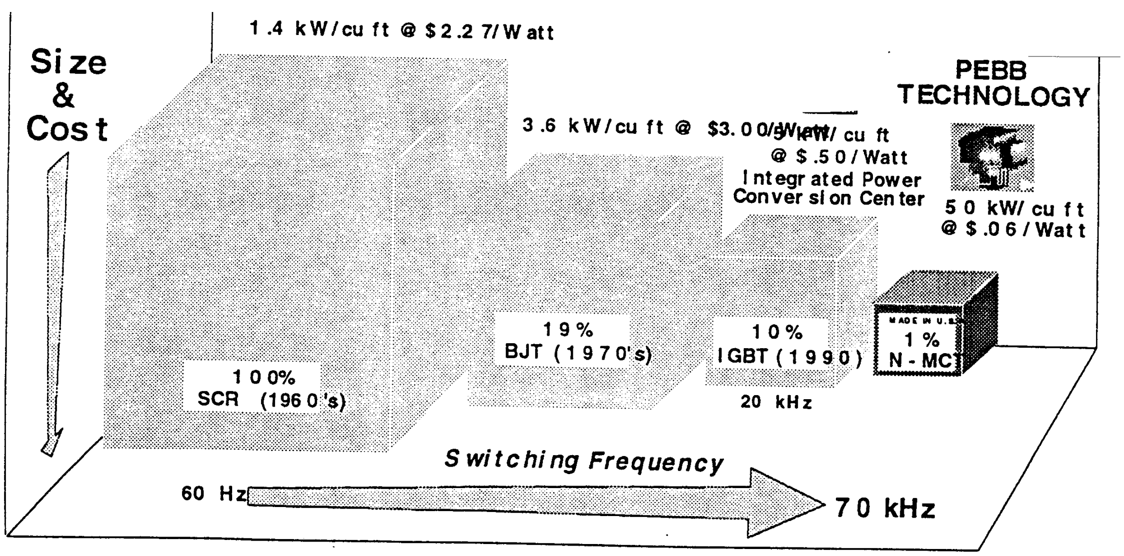
A. WHAT IS IT?
B. WHY DO IT?
C. HOW IS IT DONE: THREE GENERAL CIRCUIT TOPOLOGIES
   1. Linear Regulators
   2. Pulse Width Modulated Switching
   3. Resonant Switching?
D. SYSTEMS SPECIFICATIONS
E. AC-DC Conversion
F. SWITCH MODE POWER SUPPLIES

1. POWER ELECTRONICS or HEAVY INDUSTRY ELECTRONICS

A. WHAT IS IT?

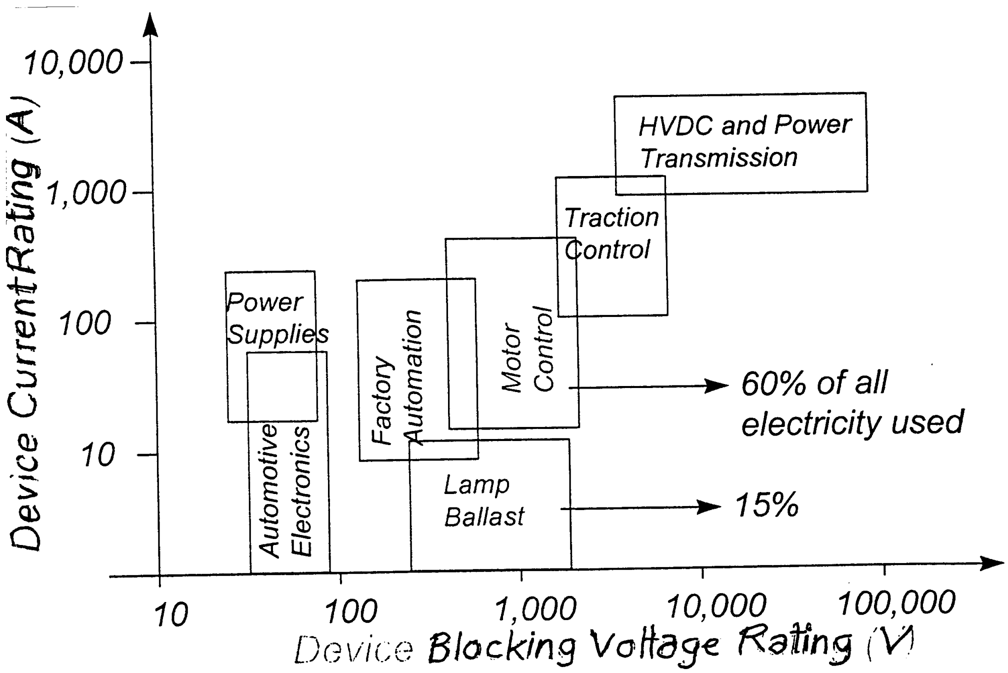
POWER ELECTRONICS USES NEW SWITCH CIRCUIT TOPOLOGIES TO MAKE SMALLER, LOWER WEIGHT AND HIGHER EFFICIENCY POWER SUPPLIES at 1W-MW levels.



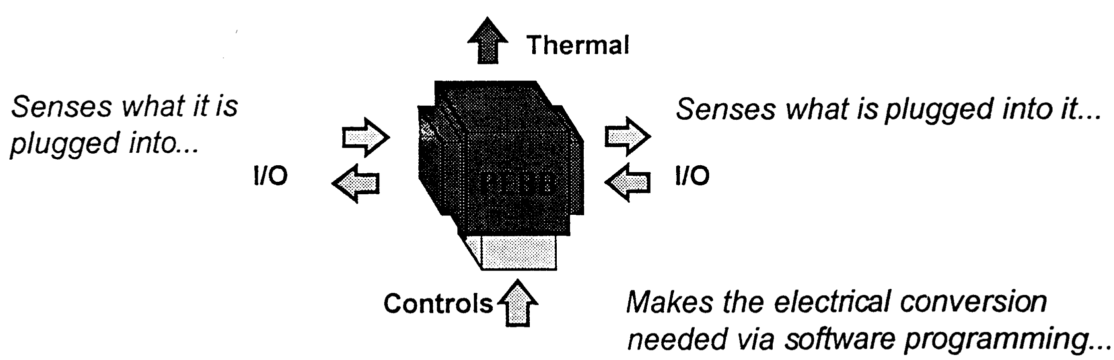


NOTE THE INCREASING OPERATING FREQUENCY
And the decreasing physical size and increased efficiency of power conversion due to reasons covered later

.BELOW WE SHOW USES OF INDUSTRIAL ELECTRONICS AND a PEBB MODULE



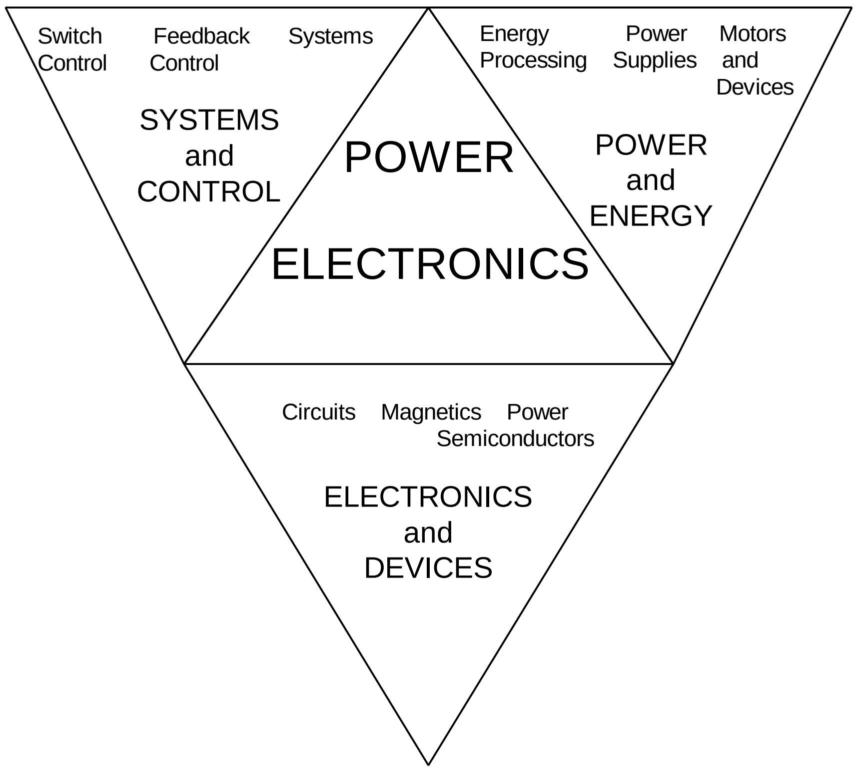
A Power Electronic Building Block (PEBB) is:



A UNIVERSAL POWER PROCESSOR. It changes any electrical power input to any desired form of voltage, current and frequency output.

It consists of:

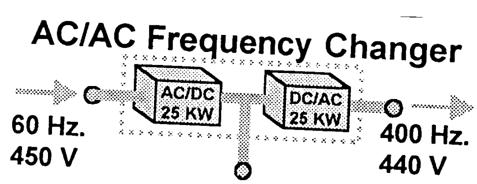
1) Solid State Switching Devices, 2) Controls & Gate Drivers, 3) Communications, 4) Passive Components, and 5) Packaging

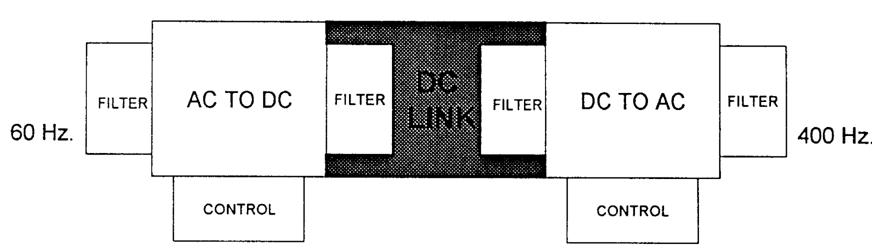


THREE EXAMPLES:

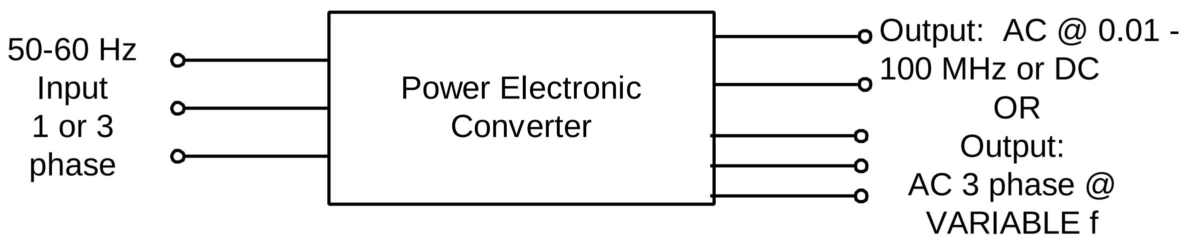
1. AC TO AC CONVERSION:

TAKE SINGLE OR 3 PHASE AC MAINS, 0.1 to 12 KV 50-400 Hz,
$1\text{-}10^6$ Watt AS INPUT AND GET EQUAL POWER OUTPUT AT A FREQUENCY OF: $0 \leq f \leq$ GHz. FOR EXAMPLE, AC @ "ARBITRARY FREQUENCY" AS OUTPUT FOR MOTOR DRIVE INVERTER, OR MHZ POWER SUPPLY.





FOR EXAMPLE, THE CABLE THAT IS PLUGGED INTO THE AIRCRAFT THAT IS WAITING AT THE GATE. In general terms the power conversion provides the following.



1 W < P < 10 MW ⇐ 10^7 range

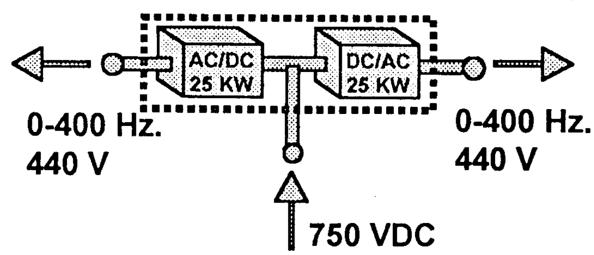
HIGH PACKING DENSITY OF POWER SUPPLIES NOW APPROACHES 30MW/m^3 BUT TEMPERATURE LIMITATIONS LIMIT IT TO MW/m^3. HENCE, KW POWER SUPPLIES APPROACH ONLY 33 cm^3 IN VOLUME AND MW SUPPLIES AS SMALL AS m^3 in volumne.

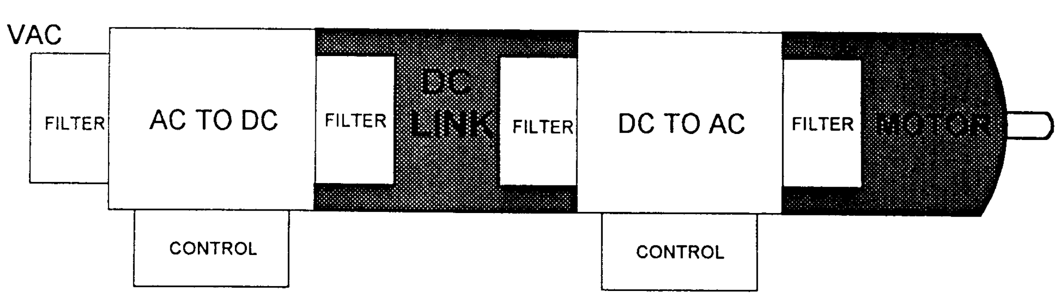
2. DC/VARIABLE frequency AC CONVERTER EXAMPLE

Two points to note:

2. Mains ac is converted to DC
3. VARIABLE frequency V (out)

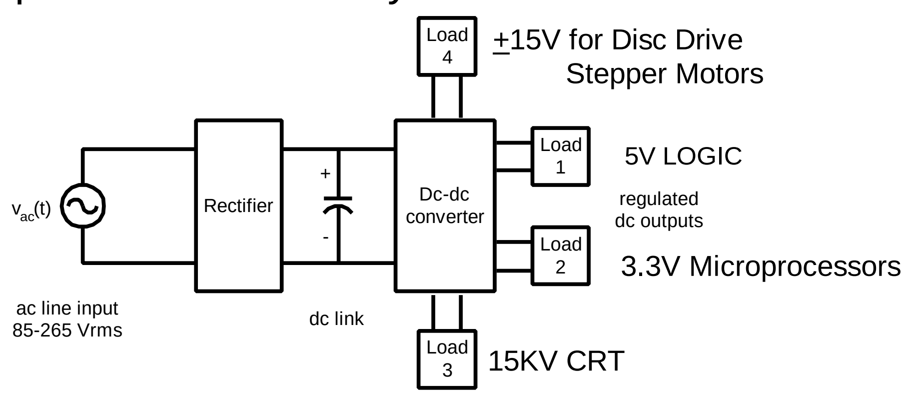
DC/AC Motor Controller (Dual)





3. AC TO DC CONVERSION:
OUTPUT DC @ ±V. FOR EXAMPLE FOR DC POWER SUPPLIES IN ELECTRONICS EQUIPMENT.
WE CAN EASILY ACHIEVE MULTIPLE DC/AC OUTPUTS, e.g. 15, 6, 3 OR 1.5 VOLTS. ALSO MULTIPLE AC OUTPUTS AT SAME/DIFFERENT FREQUENCIES

B. WHY DO IT?
For example, a computer system needs various power supplies and the total cost of a computer is at present 1/3 power supplies. Equally important the power supply buffers the system from any and all changes or variations in the mains power even allowing a programmed failure of power that results in minimum system damage. Finally, the size of the power supply made via power electronics is 10-100 times smaller and lighter as well as 10 times more efficient. Below we illustrate a power system employing one DC supply created from the mains and distributed individual power supplies for each sub-system



Below we list three power supply technologies or circuit topologies to get AC - DC conversion at a variety of DC levels.

C. THREE GENERAL TECHNOLOGIES

1. Linear Regulators

Employed where weight and heat flow are not crucial because design is fast and cost low. Efficiency is only 50 %

2. Pulsewidth modulated(PWM) converters

Employed in portable equipment or where high power flows demands the highest efficiency power conversion of about 95 %

3.RESONANT SWITCHED CONVERTERS

Utilized to achieve small size supplies and still avoid the electronic noise generated by PWM converters.

COMPARISION OF THE BIG THREE

power supply properties	LINEAR	PWM	RESONANT
Size and weight	Large	Small	Small
Electrical Efficiency	50%	85%	95%
Multiple Voltage outputs	Not Possible	Easily done	Easily done
NOISE Generated	Low Noise	High EMI	Medium Noise

We choose between the three approaches based upon the criterion for the system such as the four below:

1. Power levels in and out and required operating efficiency to minimize heat generation

% Efficiency = P(out) / P(in)

2. Size and weight limits as well as heat flow limits

3. Noise level requirements of the system
4. Static and dynamic requirements of the output voltages

D. SYSTEM SPECIFICATIONS OF POWER SUPPLIES

1. **Input Variations**
   a. V(in) maximum and minimum expected from nominal:

% Mains Regulation = [V(high) – V(low)] / V(nominal)

   b. Mains operating frequency:50,60,400 etc.
   c. Maximum input power and output noise generation seen at the input as set by regulatory agencies
2. **Output Variations**
   a. V(out) maximum and minimum ALLOWABLE by the system specifications to avoid damage or faulty operation
   b. Maximum and minimum output current allowed

% Load Regulation = [V(full load)- V(half load)] / V(full load)

3. **Dynamic Response**

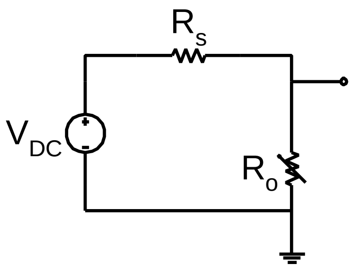
The system specification on the time an output must return to spec AFTER a step change in load

4. Regulatory Agency Requirements
   a. Noise: EMI,EMC etc.
   b. Electrical Code

E. Three step by step ways to achieve AC-DC Conversion

1. CRUDE R DIVIDER DC POWER SUPPLY APPROACH

$\Rightarrow 0 \leq V_{out} \leq V_{in}$



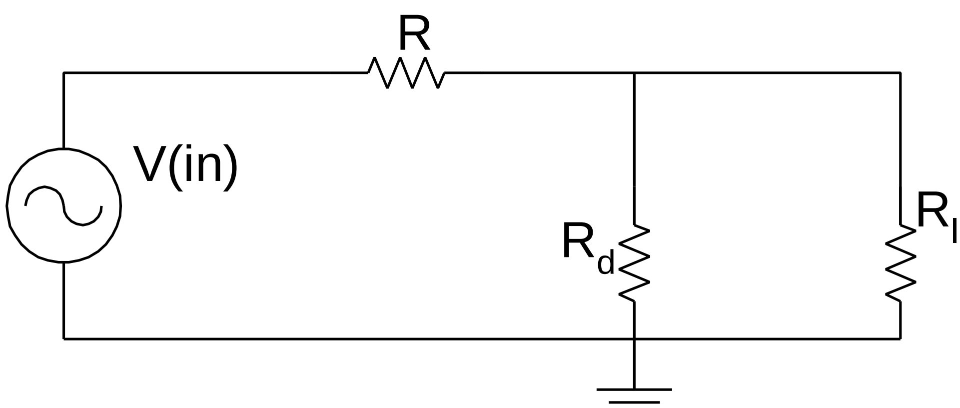
$$V_{out} = \frac{R_o}{R_o + R_s} V_{DC} \quad \text{if } I_{out} = 0$$

$0 < V_{out} < V_{DC}$

$$V_{out} = \frac{V_{DC} - I_{out} R_s}{1 + R_s / R_o} \quad \text{if } I_{out} \neq 0$$

IN SUMMARY, THIS CIRCUIT IS USEFULL ONLY FOR LOW POWER VOLTAGE SENSING BUT TERRIBLE FOR DC - DC POWER CONVERSION.

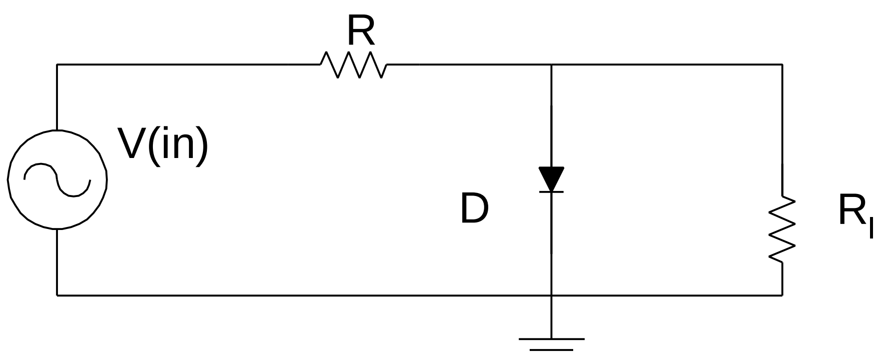
- NO STABILITY OF THE V_{out} FOR DIFFERENT R_{Load} AND V_{dc}. OUTPUT DEPENDS ON V_{DC} AND I_{out}.
- RESISTIVE DIVIDER IS NOT VERY EFFICIENT
- Lets look at the dynamic dynamic response ΔV(out) versus Δ V(in). We make Δ V(in) as an ac source and the output resistance as a dynamic variable

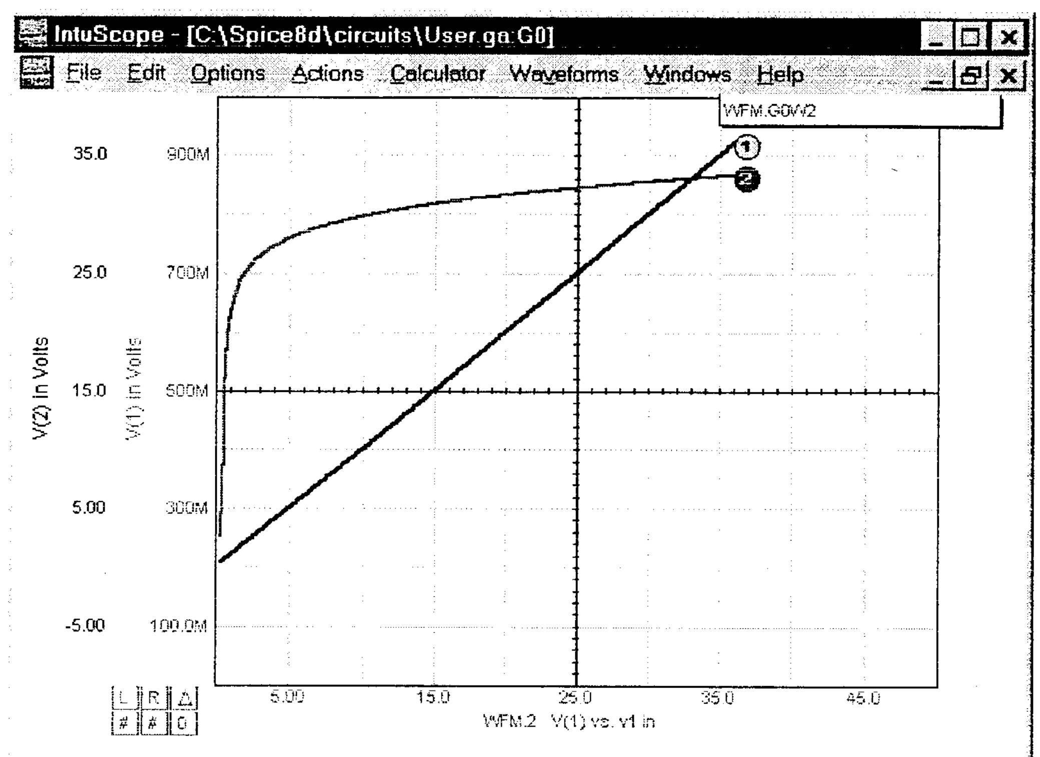


The ac response is then:

$$\Delta V(out) = \Delta V(in)\frac{R_l \times R_d}{R \times R_d + R \times R_l + R_l \times R_d}$$

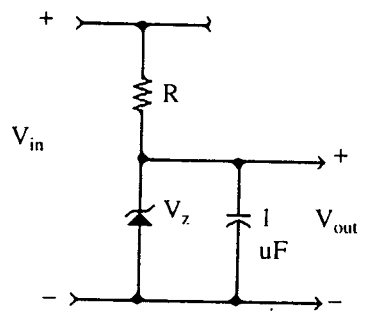
Clearly, we want R_d to be as small as possible for the best dynamic response. How to achieve this??
The simulation of the transfer function for a diode as R_d is shown below. If we choose the load resistance to be 500 ohms and the diode is a 1N4001 with V_f = 700 to 865 mV with a temperature coefficient of 10 mV/C in the circuit





How could you achieve a higher output voltage with the same dynamic diode output resistance?

- Use III-V diode with higher V_f say GaP at 1.3 V
    - Use a series of Si diodes—any other kind of diode??



$$V_{in(min)} > V_{out} + 3V$$

$$V_z = V_{out}$$

$$R = \frac{V_{in(min)}}{1.1 \cdot I_{out(max)}}$$

$$P_{D(R)} = (V_{in(max)} - V_{out})^2 / R$$

$$P_{D(Z)} = 1.1 \cdot V_Z \cdot I_{out(max)}$$

An elementary shunt regulator.

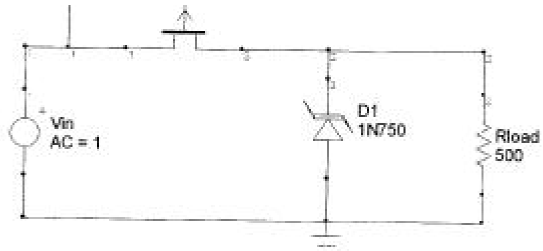
The Zener shunt regulator

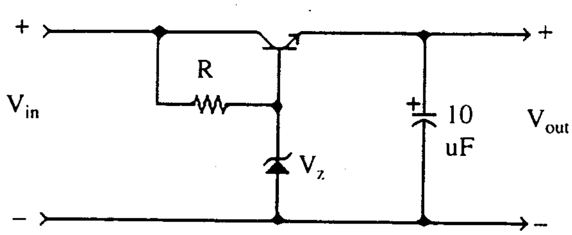
This is commonly used as a local regulator where up to 20–30 mA of load is required, such as three to five TTL circuits would represent. Its voltage drifts with temperature change and with load, but its regulation is adequate for most supply specifications for integrated circuits. It also has a higher loss than the series-pass type of linear regulator, since its loss is set for the maximum load current, which for any load remains less than that value. A Zener shunt regulator can be seen

In the next level of complexity R COULD BE A VARIABLE RESISTOR PASS TRANSISTOR (PARALLEL REGULATOR OR SERIAL REGULATOR) AS SHOWN BELOW (WE ASSUME AC MAINS ARE RECTIFIED TO A CRUDE DC)

THE NEXT thing is to model the improved output response as shown below for specific component choice.

We will derive a brief model of the one transistor pass regulator below to see better the improvement form the simple Zener circuit.





$$V_{out} + 2.5V < V_{in} < V_{CEO}$$

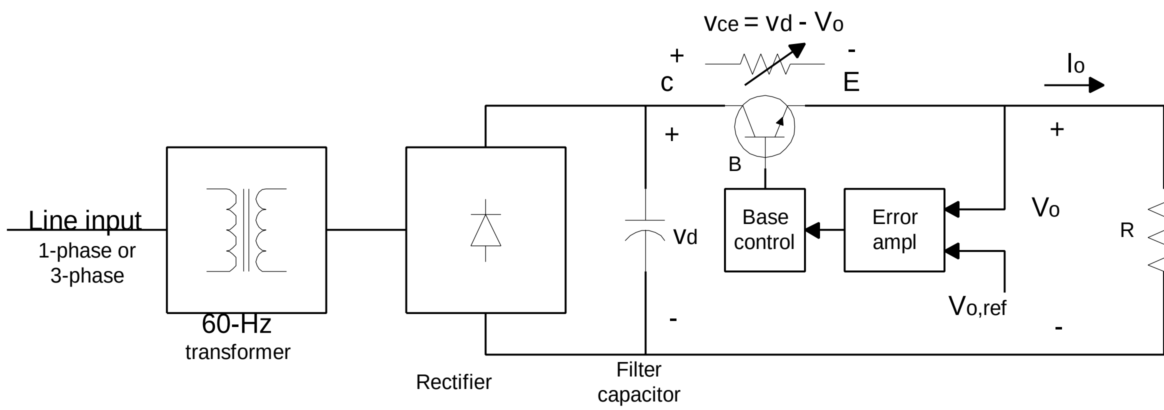
$$R \cong \frac{(V_{out} + 2.5).h_{FE(min)}}{1.2(I_{out(max)})}$$

$$V_Z = V_{out} + 0.6V$$

An elementary discrete linear regulator.

The one-transistor series-pass linear regulator

By adding a transistor to the basic Zener regulator, one can take advantage of the gain that the transistor offers. The transistor is hooked up as an emitter follower, which can now provide a much higher current to the load, and the Zener current can be lowered. Here the transistor acts as a rudimentary error amplifier . When the load current increases, it places a higher voltage into the base, which increases its conductivity, thus restoring the voltage to its original level. The transistor can be sized to meet the demands of the load and the headroom loss. It can be a TO-92 transistor for those loads up to 0.5 watt or a TO-220 for greater loads (depending on heatsinking).



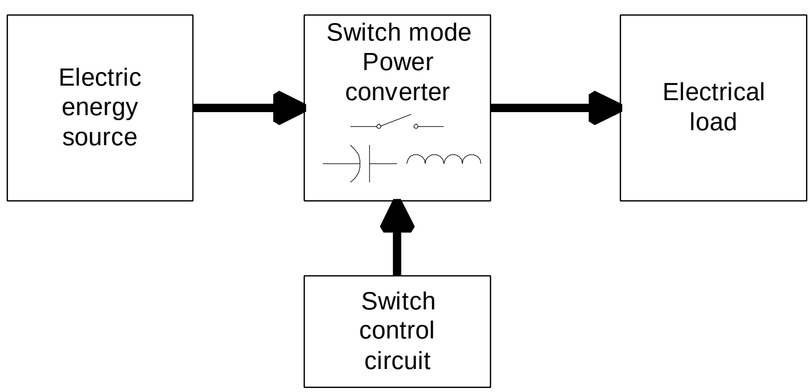
WE NOW SUMMARIZE THE Limitations of the series regulator

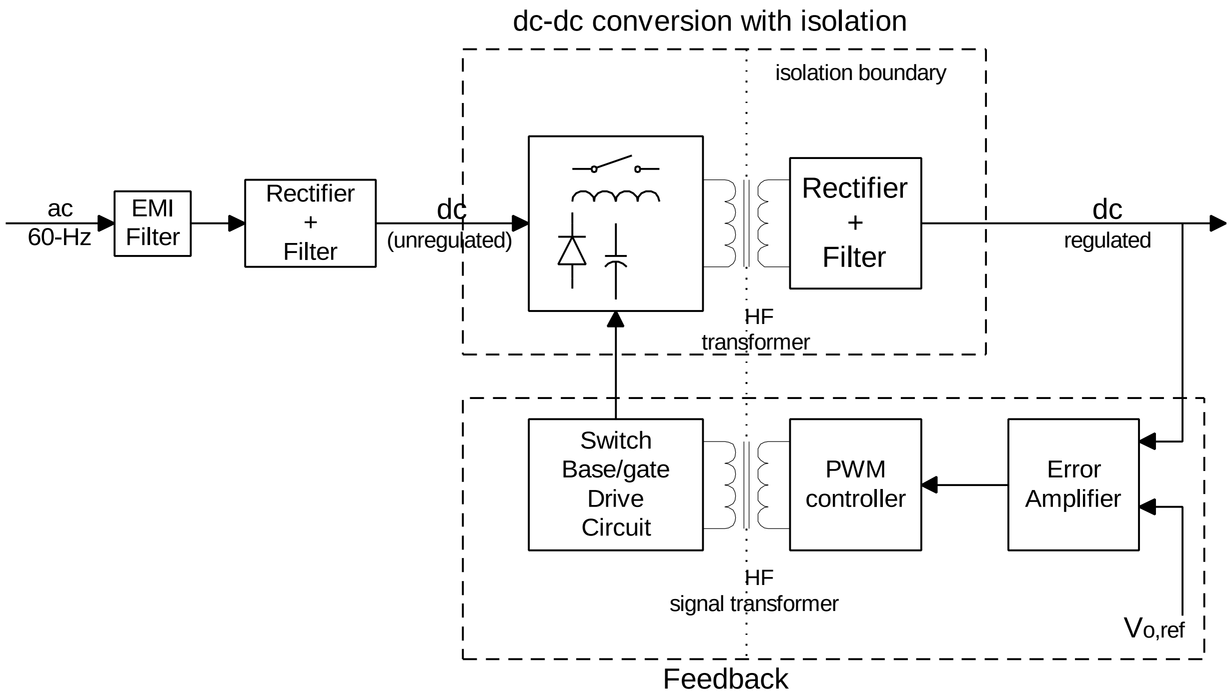
- P_{loss} IN CONVERSION IS I_{out}*V_{CE}
- EFFICIENCY OF CONVERSION IS P_{out}/P_{in}
- $V_{out} > V_{dc}$ NOT POSSIBLE
- OPPOSITE POLARITY OUTPUT IS NOT EASY
- Z_{out} OF V SOURCE IS DEPENDANT ON V_{out}

F. SWITCHED MODE POWER SUPPLIES

AN ENTIRELY NEW INNOVATIVE APPROACH TO POWER CONVERSION ELIMINATES THESE LIMITATIONS. IT USES SWITCHED MODE DELIVERY OF CONTROLLED PULSES OF POWER. SWITCHED MODE POWER ELECTRONIC CONVERTERS TO AVOID MANY OF THE ABOVE LIMITATIONS FOR CONVENTIONAL LINEAR DC SUPPLIES

THE BASIC APPROACH IS SHOWN BELOW. FIRST IN FOUR GENERIC BLOCKS AND THEN IN MORE DETAIL:





WHILE APPEARING COMPLEX, IN PRACTICE IT COSTS THE ALMOST THE SAME TO IMPLEMENT!

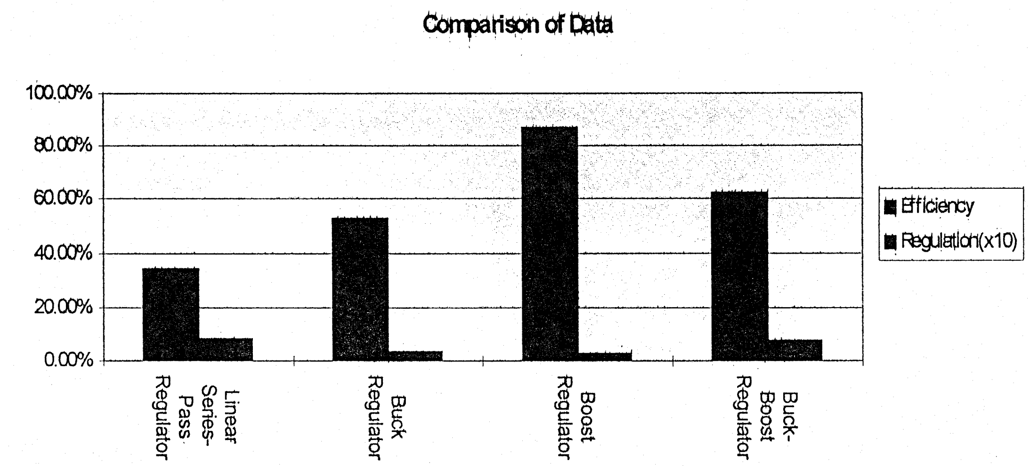
THE KEY ENABLING TECHNOLOGY IS LOW COST (< $100) AND LOW LOSS (< 1%) SOLID STATE SWITCHES THAT CAN HANDLE 1W TO SEVERAL MEGAWATTS OF POWER FLOW THROUGH THEM AT SWITCHING FREQUENCIES 60Hz < f_{SW} < 500kHz. SUCH SWITCHES ARE EASILY CONTROLLED BY CONVENTIONAL CMOS DRIVER CIRCUITS DRIVEN AT f_{SW}. LOSING 1% OF THE TRANSFERRED ENERGY IN THE SWITCHES IS A SMALL COST FOR THE VARIETY OF OUTPUT POSSIBILITIES ONE CAN ACHIEVE AS WE WILL SHOW IN LECTURE 2.

Switch-mode vs. linear regulators for DC Power

Switch-Mode	Linear
•Output voltage may be much larger or much smaller than input voltage	•Output voltage is always smaller than input. Only step down dc-dc conversion occurs.
•Output may be of opposite polarity to input	•Output always has same polarity
•Power conversion efficiency > 85% for all V_o/V_{in} ratios.	•Conversion efficiency of ≈ V_o/V_{in} means higher (only for) a V_{out} step down close to V_{in}
•Lower power dissipation and smaller size components	•Larger size components needed with external cooling
•Output controlled by duty cycle of switching signal	•Output controlled by potentiometer or voltage controlled resistor
•Dynamic response for fast input and output transients is slower	•Dynamic response is fast for input and output transients
•High voltage insulation need for the control loop	•Non-insulated feedback
•Output voltage possesses high frequency noise (EMI) EMI is now illegal	•No EMI/EMC problems

Later we will show for switch mode supplies that kHz<f_{sw}<MHz. As f_{sw} increases the required L and C components have LOWER values (cheaper). This occurs because Z_L=wL and Z_C=1/wC and we trade off between higher/lower switching frequency and OK higher weight components - with lower weight comes smaller size. In modern usage small size and lighter weight is paramount for portable equipment like pagers, cellular phones, PDA's, computers, etc.

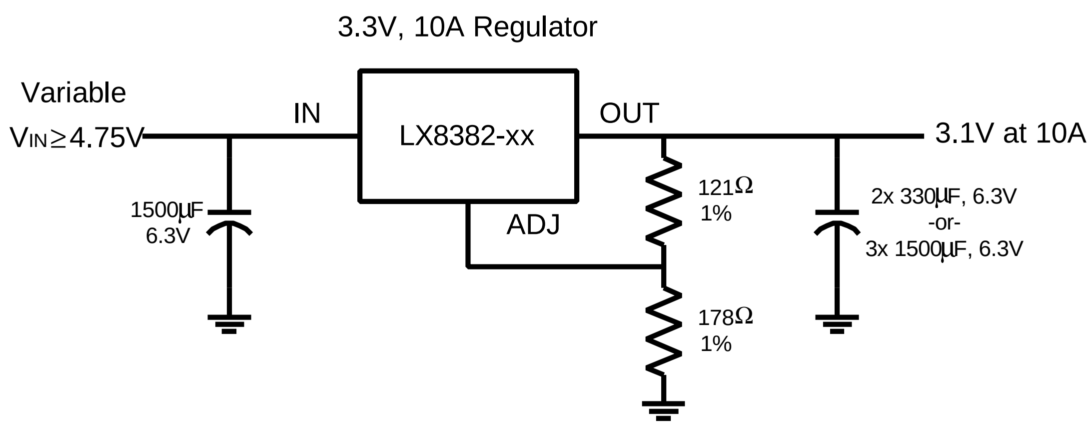
Comparison of Regulators



In examples 1 and 2 below we compare command linear vs. switching regulators for a Pentium Pro or AMD K-6 power supply/voltage regulator.

1. ILLUSTRATIVE VOLTAGE REGULATOR EXAMPLES

Example 1: <u>Linear Constant Voltage Regulator for Pentium Pro or AMD K-6 Power Supply</u>



Application of the LX8382 for a high-current microprocessor (e.g. AMD-K6) with less than 130mV dynamic response to a 7.5A load transient.

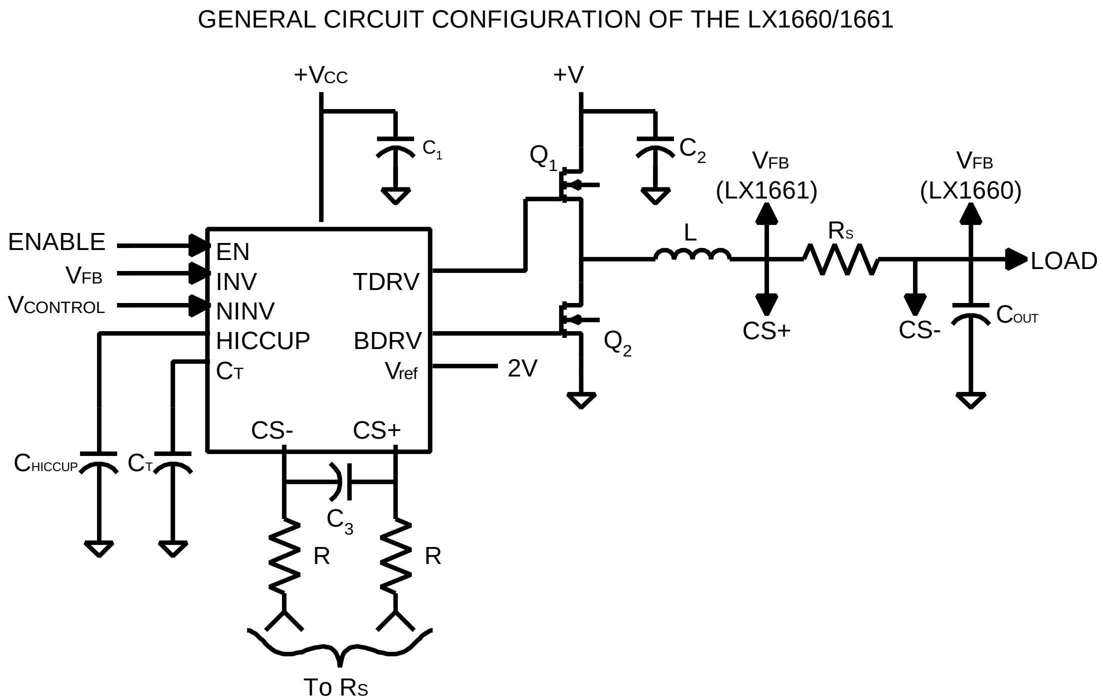
Below we compare Power In, Power Loss in Regulator and Power Output with V_{inmax} = 5.25 V assuming we draw 10 mA for control:

a. $P_{inmax} = V_{inmax} * I_{outmax}$ = 5.25 V * (10 A + 10 mA) = 52.5525 W
b. The power losses in this circuit are approximately:
   $P_{loss} = (V_{inmax} - V_{outmax}) * I_{outmax} + 10\ mA * V_{in}$
   P_{loss} = (5.25 V - 3.1 V) * 10 A + 5.25 V * 10 mA
   P_{loss} = [21.5 + 0.0525] W = 21.5525 W ≈ 21.5 W
c. $P_{outmax} = V_{outmax} * I_{outmax}$ = 3.1 V * 10 A = 31 W
   $\eta = P_{outmax} / (P_{inmax})$ = 31 W / 52.5525 W = 0.5898 = 58.98 %

If the input voltage V_{in} is greater than the required output voltage V_{out} the circuit may maintain constant voltage at the output for different output currents. The PENTIUM PRO like most μPs can change their supply current within one clock cycle (f_{clock} = 266 MHz t_{clock} = 2.76 ns) from sleep mode with very low current (few mA) to the max power supply current (tens of A). During this transient time the power voltage should maintain 3.1 V ± 5%.
No control loop can in reality maintain such performance. The only solution is to use very strong (low ESR) bypass capacitors at the 3.1 V output to ensure the short-term stability (ns to μs). The long-term stability (μs and longer) is maintained by the control loop of the regulator.

Next lets see if we can do better with our power supply losses which were 40% in this approach.

Example 2: Switching Voltage Regulator for Pentium PRO



This circuit can have a very high efficiency, about 85 - 95%. To reach this efficiency the switches Q1 and Q2 must have very low R_{dson} and very short turn off and turn on times. The series output inductance L should have very low parasitic resistance and low magnetic losses. The printed circuit board also needs to be carefully optimized for high currents and low parasitic inductance. Capacitor C_{out} and C_3 have to carry the full load current at the switching frequency 200 kHz.

Assuming no switching losses and R_{dson} for Q1 and Q2 is 20mΩ, Rs= 5 mΩ and no other lossy parts are involved. With 10 A output current:

$P_{loss} = (I_{out})^2 * (Rs + R_{dson}) = (10\ A)^2 * (5\ m\Omega + 20\ m\Omega) = 2.5\ W$

$P_{out} = V_{out} * I_{out} = 3.1\ V * 10\ A = 31\ W$

$P_{in} = P_{out} + P_{loss} = 33.5\ W$

$\eta = P_{out} / (P_{in}) = 92.54\ \%$

In reality actual efficiency values are 85% to 90% due to losses in the parasitics.
The switching regulator generates very high transients of the electric and magnetic fields at 200 kHz. This generates both conducted and radiated electromagnetic noise. This noise can be easily higher than the 5% tolerance window of the supply voltage 3.1 V for the Pentium. To avoid malfunction of the processor it is necessary to filter this noise for all conditions. Moreover, this noise must not pollute the ac mains.

Which regulator, Example 1 or 2 is a best choice for a laptop computer?