Power Electronics and the New Energy Revolution:

The *How* of Energy in a Transitioning World and an Introduction to the Course

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The 21st Century Energy Revolution

- Life in rural Asia even today:
  - No electricity
  - No cars
  - No land-line telephones
  - No appliances other than a basic stove
  - No radio or TV
  - No running water
- Electricity is changing *everything* and it will again.

Basics of *Power Electronics*

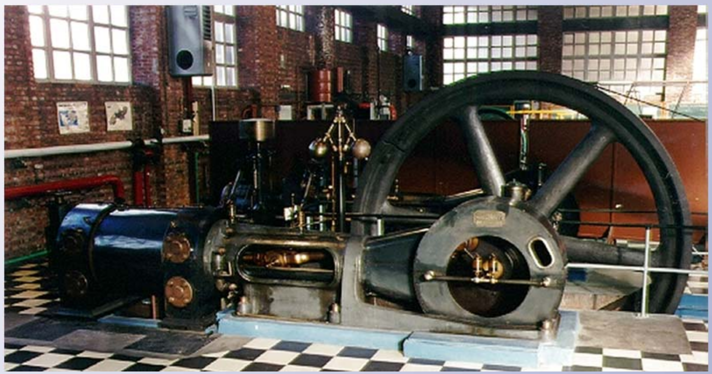
- Instructor: Prof. P. T. Krein
- Web site: courses.engr.illinois.edu/ece464
- Book (yes you will need it): P. Krein, *Elements of Power Electronics*.

The 21st Century Energy Revolution

www.foag.org

History is a sequence of energy revolutions.

www.waterwheelfactory.com



www.mech.kulueven.be

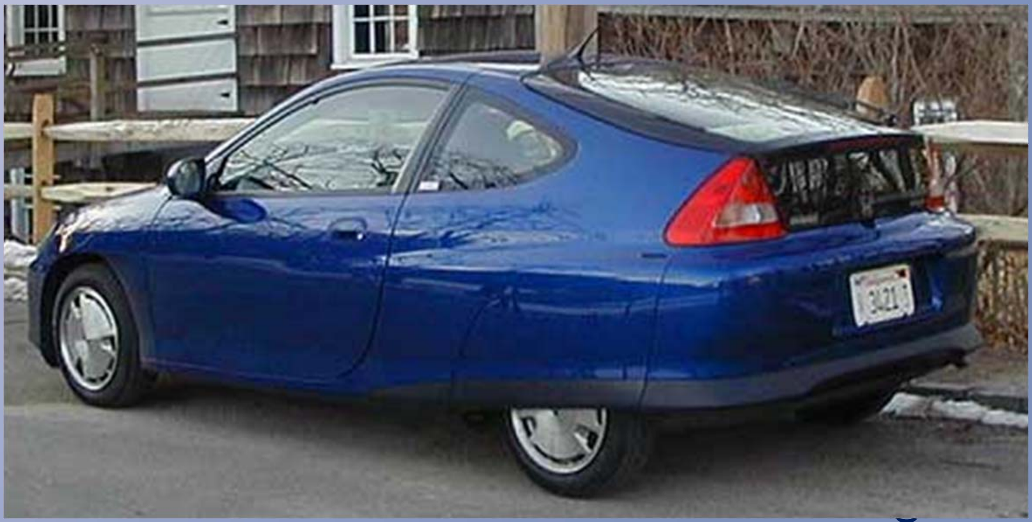
www.lightbulbmarket.com

www.xtec.es

Each *completely changes* the way people live and work.

The 21st Century Energy Revolution

- Today, we are in early stages of a new energy revolution.
- We see it in explosive growth of portable devices, industry processes, and many others.
- We see it in hybrid cars now on the road.



www.familycar.com

The 21st Century Energy Revolution

Modern electrical demands are much different from the

– Incandescent lights
– Electric stoves
– Motors

that represent the 20th century electrical energy revolution still sweeping the world.

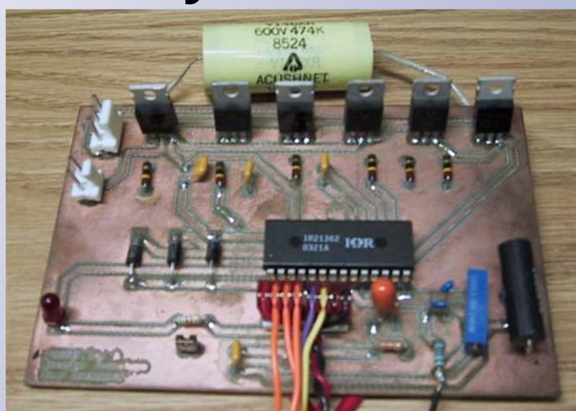
Solar Two thermal solar power plant.
www.nrel.gov

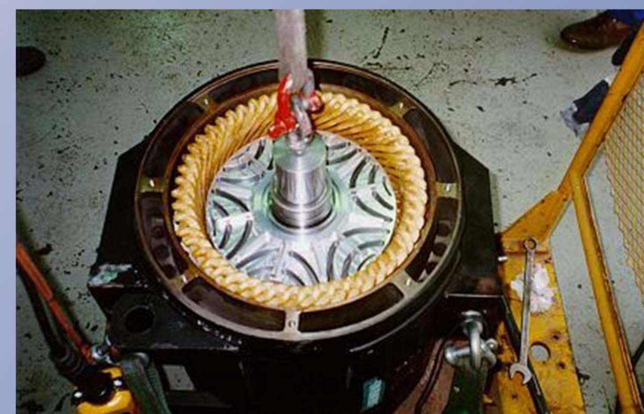
The 21st Century Energy Revolution

What will change?

The answer is easy – EVERYTHING.

research.ee.sun.ac.za





www.edmunds.com

www.osesemi.com

Signs of Revolution

Jetliners are moving to all-electric

- Electric motors in place of hydraulics
- Adaptable surfaces

www.boeing.com
© Boeing

www.mpcproducts.com

Car electrical systems are retooling.

- Electric air conditioning, power steering, suspension, control, pumps are better.
- Car electric power approaches that of a house.
- The 12 V system is inadequate.

Source: Delphi Corp., Saginaw Steering Systems Div.

Signs of Revolution

- Wind power has crossed a cost threshold.
- Long-anticipated energy growth in east Asia and south Asia is occurring.
- Fossil fuel consumption now exceeds the rate of new reserve discovery.

Trondheim Univ., Norway

Jinzhushan coal plant, China.
www.ens-newswire.com

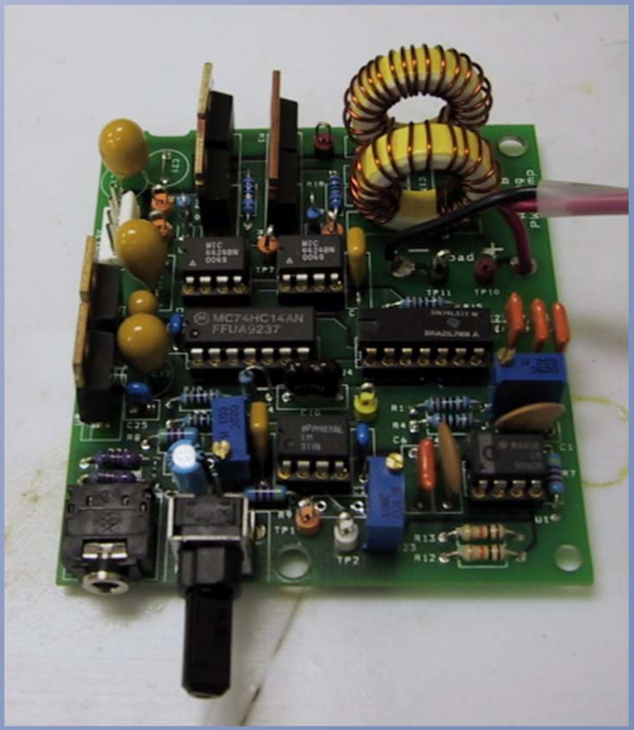
Signs of Revolution

- Electricity continues to grow as a fraction of all energy use.
- Electrification: a key element of economic development.
- Much of the world has yet to “be electric.”
- Many countries are leapfrogging wire grids.

www.ccm.co.nz

Why a Revolution?

- Much of the revolution is based on using electronic circuits to process *energy*.
- **Power electronics** is the application of electronic circuits to the control and conversion of *electrical energy*.
- This is fundamental to any electrical product.
- It cannot be done with linear circuits.

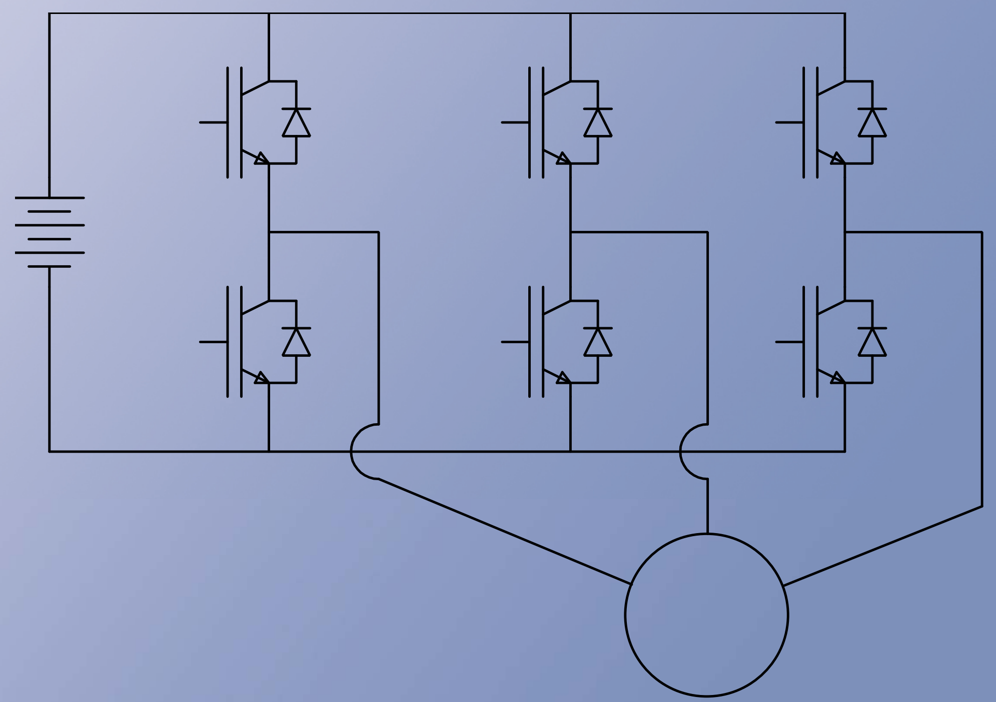


Why a Revolution?

- *People do not use electricity.*
- They use light, heat, information, and all the things we can *do* with electricity.
- Electrical engineering is about *conversion* – mostly between information and an electrical form.
- Growth of energy today means growth of *electrical* energy.

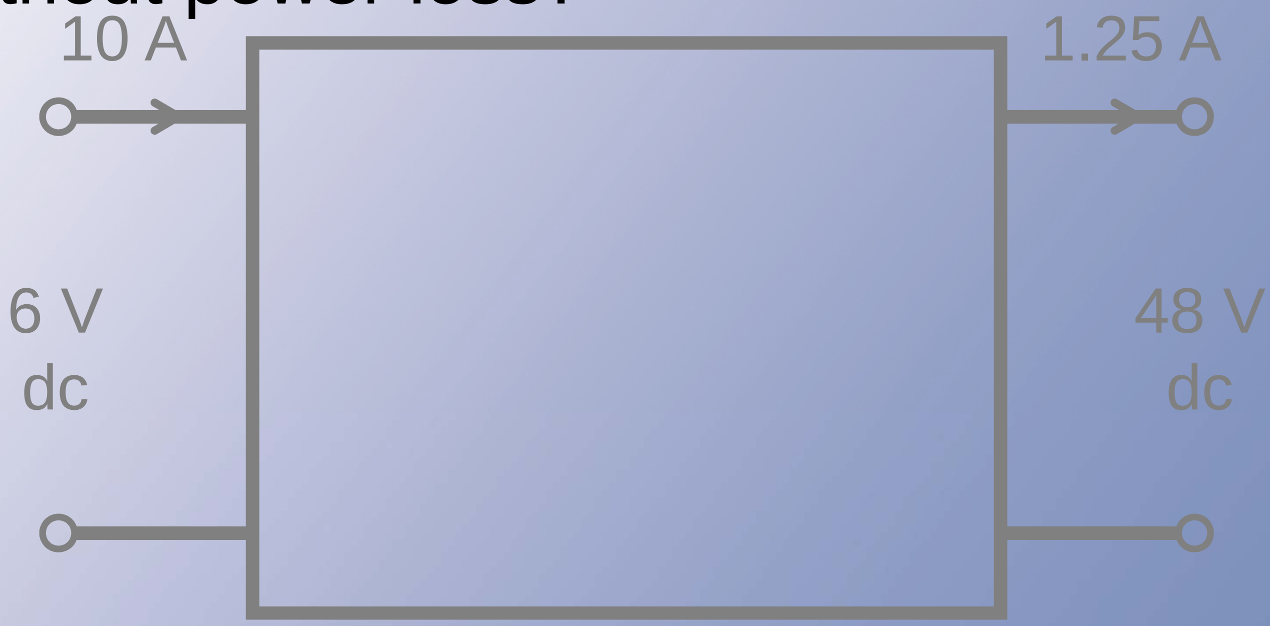
Principles

- Power electronic circuits use switches.
- A switch controls energy flow without any loss.
- We must find good ways to operate and control switches to convert energy in a desired way.



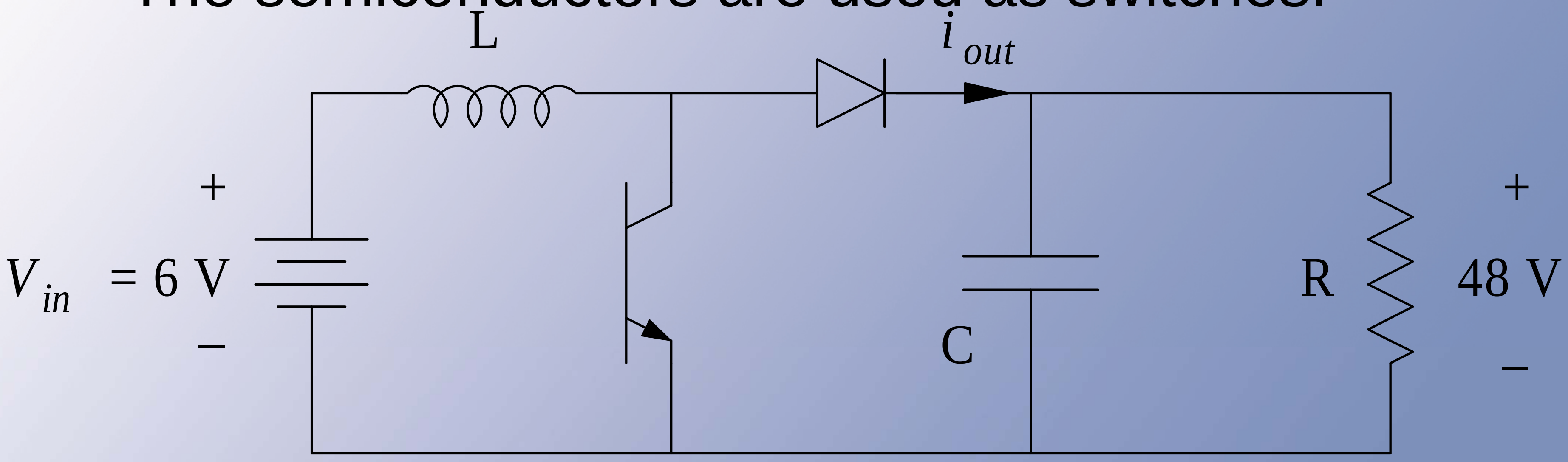
Example

- Many seasoned engineers will tell you the function below is impossible. How can you put in a dc voltage and get a higher one out without power loss?



Example

- The circuit to do this is deceptively simple, but is challenging to analyze and control.
- The semiconductors are used as switches.



R = 38.4Ω

Example

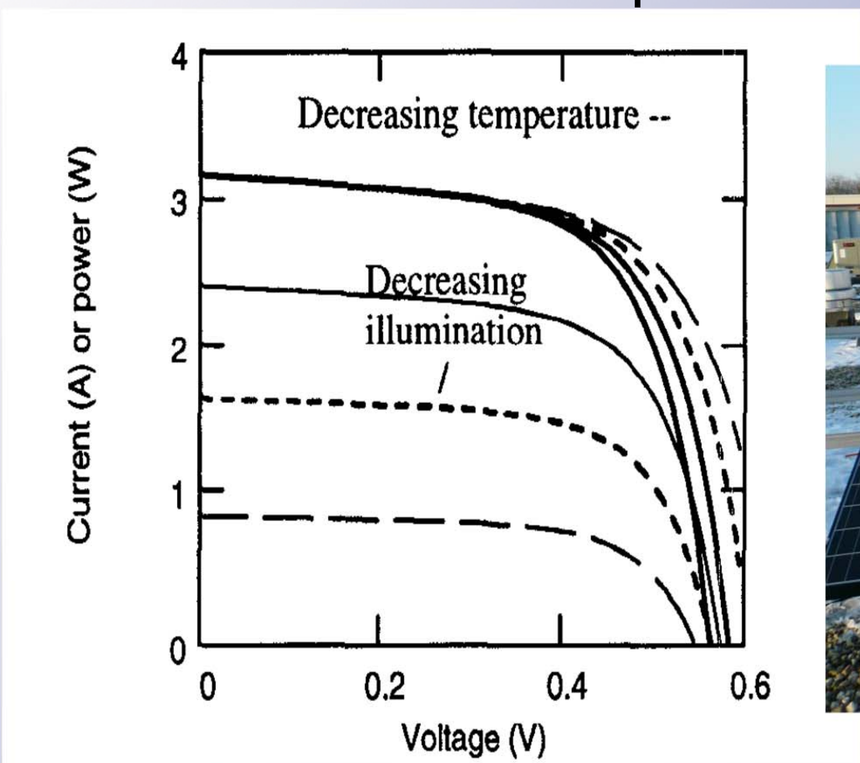
- Good analysis methods for this circuit appeared in the late 1970s, but they were justified only in the 1990s.
- Good controls for it remain a research topic.
- There are still circuits for which good design techniques have not been fully developed.

Space station: the design is dominated by power.

www.nasa.gov

Example

- Deliver maximum energy from a solar panel.
- Track this “maximum power point” as it changes with illumination and temperature.



Example

- A 200 W converter to draw maximum energy from a solar panel and deliver it to the grid, with control of the grid interface:

Emerging Buildings

Zero net energy homes and schools

Lewis Center, Oberlin College

Grand Challenges

- The current energy revolution has power electronics at its heart.
- Within ten years, nearly *all* electrical energy will be processed through power electronics.
- Power electronics is a critical enabler.
- *Build the industry* that will do this in a cost-effective high-quality manner.
- Create the tools that will lead to *sustainable energy use*.

The Dilemma

- Today, few engineers have a thorough understanding of power electronics.
- The need is so vast compared to the expertise that the problem is hard to grasp.
- Good work in the area requires a broad background and innovative thinking.

Source: www.theautochannel.com

Challenges -- Digital Power

- A sample design challenge:
  - Digital designs are moving to lower voltages to "reduce power" and squeeze dimensions.
  - Near-term example: 1 V power (at 70 W) for microprocessor
  - Longer-term: 0.5 V power, still at 70 W
- How do you deliver 140 A to a chip without burning something up?
- If a conversion circuit includes a diode (they always do) with a 0.7 V drop, then providing 0.5 V power yields at best ~40% efficiency.

Challenges – Digital Power

- It gets worse.
- Whenever an electrical connection is made to something, there is wire involved – and wires have inductance.
- A typical value of inductance is about 5 nH/cm.
- Does that matter?

Challenges – Digital Power

- A 3000 MHz microprocessor can swing from almost zero current to almost full current (up to 40 A) in just a few clock cycles.
- Estimate: a 40 A swing in 3 cycles yields 40 A in 1 ns, or $di/dt = 4 \times 10^{10}$ A/s.
- Connect through 2 cm of wire → 10 nH inductance.
- Fast current change induces a voltage across the wire.

Challenges – Digital Power

- Voltage drop: L di/dt = (10 nH) x (4 x 10^{10} A/s).
- This gives 400 V, and the processor is destroyed.
- In the end, power processing and distribution must be designed into the chip itself.

Challenges – Vehicles

Power electronics is an essential enabler for electric and hybrid cars.

The electric motor, batteries, extra equipment, and major operating components such as brakes all use power electronics.

Tesla

www.gmev.com

www.popularmechanics.com

Challenges – Vehicles

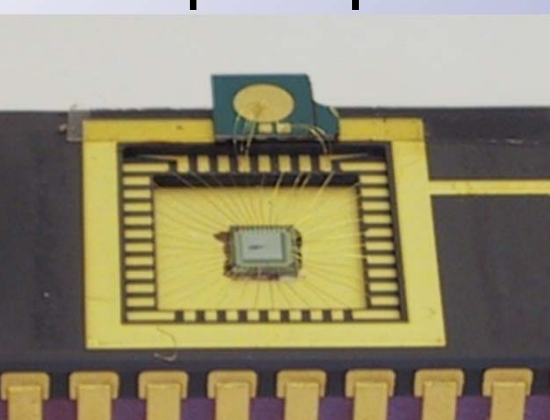
The designs are recent and immature.

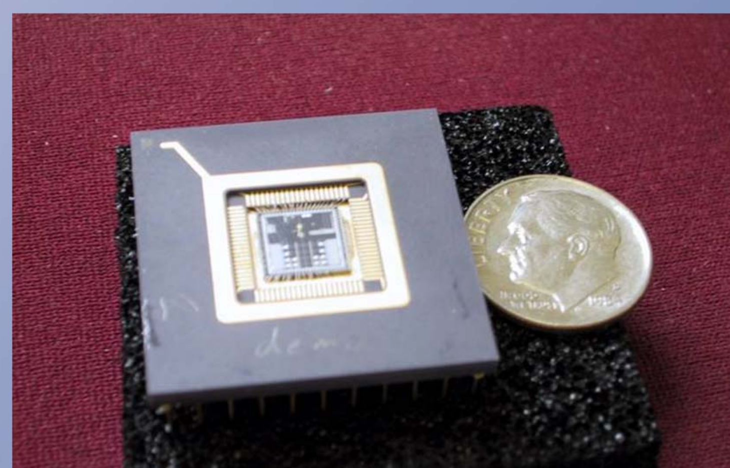
The target power level for a car is at least 100 kW for the drive. This is equivalent to roughly 200 HP.

Illinois plug-in hybrid prototype

Challenges – Miniature Power

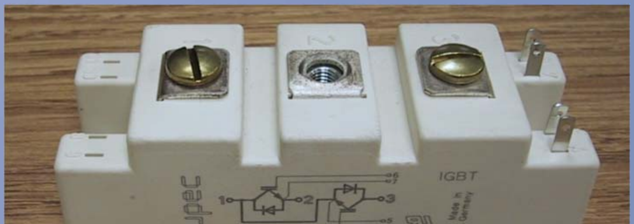
- A sample design challenge:
  - Efficient miniature power for communications and for network nodes.
- Supply just a few milliwatts, with very high efficiency.
- Example: power on a chip.





Unusual Devices

- Several widely-sold devices are unique to power electronics.
- About *half* of the discrete semiconductor market.
- Example: the IGBT (insulated gate bipolar transistor).
  – A special voltage-controlled transistor.
  – Optimized for switch applications.
  – Small devices have ratings on the order of 600 V and 10 A. Larger ones for HEVs reach 1700 V and 600 A.



Advanced Applications

- Switching audio amplification – full fidelity output from a digital music source.
- Direct energy processing to the loudspeaker.
- Efficiency of about 90%.
- Compare to clunky old-fashioned class AB amplifier.

Summary

- An accelerating 21st century revolution is underway.

- The ways we use energy, the ways we produce it, and the ways we process it are changing.
- Energy alternatives and sustainability are the expected outcomes.
- Power electronics is the innovation that drives this revolution.
- The challenges are vast and the issues are growing.

So What About This Course?

- In this course, the fundamentals of power electronics are presented.
- Assignments and tests are intended to give you practice with realistic problems.
- Everything we consider is motivated by practical applications – if they are not clear or obvious, *challenge* your instructor to show what the topic is used for and why it is included.

Power Electronics

This *is* a course about alternative energy systems, *because there is no alternative energy ithout power electronics*.

Because power electronics is an integral part of *all* energy systems, from basic systems in a conventional car to the most advanced photovoltaic energy systems on a spacecraft, it is central to the new electricity revolution.

Details

- Homework assignments regularly.
- Tests and a final examination.
- Yes, we will discuss and cover material beyond what is in the book.
- Yes, you will be responsible for some materials in the book that we do not cover in class. This will be made explicit during class sessions.

Grading

Grades are on an *absolute* scale. You are being compared to a standard of performance, not to others in the class.

The Course

- Power electronics is a relatively new field, recognized as a distinct discipline for about 35 years.
- The textbook will be followed closely.
- Assignments are intended to provide practice and help you follow along.
- Please ask questions.

Key Web Sites

http://courses.ece.uiuc.edu/ece464

Course Coverage

Key concepts

Dc-dc converters

Rectifiers

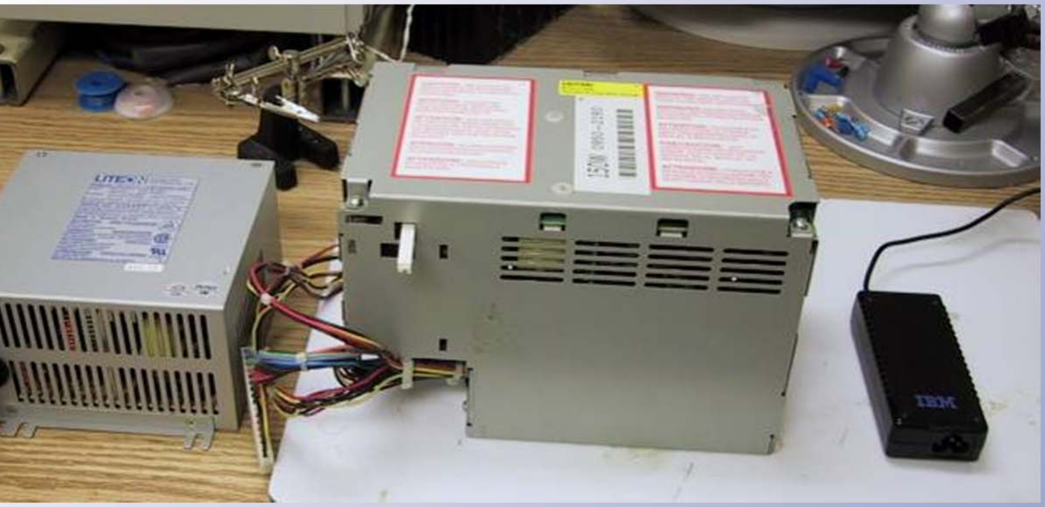
Inverters

Applications

Course Coverage

- Passive components as they relate to energy conversion
- Magnetics
- Active components
- Systems integration issues

Rapid Progress



www.powerconversion.com

Premise

People do not use electricity.

Brad Waddell. Used by permission.

.philipslumileds.com

Energy is Our Business

2008 was the 260th anniversary of Franklin’s electric motor, and 2010 was the anniversary of the lightning rod, the first inventions of the electrical age.

The impetus for electricity use is the ease of conversion and transport of energy -- both at the sending and receiving ends.

Energy is Our Business

- Ease of conversion means that electricity comes in a wide variety of forms.
- Various voltages, frequencies, waveforms, polyphase connections, and others are common.
- The “best form” depends on the situation and application.

Examples

- Ac, 50 Hz in Europe and most of Asia, 60 Hz in North America
- Dc, 12 V for analog circuits
- Dc, 5 V for conventional digital circuits
- Dc, 3 V for memory and other digital circuits
- Dc, 1.2 V for advanced microprocessors
- Ac, medium frequency for fluorescent lighting
- Ac, 345 kV, 60 Hz for bulk transmission
- Ac at RF for communications

Capacitor Energy Storage

Capacitor value: 300,000 uF

Voltage rating: 7.5 V

Energy storage: $\frac{1}{2} C V^2 = (0.15)(7.5)^2$

$= 8.5$ J

Compare to: 1.5 V battery

~ 5000 J (AA cell)

The Implications

- People *do not use electricity.*
- They use light, heat, information, mechanical work, and direct results of energy.
- All electrical engineers are in the business of conversion.

What is Power Electronics?

- If electrical engineers are in the conversion business, who is it that takes care of *energy* conversion?
- We are used to circuits that handle information, whether analog, digital, or RF. What about energy?

What is Power Electronics?

- In power electronics, the energy conversion process is primary.
- We study the application of electronic devices and circuits to the conversion and control of energy.
- We are interested in conversion of electricity among its many forms.

My Definition

Power electronics involves the study of electronic circuits intended to control the flow of electrical energy.

These circuits handle energy flow at levels much higher than individual device ratings.

Field Effect Transistor Example

IRF 4227

Power rating: 3 W (without heat sink)

Voltage rating: 200 V

Current rating: 50 A

Power electronics “rating”: 10000 W

This is called the *power handling* rating.

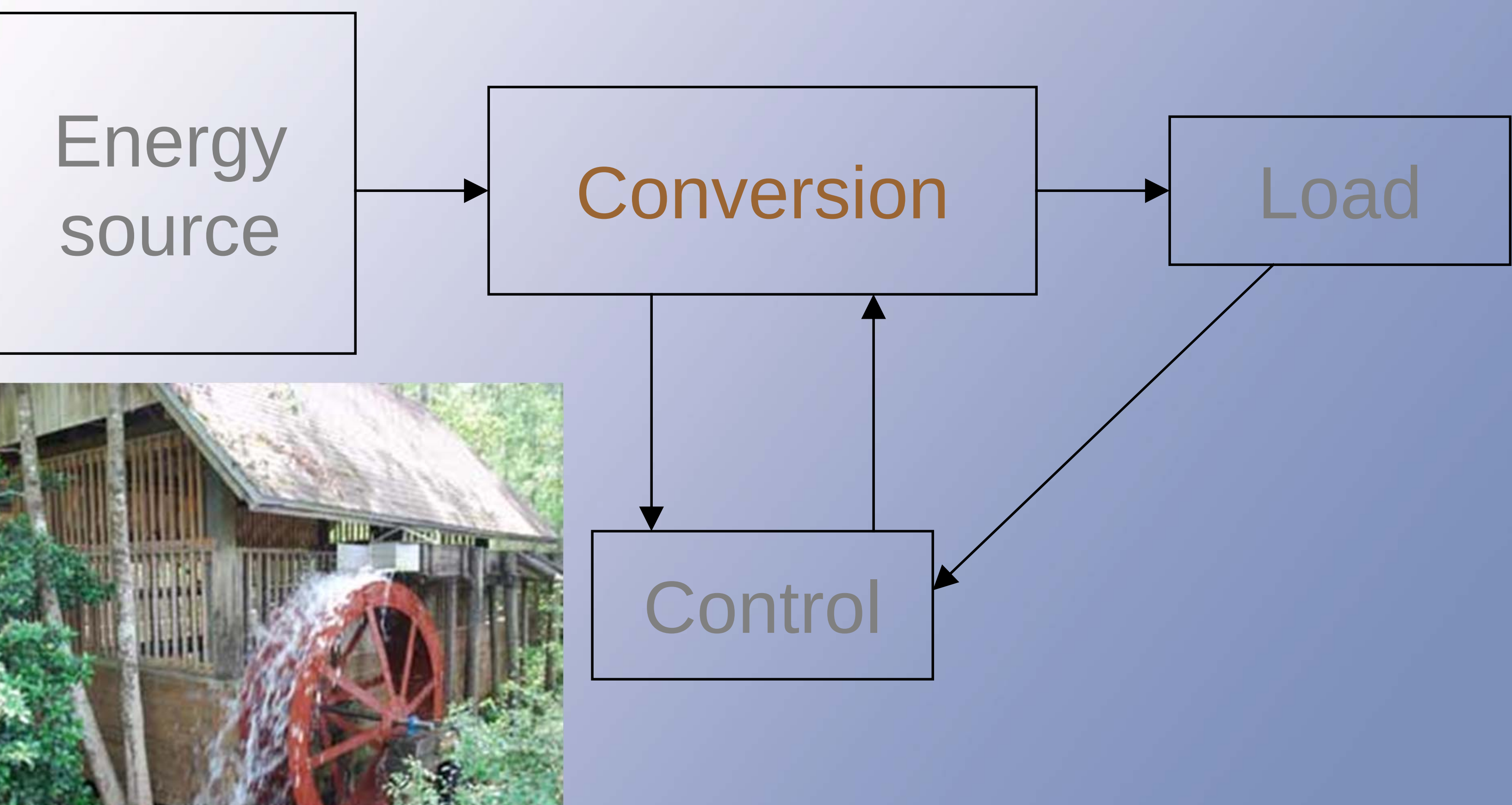
History

- In the 1880s, Edison (and his General Electric) advocated dc power.
- Westinghouse advocated ac power.
- Dc to ac conversion was an issue from the beginning.
- But ac and dc arguments are misleading:
  - Two power systems exist today – power grid and telecom power, ac and dc
  - There is a broad trend to dc

How?

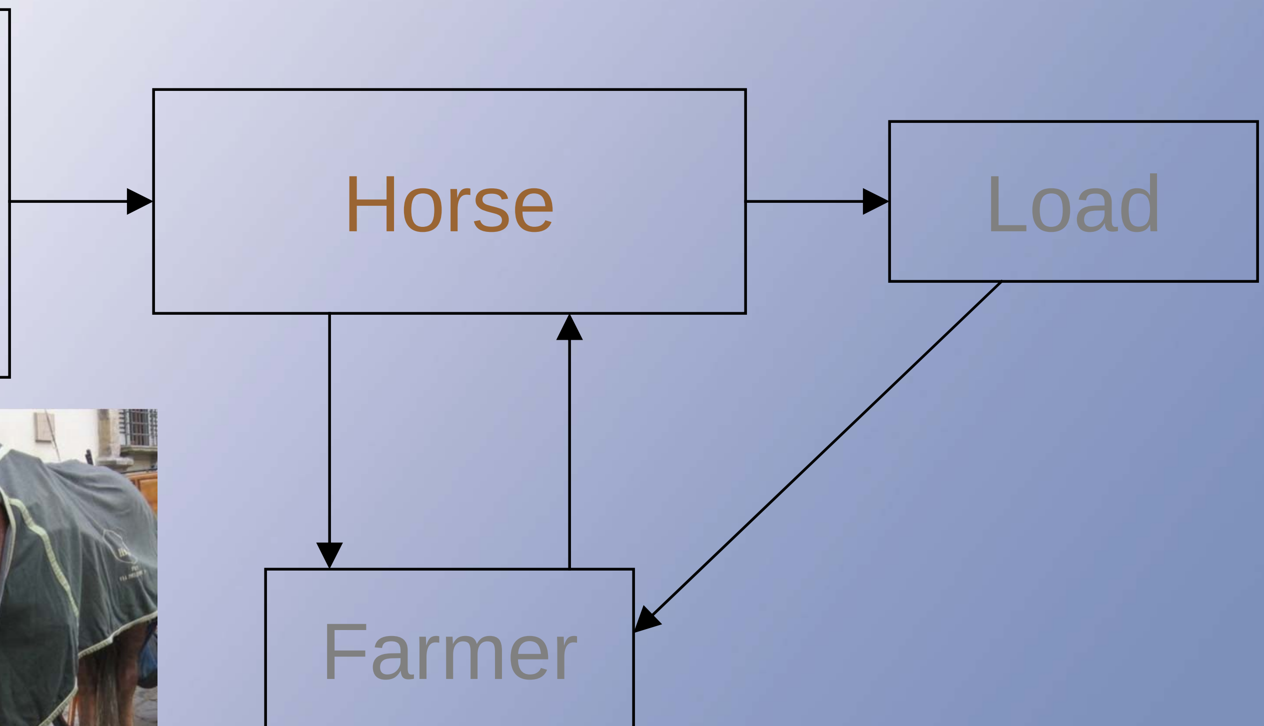
- For dc, the original option was electrical to mechanical to electrical conversion: a motor driving a generator.
- For ac, we also have the transformer, which can adjust voltage levels.

Energy Conversion System

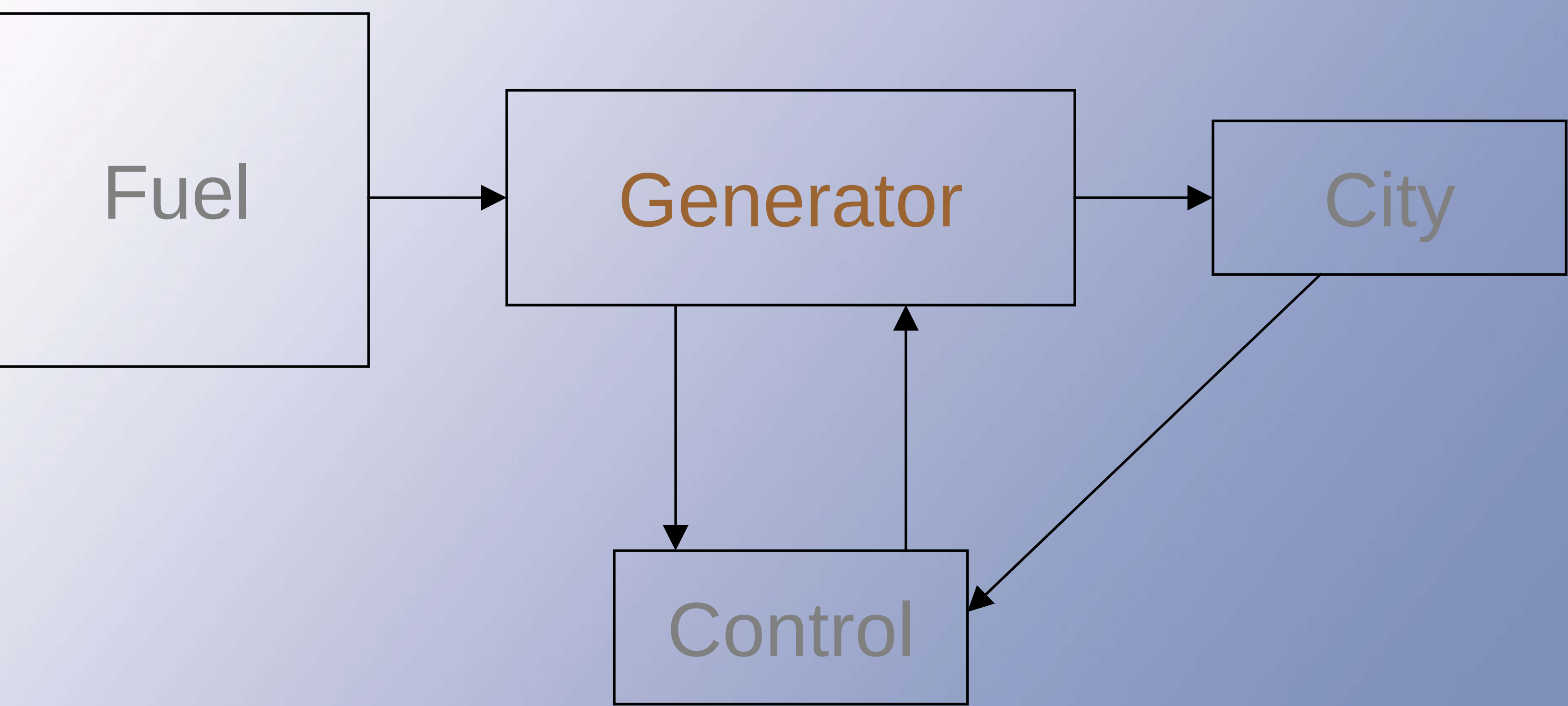


www.waterwheel.com

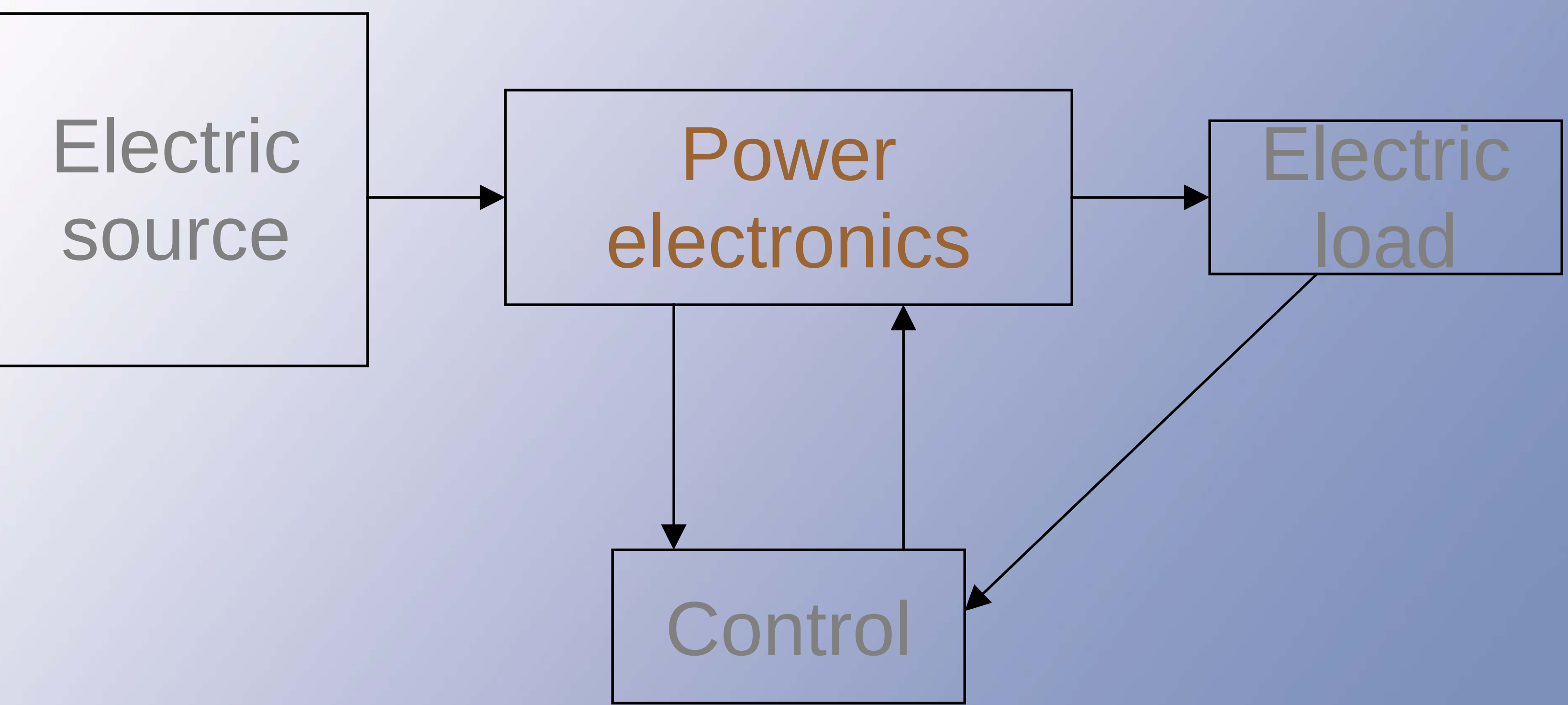
Energy Conversion System



Energy Conversion System



Energy Conversion System



Why is it Challenging?

Energy conversion is a nonlinear process: The form we want differs in basic ways from the form we start with.

Even today, many aspects of nonlinear circuits and systems are only partially understood.

Conversion involves intermediate stages.

Historical Sequence

Motor-generator sets for conversion

Transformers for voltage levels (ac)

Nonlinear circuit elements: nonlinear materials as *semiconductor* rectifiers, electronic devices (tubes) as rectifiers

Thyratrons and triodes: rectifier control, inverters, cycloconverters

The Silicon Age

Selenium diodes, copper oxide diodes --- silicon P-N junction diodes.

The thyristor -- the silicon controlled rectifier (SCR). Support for high-power rectifiers, inverters, and cycloconverters

Power bipolar transistors. Voltage-sourced inverters, pulse width modulation, dc-dc converters.

More Recent

- Power field-effect transistors: high-performance dc-dc conversion
- Combined devices, such as the insulated gate bipolar transistor (IGBT): high-performance inverters
- High power thyristors, SCRs and gate turn-off (GTO) devices: power levels of many megawatts

Near Future

- Efficient conversion below 1 V
- Power electronics in almost every motor, appliance, or electrical product
- Almost all energy processed through an electronic circuit
- Alternative energy

Summary

- Energy conversion is our business.
- Power electronics is distinct because we study circuits and devices for energy conversion and control.
- Modern devices can manage energy flows from less than 1 W to more than 1000 MW.
- There are significant future challenges in computers, automotive systems, motors, home applications, light industry, and a host of other areas.

Power Electronics Today

- The fraction of energy processed electronically is growing rapidly.
- Power electronics: every computer, almost every appliance or new electrical product

Power Electronics Today

- Soon in every motor, alternative energy system, and automobile
- Modern devices can manage energy flows from 0.1 W to more than 1000 MW.

Challenges

onsider a PC:

- Power supply is the largest part.
- Significant cost, reliability impact, system issues
- Yet there are perhaps 100 digital circuit design engineers for every power electronics engineer.

Challenges

Computer industry -- low voltage at high current. High reliability. Data servers.

Telecommunications -- distributed power, battery power.

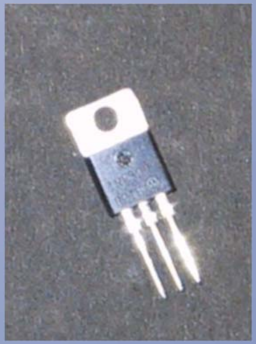
Aerospace -- aircraft and satellite systems. Distributed systems.

Heavy industry – mining, construction.

Challenges

- Automotive industry -- electric traction, actuators, motor control, networks, . . .
- Energy industry -- energy management and control, power quality
- Devices -- power semiconductors, magnetics, . . .

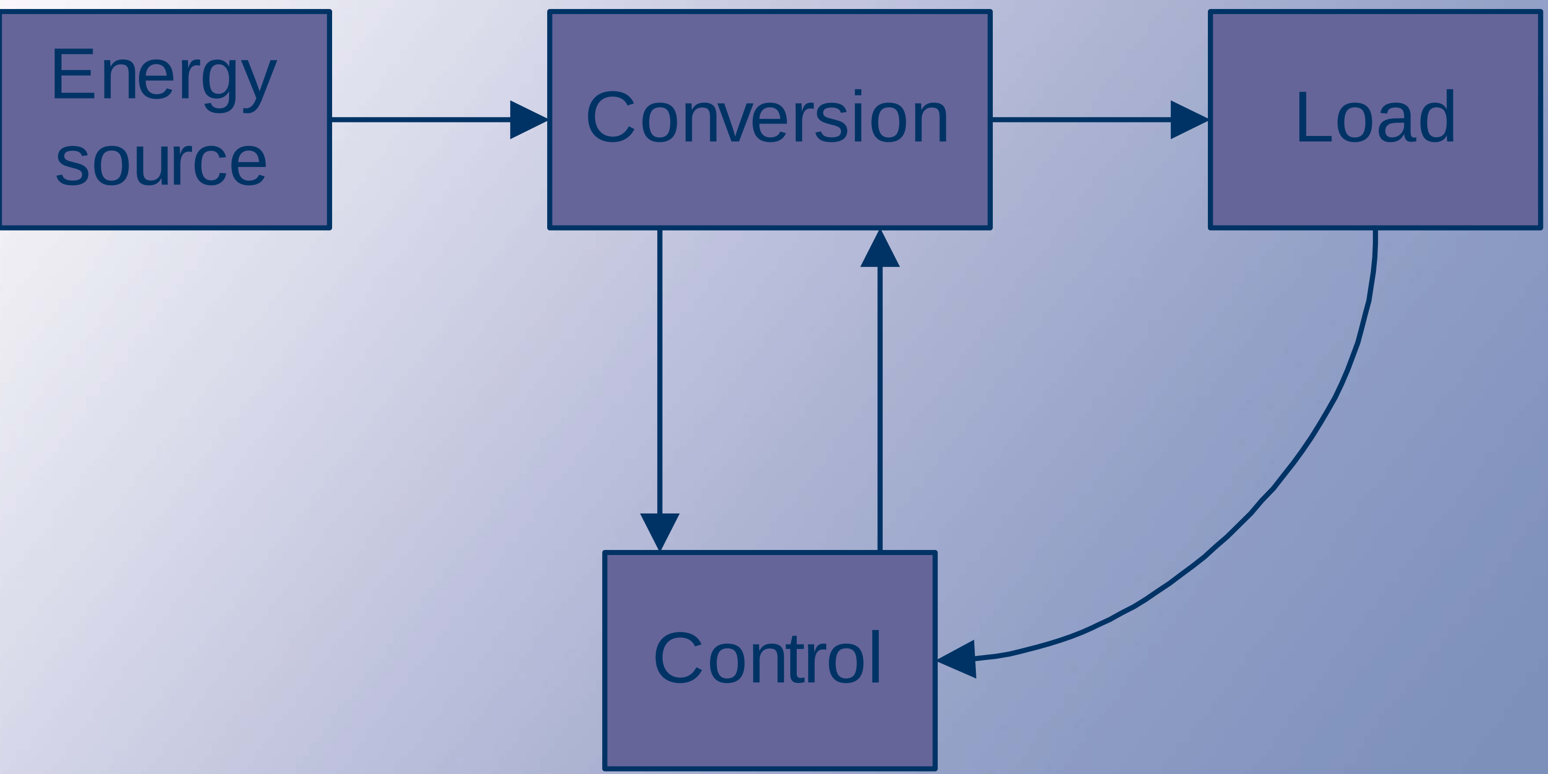
Examples of Components



Summary So Far

- All electrical engineers are in the business of conversion.
- Power electronics is distinct because we apply electronic devices and circuits directly to energy conversion.
- Long-standing needs, new challenges; not nearly enough expertise.

The Objectives



Objectives -- Intro

- Converter sits between source and load.
- Any energy consumed in conversion is lost to the system.
- Any failure in the converter results in failure of the system.

Efficiency

Consider only lossless methods.

Efficiency target: 100%

Consider only simple systems

Reliability target: 100%

How?

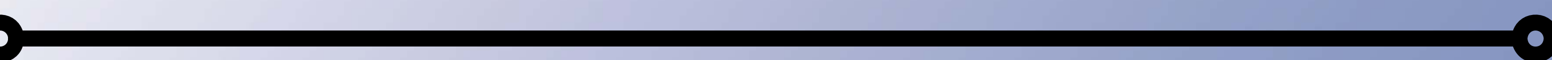
$$P_{SWITCH} = V_{SWITCH} \cdot I_{SWITCH}$$

The switch -- a simple lossless element

The Open Switch

$I_{SWITCH}=0$ $P_{SWITCH}=0$

The Closed Switch



$V_{SWITCH}=0$ $P_{SWITCH}=0$

The Switch

When on: $v = 0$

Zero power

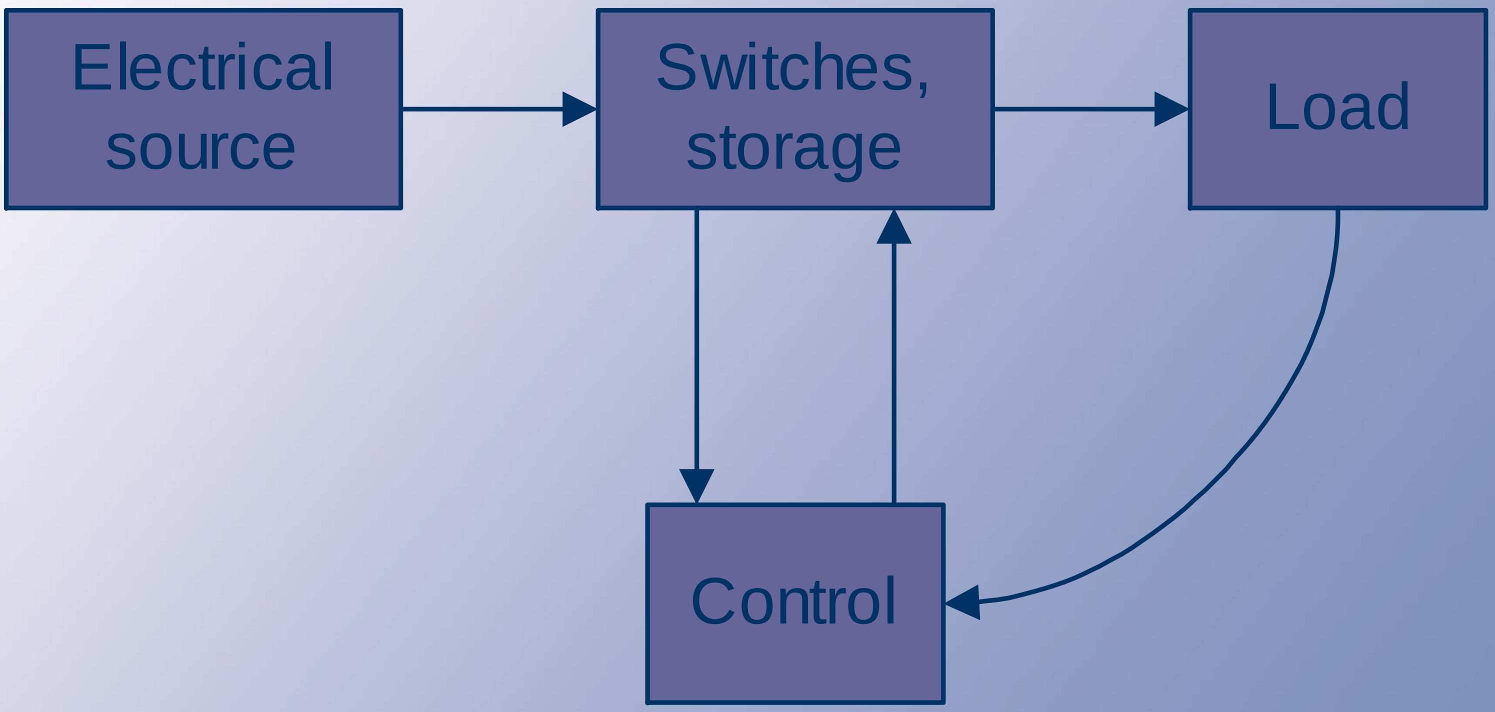
When off: $i = 0$

Zero power

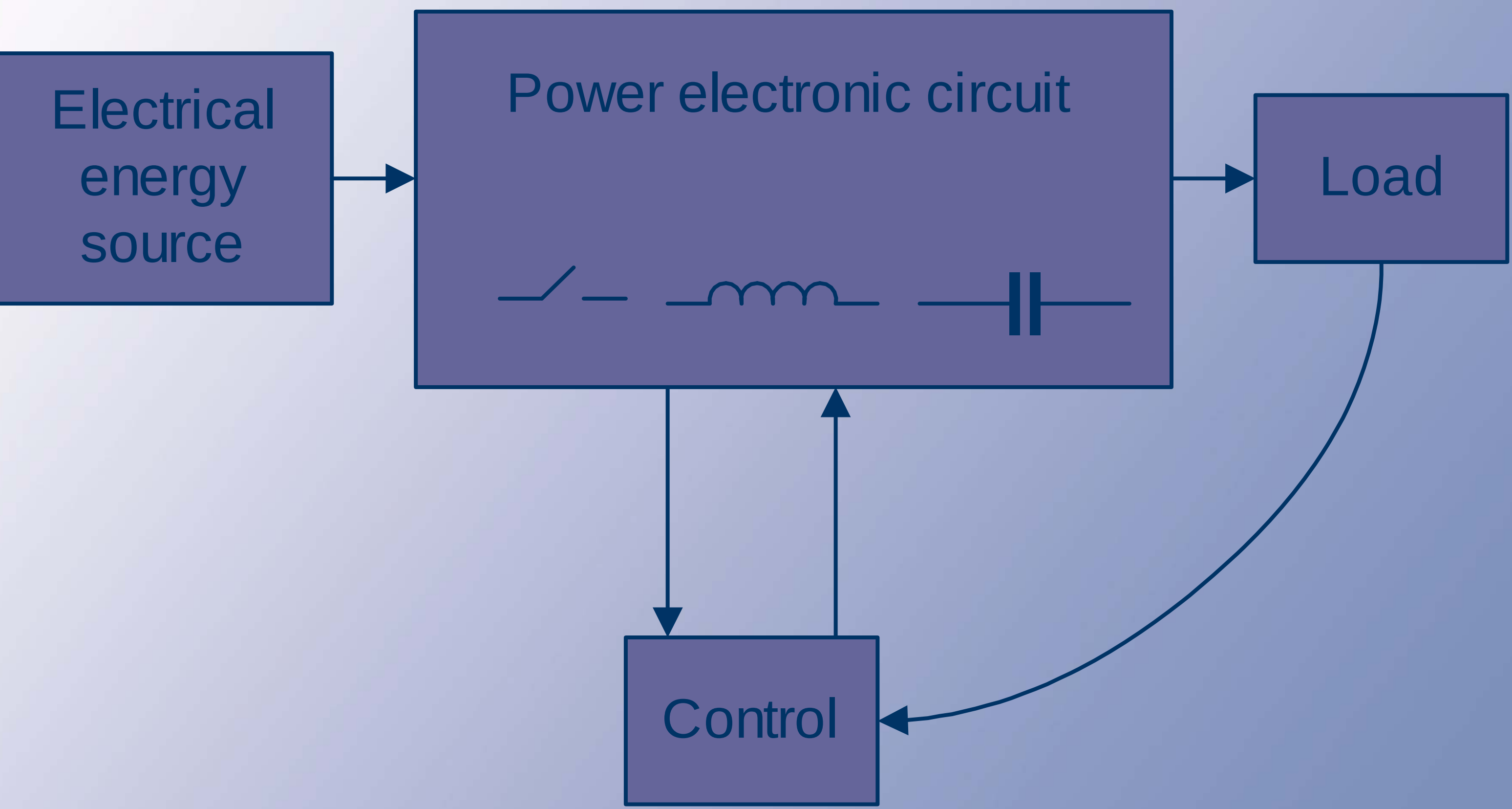
Type of Switches Required

- The switches need to be operated at high rates, presently, up to a few MHz.
- Mechanical devices have a life of ~100,000 operations, making them unsuitable for high rates.
- Semiconductor switches
  - Exhibit a much longer life.
  - Many different varieties.

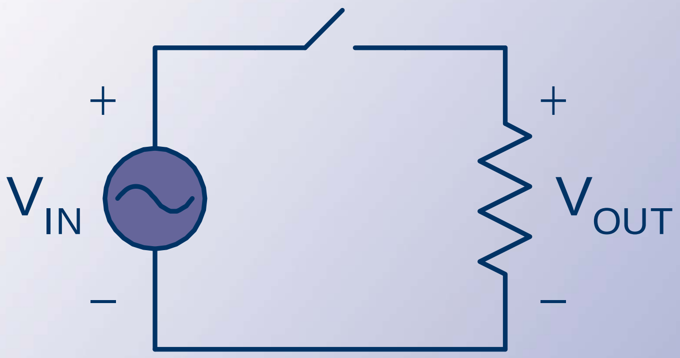
Power Electronic System

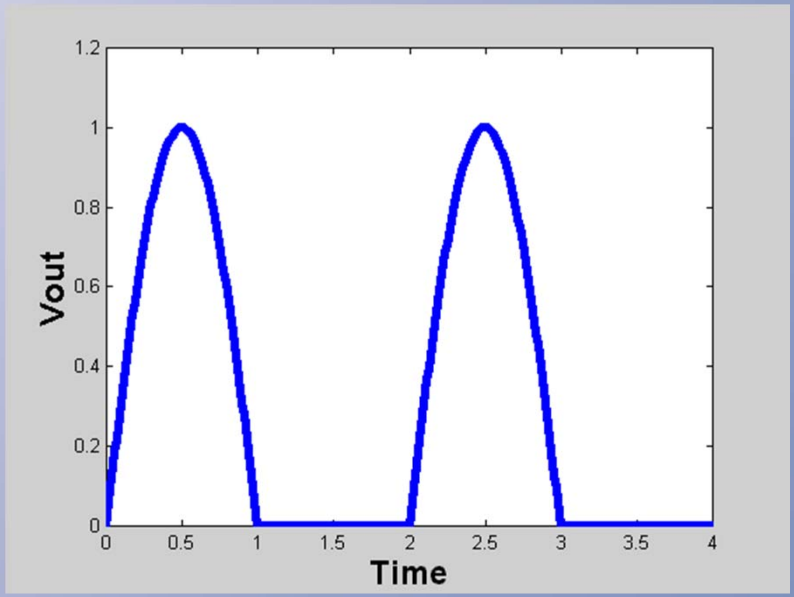


Power Electronic System



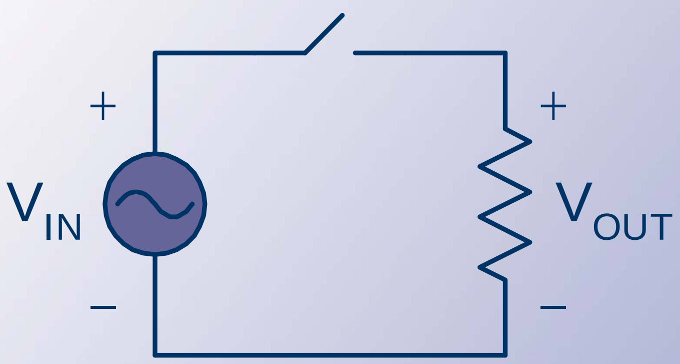
Examples

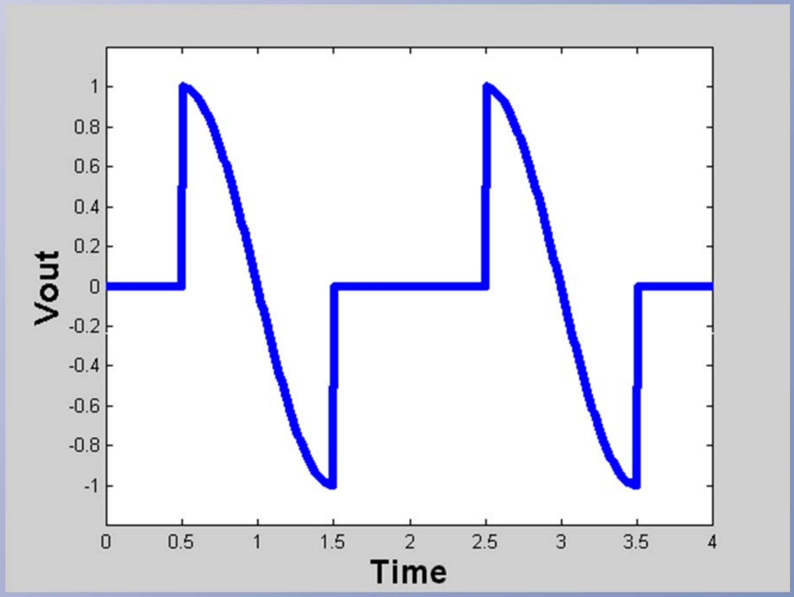




Switch ON if Vin > 0
Switch OFF if Vin < 0

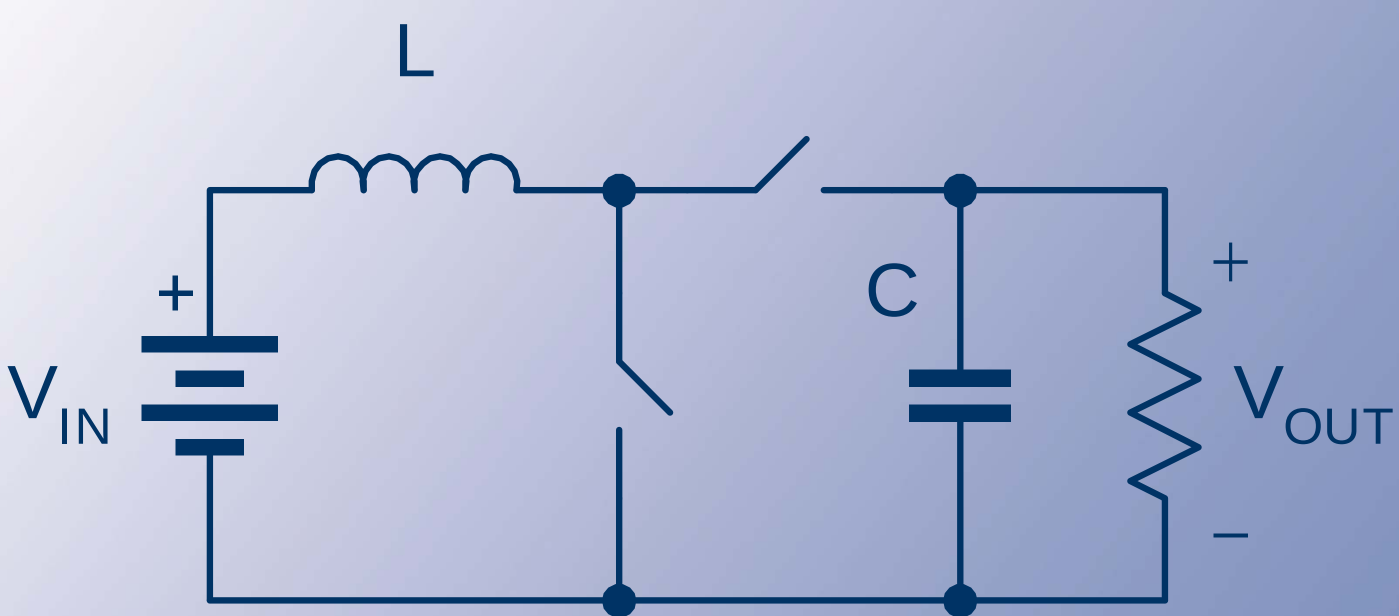
Examples





Switch ON at Vin peak
Stay ON for 1/2 cycle
Then OFF for 1/2 cycle

Examples



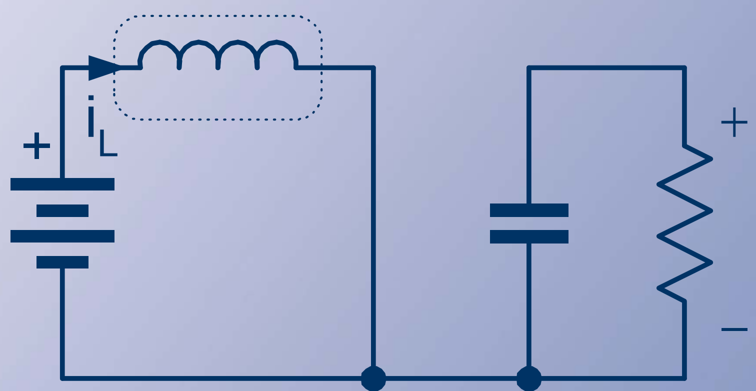
Alternate switching.
Balanced intervals.

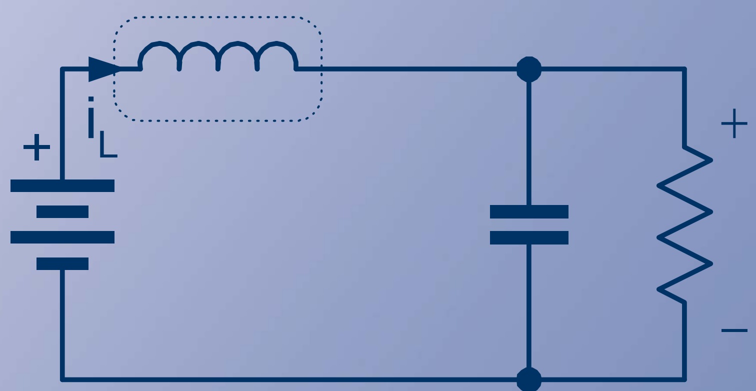
Analysis

- It is tempting to try to write loop and node equations for analysis.
- This does not work – loops and nodes change with switch action.
- How?
- Analyze *one configuration at a time* then assemble results.
- Conservation of energy is key.

Examples

Two possible configurations:





Examples

Total energy in over a whole interval:

$$W_{in} = \int_0^{T/2} V_{in} i_L dt + \int_{T/2}^{T} \left(V_{in} - V_{out}\right) i_L dt = V_{in} i_L T/2 + \left(V_{in} - V_{out}\right) i_L T/2 = 0$$

$$\boxed{V_{out} = 2V_{in}}$$

Ex.: V_{IN} = +12 V V_{OUT} = +24 V

BOOST CIRCUIT

Examples

Two analysis methods

- –Circuit laws → later
- –Energy balance

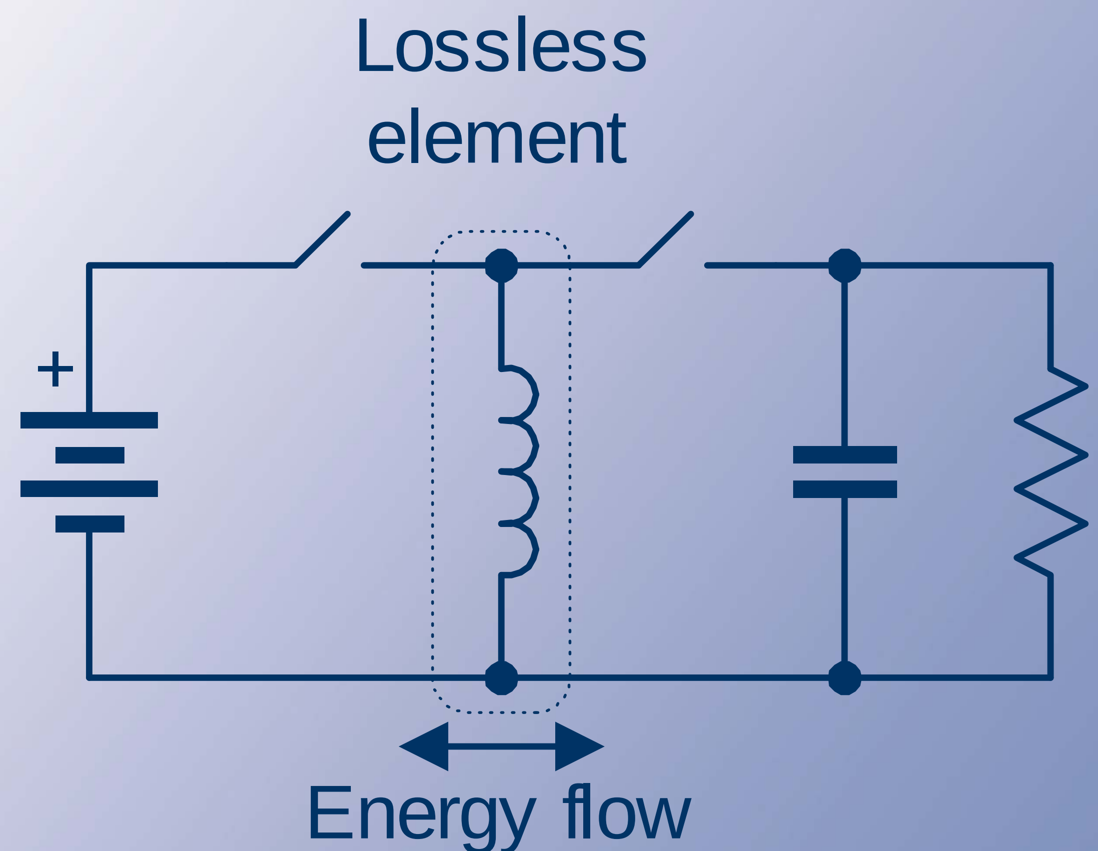
Examples

Many types of power supplies.

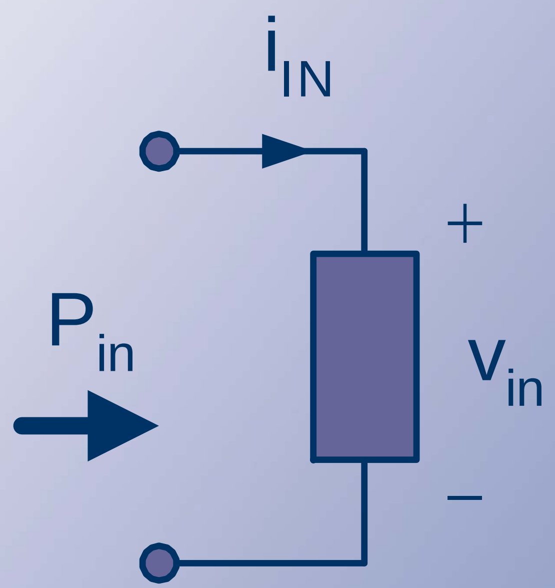
Energy Balance

- Energy balance works if we can identify a specific element.
- The element is analyzed as a one-port network.
- If the element is lossless, input and output energy must balance, at least over an extended time interval.

Energy Balance



One-Port Model



Define polarities and input power.

One-Port Model

- All power input is either stored or consumed (lost).
- Over a long time interval, the net stored power is zero.

Example: Battery

- A “primary” battery:
  - Over modest times, it acts like a dc voltage source.
  - After a long time, it is dead.
- Rechargeable battery:
  - Over a long time, whatever energy is drawn out must be restored through recharging.

Example: Resistor

All input power is consumed immediately.

The net input power must be I^2R.

Example: Capacitor

- Non-zero input power is stored.
- We cannot increase stored energy indefinitely, since ½ CV^2 will be limited by voltage ratings.
- Ideally, there is no loss.
- Over an extended time interval, the net input power must be zero.

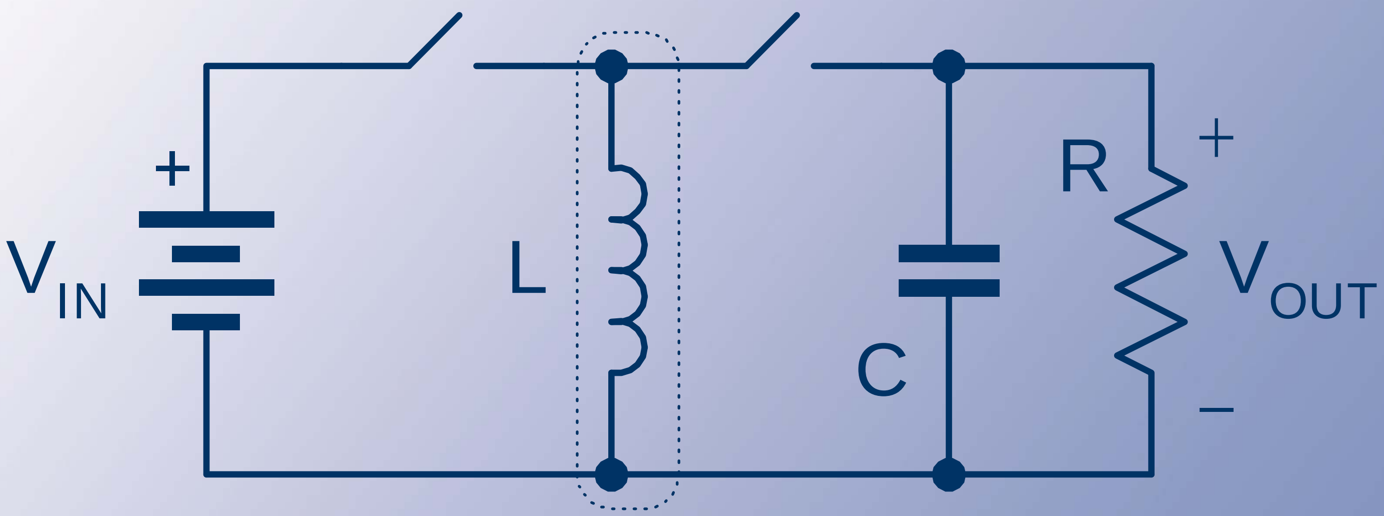
One-Port Model

- The input power is defined as (v)(i), positive with current and voltage polarities as shown.
- This means the output power is -(v)(i).

P_{in}

- With a storage element inside, there is a lossless energy balance over time.
- For lossless balance, we can either take P_{in} = P_{out}, or we can take a total P_{in} of zero.

Back to Polarity Reverser



Left switch ON : $P_{in} = V_{out} \cdot i_L$

Right switch ON : $P_{in} = V_{in} \cdot i_L$

Energy Balance

- We know the inductor is lossless, so the net input should be zero.
- Thus, the total input energy over a switch sequence should be zero.
- If each switch is on for an interval T, this means:

$$W_{in} = V_{in} i_L T + V_{out} i_L T = 0$$

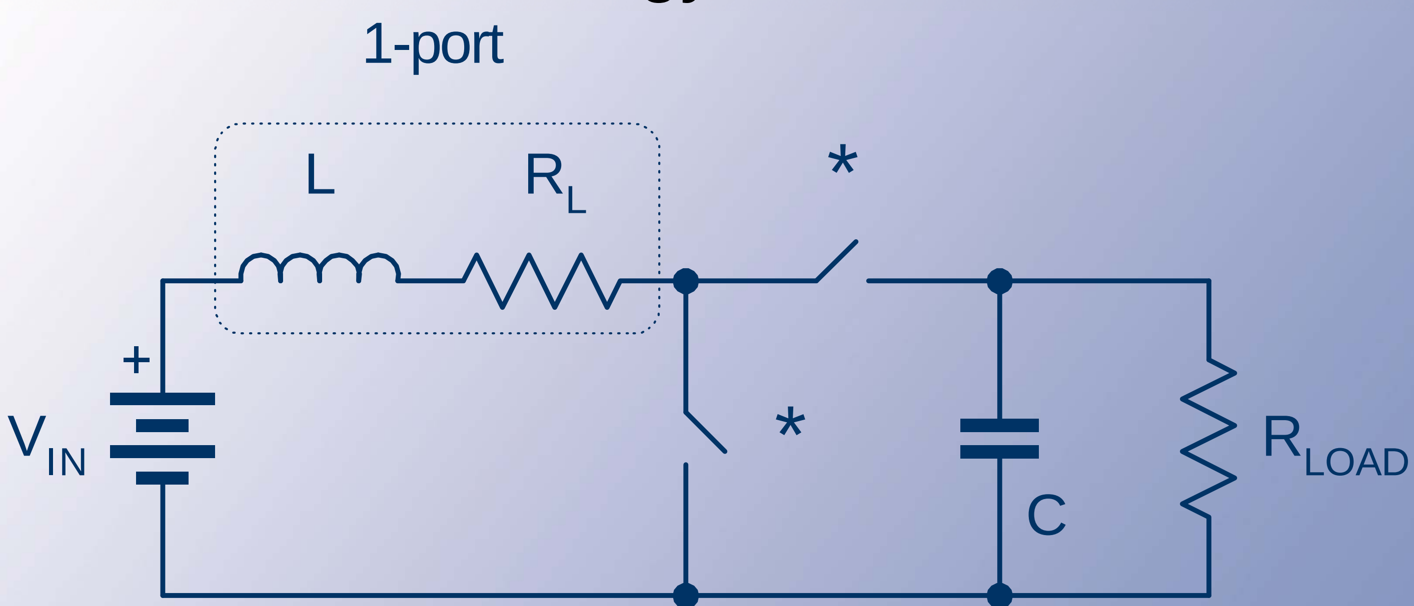
Energy Balance

This requires $V_{out} = -V_{in}$ if the currents and times are nonzero.

Energy Balance

- Now, let us try a more challenging case, such as a boost circuit with loss.
- The inductor is now in series with a resistor.

Energy Balance



- Again, let L and C be large.
- Let switches act in alternation, for equal times.
- Each closed T/2 sec.

Energy Balance

In this case, the net one-port input power is no longer zero. It must also include the resistor I^2R loss for proper balance.

But notice that energy is still conserved. The total energy drawn from the input source must supply losses and the load.

Energy Balance

$$\text{Left ON}: W_{in} = V_{in} i_L T / 2$$

$$\text{Right ON}: W_{in} = \left(V_{in} - V_{out}\right) i_L T / 2$$

$${}_{in} i_L T / 2 + \left(V_{in} - V_{out}\right) i_L T / 2 = i_L^2 R_L T$$

We have two unknowns (i_L, V_{out}) and one equation.
We need one more equation.

Energy balance from source to load

$$V_{in} i_L T = i_L^2 R_L T + \frac{V_{out}^2}{R_{load}} T$$

$$V_{in} i_L = i_L^2 R_L + \frac{V_{out}^2}{R_{load}}$$

Now we have two equations and two unknowns.

Balance

The result is a solution of a quadratic.

If the loss resistance is too high, the process does not work to perform conversion.

EFFICIENCY TARGET → 100%

If loss is very low, $V_{out} \sim 2V_{in}$.

If the loss resistor is 1% of the load resistor, $V_{out} = 1.91\ V_{in}$, ...

Result

R_L	V_{out}
$\rightarrow 0$	$\rightarrow 2V_{in}$
$\rightarrow \infty$	Process breaks down
$\approx$ 1% of R_{load}	$\approx 1.91V_{in}$
…	…

Efficiency Examples

- Power electronic circuits, with switches and storage elements, are lossless in principle.
- Individual devices are pushed hard to handle high power levels.
- *But*, switches and other devices are not perfect. There will be a little energy loss.
- We still require 100% efficiency *in principle*, but must accept 90%, 95%, or …

Efficiency Examples

- The actual loss is not zero. Losses in devices (power dissipation) will cause heating.
- Any device has a power dissipation limit above which it can fail.
- Even at very high efficiency, dissipation limits can be a key factor.
- The hottest part will likely limit system performance.

Efficiency Examples

Q: (Typical example) A converter is 95% efficient, and uses six power MOSFETs as switches. The devices can safely dissipate up to 50 W each. What is the system power limit?

Efficiency Examples

A: The designer should make sure the dissipation is even so that no single device will limit the system. The total loss can be up to 6x50 W = 300 W. At 95% efficiency, $P_{out}/P_{in}=0.95$ and $P_{in}-P_{out} \leq 300$ W.

Result: $P_{out} \leq 5700$ W.

Efficiency Examples

Q: We want a power converter to provide up to 100 kW output for an electric vehicle application. The control power is 100 W. The total dissipation in the converter must not exceed 1000 W. What converter efficiency is required?

Efficiency Examples

A: Since the controls already dissipate 100 W the converter hardware must not dissipate more than 900 W. This means $P_{in} – P_{out} < 900$ W. Since $P_{out} = 100$ kW, the efficiency $\eta = P_{out}/P_{in}$ must be

$$\eta > 99.1\%.$$

Efficiency Examples

- What if the efficiency is “only” 98%?
- At 100 kW output, the dissipation will be 2040 W plus the 100 W control power.
- The total is more than double the limit, and the system is likely to fail quickly.
- Or we could limit the output to 44 kW, but this is less than half of what is needed!

Efficiency Considerations

- To attain high power levels, we need devices that are:
  - Extremely efficient.
  - Or can dissipate a lot of power (or both!).

- The devices are selected in part of efficiency.
- Their packages and cooling are selected to permit high dissipation.