

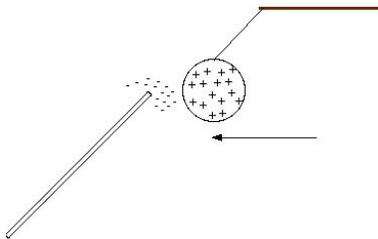
Basics on electricity and electrical generation

EJ Moyer, U. Chicago

April 18, 2010

History:

Around the same time as the birth of the steam engine, various gentleman-scientists were experimenting with some interesting phenomena involving electricity, starting with the observation of “static electricity”: by rubbing certain materials together (e.g. glass and silk, or rubber and wool) those objects would then attract or repel each other. In the terminology that developed, the objects acquired electric “charge”. Benjamin Franklin defined the sign of this charge by declaring that rubbing silk on glass produced positive charge, and his definition has stuck ever since.



We now know that what these early experimenters were doing was stripping apart electrically neutral atoms and transferring electrons from one material to another, leaving each material with an excess or deficit of electrons (which, when you think about it, is pretty remarkable for simply rubbing a glass rod with silk). These electrons (and the rest of the atoms that are left behind) carry a quality we call charge. Since we’re stuck with Franklin’s definition, we have to declare that the electron carries negative charge and the atomic nucleus positive charge.

Over the course of the late 1700s and early 1800s, more and more was discovered about the forces that electricity could produce. For more than a hundred years these produced no usable technology, but the public was fascinated and people flocked to public lecture-demonstrations at the Royal Institution of London (see this site for pictures and discussion of the phenomenon of Victorian science demonstrations).

Electricity found its first practical use not in generating mechanical work but in lighting, with the arc light (invented in the first decade of the 1800s but not commercial for another 50-70 years) and, starting later but ultimately killing off arc lights, the incandescent bulb (with different designs patented by a number of inventors in the 1870s, of which Edison’s was the most practi-

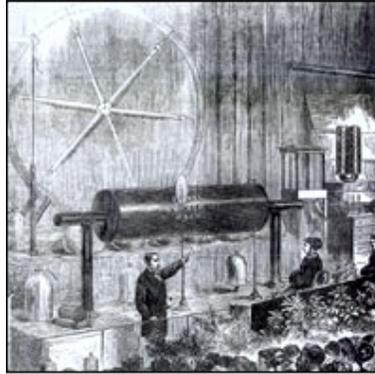


Figure 1: Nikola Tesla demonstrating AC electricity before the Royal Society, (*image from Queen's Univ. Belfast*)

cal, allowing him after 10 years of patent litigation to get declared the father of electricity). In a lightbulb, electric charge moving through a highly resistive filament generated tremendous amounts of heat, which in turn (as we learned in the first lectures) produces radiation. Demand for electric lighting was rapid, with the first house in England electrified only three years after Edison's patent. The first electric companies providing electricity (one of which was Edison's own business) were meeting demand for lighting, not electric motors.

Large-scale electricity use required some means of producing electricity other than the earliest primitive batteries, and was possible only because of the development of the generator, which converts mechanical work to electrical energy. The connection between electricity and mechanical work was known since 1821, when the great Michael Faraday (another English scientist) figured out that when he ran an electric current near a permanent magnet, he generated a force that moved the wire carrying the current. That's the principle of the electric motor, but for the next 50 years, motors were toys and laboratory demonstrations only. (See these pictures of early electric motors, only the latest of which are commercial). Most technical development concentrated on generators instead.

In the first electric generators, or "dynamamos", some source of mechanical work turns loops of wire within the field of a permanent magnet. That motion forces electrical current to flow through the wires, producing a flow of current in one direction, what we call direct current or DC. The electric



Figure 2: Ritchie motor from 1830's (*image from website cited above*)

motor didn't get commercial use until one dynamo manufacturer realized at an industrial exhibition in 1873 that one of his dynamos that was actively producing electricity had gotten accidentally connected to another and was turning its shaft: that is, a dynamo run in reverse was a motor. From that point on using electricity to move things became a focus of industrial development.

By the 1893 Chicago world's fair (held here in Hyde Park!), one exhibit showed an 'All Electric Home' complete with electric lighting but also washing machine, dishwasher, doorbells, phonographs, and carpet sweepers. By 1900, in Paris, Henry Adams was stunned by his inability to understand the new technology. By 1911, as you saw in class readings, factories were considering replacing their water- or steam-driven shafts with electric motors.

Just as the birth of the lightbulb was torn by patent litigation, the early electric industry was torn by a battle over standards, between Nikola Tesla and his business partner George Westinghouse who advocated alternating current (AC) and Thomas Edison who had pushed DC from that start. It took awhile to sort out: Tesla's AC generators were shown in the 1893 Chicago world's fair; Adams was swooning over Edison-favored DC dynamos in 1900. In the end, AC won out, Westinghouse got rich, (though Tesla died in poverty; life is not always fair to inventors), and most electricity used now is AC rather than DC.

The electrical current that you can get from a wall socket is AC current, alternating direction 60 times a second, i.e. at a frequency of 60 Hertz (in the U.S., that is. In most of the rest of the world, the frequency is 50 Hz. The U.S. just has to be different).

A battery however produces direct current: hook up the battery terminals and current flows steadily from one terminal to another. The increasing use of portable, battery-powered devices creates some conflict and necessary



Figure 3: Hall of Machines at the Paris Exposition of 1889

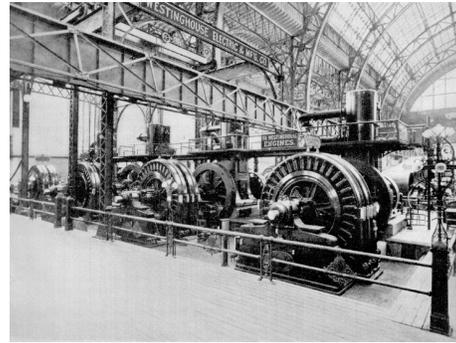


Figure 4: Tesla's AC generators at Chicago Exposition of 1893

wastage of power. Your laptop, which must sometimes run off batteries, must then always run off DC current. When it is plugged into wall power, that AC power must be converted to DC. That's why your laptop power cord has that square or rectangular “brick” on it: it's an AC-DC converter. All chargers, in fact, that plug into the wall and charge up battery-powered devices (cellphones, cameras, etc.) have to have AC-DC converters. Those converters are not perfectly efficient, which is why they feel hot to the touch when plugged in. That is waste heat from imperfect conversion.

Solar photovoltaic power production generates another conflict between AC and DC standards: what you get out of a solar panel is DC power, easy to store in a battery but hard to feed into the AC electrical grid. Industrial solar PV facilities use DC-AC converters, again not perfectly efficient, to make their power saleable. People with household solar PV who want to use “net metering” or otherwise sell power back to the grid must also DC-AC convert. Some PV-panel owners, however, who live off the grid entirely, buy special DC-powered appliances to avoid the expense and wastage of converting their solar power to AC, as do boat owners who run appliances off solar panels.

Bare-bones review of electricity and magnetism:

Electric charge, field, and voltage

The basic unit of electric charge in SI units is the Coulomb. The smallest unit of charge in nature is a single electron, but as it is not practical to book-keep individual electrons the Coulomb is defined at over 10^{18} times larger than an electron's charge. Because of Ben Franklin's mistake, the electron has a negative charge, with

$$e = -1.60219 \cdot 10^{-19} \text{ C}$$

The universe as a whole must be neutral in charge, i.e. positive and negative charges must balance each other. Locally, however, you can have an imbalance of charge. (If you couldn't, there'd be no electricity for us to discuss).

Any charge produces an electric field that falls off as the square of distance

$$\mathbf{E} = \frac{kq}{r^2}$$

for a point charge, where q is the charge and k is a physical constant, the Coulomb constant. The boldface notation indicates that electric fields have a direction and are not simply scalars.

If another charge - call it q_o - interacts with an electric field, it will experience a force, either attractive or repulsive:

$$\mathbf{F} = q_o \cdot \mathbf{E}$$

where E is the electric field and q_o the charge. The force exerted by two point charges q and q_o on each other is then

$$\mathbf{F} = \frac{kqq_o}{r^2}$$

That definition seems awfully analogous to the force of gravity between two bodies, another force that depends on the properties of the interacting bodies and falls off as $1/r^2$: $F_{grav} = Gmm_o/r^2$, or $F_{grav} = m_o \cdot g$, if we fold all the other constants into one constant g , the acceleration of gravity, and assume it's constant.

Drawing on the analogy with gravity further: We have already defined gravitational potential energy as the energy we'd get out if an object is allowed to fall pulled by the force of gravity from a height h :

$$P = g \cdot h$$

In other words, gravitational potential energy is the energy that could be extracted if a unit mass were allowed to move a distance h under the influence of the Earth's gravitational field. Its units are J/kg.

Similarly, an electric potential is the energy that could be extracted if a unit charge is allowed to move under the influence of an electric field: If that field is constant (as we'd assumed the Earth's gravitational field was above), then

$$V = -E \cdot h$$

where E is the electric field and h is the distance over which that potential is measured. (If E isn't constant over the distance h , you'd have to integrate to get the resulting potential).

The units of electrical potential are Volts, where 1 Volt equals 1 Joule per Coulomb (1 J/C). We will talk about voltage frequently in all parts of the class that have to do with electricity. Think of voltage as a kind of height from which electrons can "fall". We define the bottom of this fall, the location of zero voltage, typically as the average Earth ground. So any charge at higher voltage will "want" to flow to the ground.

Note this this analogy of falling bodies was the same that Carnot used when he thought of heat as flowing from a hot to a cold body. It's a useful analogy in many areas of physics.

Electrical current and resistance

An electrical current is a flow of charge, i.e. charge per time. The basic unit is an Ampere (usually abbreviated to "amp"), which is a flow of 1 Coulomb of charge per second. In the real world, the electrical currents we use and measure are flows of electrons, which by Franklin's mistake have negative charge. A positive electrical current then means that electrons are actually flowing away, in the opposite direction. (You never need to worry about this unless you really want to think of what individual electrons are doing, and then you have to grasp the mind-bendingness of having the world working backwards from what your math seems to describe).

If two objects of different voltage are connected, charge will “want” to flow from the high to the low voltage. Think of this again on the gravitational analogy: imagine a dam holding water at a high elevation whose gates are suddenly opened; that water will “want” to flow to low elevation.

In both the water-flow analogy and in an electrical system, there must be some physical limitation to flow: the dam does not empty instantly, nor does infinite current flow when you connect an electrical circuit. The physical something that limits electrical current is termed resistance. For a given voltage, the higher the resistance, the lower the flow:

$$I = V/R$$

This is Ohm’s law.

Thinking through what causes resistance: you’d imagine the resistance of wire is a function of some property of the material (let’s call it “resistivity” and give it the symbol ρ). You know that wires for carrying electricity are made of metal and not plastic, and there’s a good reason for that.

You might also imagine that the resistance of a wire is a function of its shape. You’d intuitively guess that a long wire has more resistance than a short one.. if you make the analogy that electrical resistance is somehow like obstacles that each electron runs into, the electron obviously has more chance to run into an obstacle the longer the distance it travels. You might intuitively also imagine that it’s easier for current to flow through a fat wire than a thin one, just as traffic flows better on a multilane highway than a narrow road. You’ve likely noted in everyday life that cables or extension cords used to connect to high-power appliances must be fatter than normal, so somehow bigger-diameter wires are used to carry more current.

Combining these intuitions, we can write

$$R = \rho \cdot l/A$$

where ρ is the intrinsic resistivity of the material, l is the length in the direction the current is flowing, and A is the cross-sectional area perpendicular to the direction that current is flowing.

We use copper wires for carrying electrical current because copper has a very low ρ and current can flow readily without many losses. Plastic has a resistance so high that it effectively does not carry current at all; for that reason electrical wires are insulated in plastic (teflon, for the best wiring). Your body has a resistance intermediate between metal and plastic, which is

why you need to be careful about not sticking fingers into electrical sockets; the current will happily flow from the high-potential socket through you and down to the lower-potential ground.

Electrical power and Joule heating

The power carried by an electrical current must have the units of power, J/s. Looking back at our previous definitions it's easy to deduce from units alone that power (J/s) must be voltage (J/C) times current (C/s).

$$P = I \cdot V$$

This definition is entirely consistent with our analogy with gravitational potential. If you analogize electrical current (in units of charge /s) to water flowing in a river (kg/s) and the electrical potential V with the the gravitational potential as water goes over a waterfall $g \cdot h$ then the expression for electrical power P carried as current “falls” down a potential difference is the same as that for the kinetic energy gained by of water going over a waterfall.

What happens to that power? It can't all go to doing work, because we know that sometimes current can flow in a circuit without doing any work at all. Inevitably some goes to, you guessed it, heat. If there is resistance, there is loss to heating.

The amount of current flowing down a potential difference V in a medium that has a resistance R is constrained by the resistance and Ohm's law to be $I = V/R$. Plugging this in we get

$$P = I^2 R$$

This is what is called “Joule heating” (or sometimes “resistance heating”), and it's an inescapable feature of the world.

Wait, you might say. Does that mean that all electrical power goes into heat, and can never do work? Sometimes of course you *want* all your electrical power to go into heat, as for example in a space heater or a lightbulb. But in an electric motor you want to use as much of your power as possible on producing motion, and joule heating is an irritating loss. And yes, $I^2 R$ heating happens whenever you have I and R . And if your only voltage drop is across a resistance, then yes, all your power will be consumed in resistance heating. But luckily resistance heating need not consume all the electrical power carried by a current. Current flowing through an electric

motor spinning a load necessarily shows an additional voltage drop, and some fraction of that can be converted to mechanical work.

Note: Appliances whose only function is to turn electrical energy into heat by Joule heating don't "care" whether the current you put across them is AC or DC. Joule heating doesn't depend on what direction the current is flowing. An electric motor, though, is designed only to work with one or the other.

Also: the fact that not all electrical power is lost as resistance heating doesn't mean that heating losses are negligible. A big driver for the development of practical superconducting materials is that superconducting materials have essentially no resistance and therefore no losses to heat when they carry current. Finally: I suppose really people ought to differentiate between V as an absolute voltage and ΔV to imply a drop in voltage, but somehow the two meanings get conflated into one symbol V , which is confusing.

Relation between electric and magnetic fields:

19th century scientists spent decades puzzling over the interactions between electric and magnetic fields and the ability via that interaction of producing mechanical forces. As noted above, Faraday first observed that when he ran a current through a wire near a magnet, he could generate a force that pushed on the wire. The current appeared to produce its own magnetic field, which repelled the magnet. (You've played with magnets before, and can feel how they attract or repel each other). This observation became codified as "Ampere's law," as Ampere rushed to publish (in 1821) his explanation of others' experiments that he had read about.

Despite losing out to Ampere on that one, Faraday did manage to get a law named after himself based on his writings of the next year, 1822. He had also experimented with wires that carried NO current, and had discovered that although an inert current-less wire did, as expected, nothing when simply sitting next to a magnet, he could generate interesting behavior when he moved either the wire or the magnet. Either movement would make current flow in the wire. After long experiments with loops of wires and magnets, Faraday concluded that an electric current can be produced by any changing magnetic field, and would be proportional to the rate of change of that field. He got a current in a loop of moving wire because moving the loop effectively changed the magnetic field "flux" - the field captured by the loop of wire - and so drove a current around the loop. The observations produced

Faraday's law, which relates an "electromotive force" - a voltage that pushes a current - to the changing magnetic flux:

- Ampere's law governs how electric motors work: flowing a current generates a magnetic field and, in the presence of another magnet, generates mechanical force.
- Faraday's law governs how generators work: changing the magnetic field through a loop of wire (by mechanically moving the wire or the magnet) generates current.

Generators, AC and DC:

AC generator

The earliest AC generator is in some ways the simplest possible way to convert mechanical work to electricity. Some source of motion is used to turn a loop or coil within a fixed magnetic field. Voila, a current flows around the loop. The only hitch is that to get the current out to do something useful, that loop has to be connected to wires, and the wires can't themselves revolve, or they'd be twisted into a knot instantly. The solution is to connect the rotating loop to fixed wires via "brushes" or "slip rings" made out of some kind of electrically conductive material. The brushes slide along a ring and maintain electrical contact as the loop rotates.

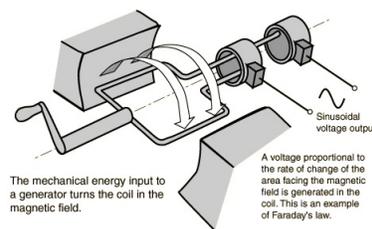


Figure 5: Simple AC generator with rotating loop

Since the loop rotates 360 degrees through the field, the changing magnetic flux through it changes sign: sometime the magnetic field points up through the loop, sometimes down. That means that current around the

loop also has to change direction. The output is AC current flowing back and forth in a sine wave.

$$I(t) = I_{max} \cdot \sin \omega t$$

where ω is the angular frequency $\omega = 2\pi f$ and f is the frequency we're used to thinking about, e.g. 60 Hz for American electrical current.

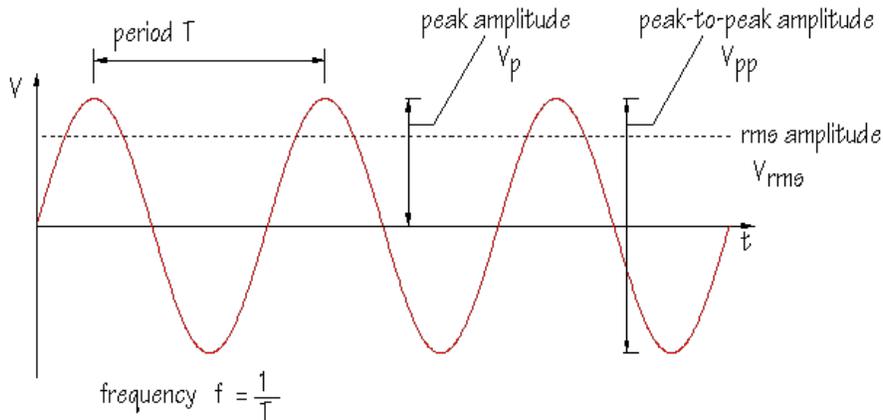


Figure 6: Sine wave terminology. The y-axis here is voltage or current, the x-axis is time. The current that comes from a wall socket in the U.S. oscillates at 60 Hz, i.e. switches direction every 1/60th of a second.

Note that in the simple loop generator, if you want AC current alternating at exactly 60 Hz, you have to spin the loop *exactly* 60 times a second. You get out what you put in. Modern power generation is all based on similar “synchronous” generators, whose frequency of output current oscillation is directly tied to the rotation speed of the generator. As we’ll talk about more when we talk about the electric grid, you can’t add electrical power to the grid effectively if its frequency isn’t matched *precisely*. Frequency stability is an important part of grid operation, and the need for it is one of the problematic aspects of adding electricity from wind to the grid.

Also note that the more coils you have, the more force pushing electrons around, because Faraday’s law says that each loop that turns in the field produces the same electromotive force. Commercial generators you see have not a single loop, as in the diagram here, but a dense winding of wire. It

takes more mechanical work to push all those coils through the magnetic field, so if you are rotating at a given frequency, adding coils gives you correspondingly more electrical power out. You want to have a single generator that is matched your source of mechanical work, since it's cheaper to build one generator with lots of coils than many small generators with single coil each.

Although brushes are fine for a low-power laboratory demonstration, they are problematic for commercial use, especially at high power: they spark, they wear out, and they cause energy losses. For this reason no modern AC generator is laid out as in the simple example above, with a spinning loop inside a fixed magnet. Instead, AC generators have fixed coils that carry current surrounding a spinning magnet. As the magnet passes by each coil, the changing magnetic field induces a current. (The interaction is amplified because the coils are wrapped around ferromagnetic cores to be electromagnets). The result is the same output alternating current, but the generator is mechanically more robust.

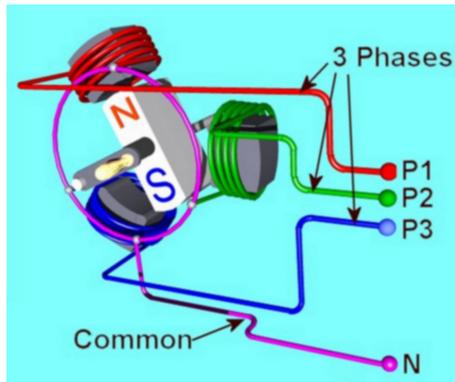


Figure 7: Schematic of an AC generator with fixed coils, rotating magnet. The three coils provide three separate circuits whose AC oscillation is out of phase: three-phase power. This is the standard for electrical power generation, to minimize transmission losses. For an animation click [here](#).



Figure 8: An AC generator with multiple coils, looking very much like the simple cartoon, only with a greater number of “poles”. This is an alternator from a motorcycle, that uses rotation from the driveshaft to produce electricity for lights and ignition. (See also the section below).

Generators used in industrial power production work on these same principles, with a rotating magnet (a “rotor”) turning within a set of coils that

carry the generated current in a fixed ring (the “stator”). The only difference in a large-scale industrial generator is that the magnetic field of the rotor is not generated by a permanent magnet, which would be too heavy at the field strengths needed for large-scale power production. Instead the magnetic field is generated from a smaller current flowing through a separate set of windings on the rotor itself: the rotor is an “electromagnet.” So there *are* some brushes needed after all, to carry current to the turning rotor. That rotor draws much less current than flows in the stator, however, making the use of brushes less problematic.

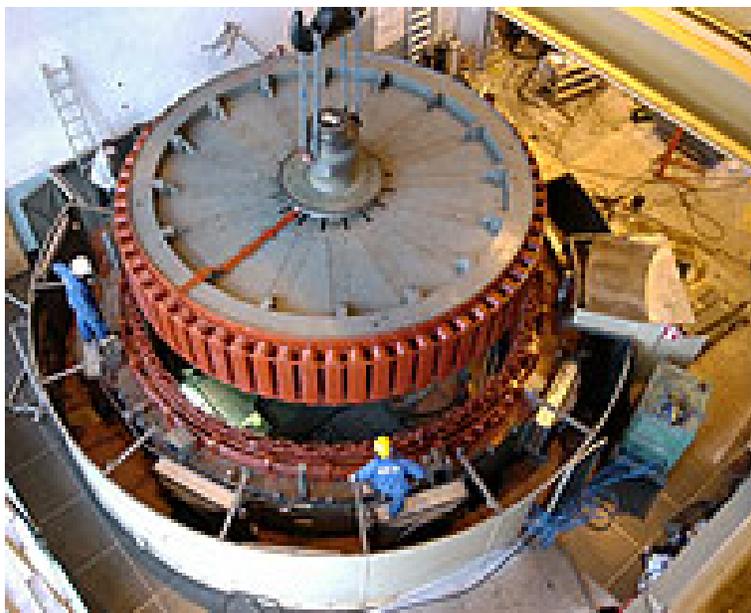


Figure 9: The rotor being lowered into the stator of a hydropower generator at Tyrvää, Finland. *Source: Alstom.*

DC generator

The DC generator in some ways is simpler than the AC generator. As discussed above, in an AC generator, a magnet turns inside fixed loops of wire that carry the current produced. A DC generator looks like the simple cartoon of Figure 5, with current loops turning inside the field produced by

a fixed magnet. Most DC generators are essentially simple rotating-coil AC generators in which the builders have made an effort to keep the current from reversing direction. The connection between rotating loop and brushes is a “split ring” that acts to reverse the direction of the current. (This device is also known as a “commutator”). The resulting output current is a rectified sine wave (see picture).

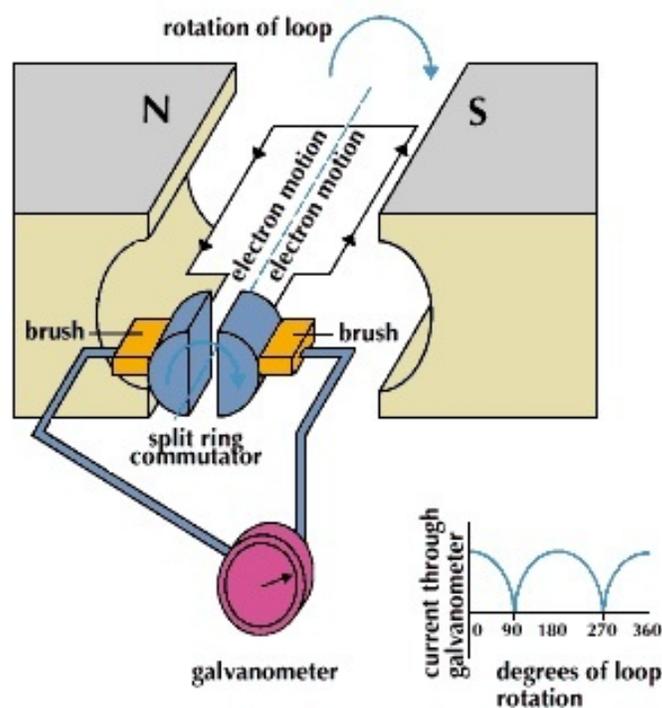


Figure 10: Simple DC generator with rotating loop, brushes and split-ring commutator (*Encyclopedia Britannica*)

Note that although a DC generator makes current flowing only in one direction, it doesn't make constant current - the current still varies between zero and maximum, meaning that power produced will be jerky (Figure 9). For this reason, all but the earliest and most primitive DC generators are arranged with many coils of wire at different angles, so that the power output is the sum of many rectified sine waves and is therefore much smoother (though it can never be perfectly smooth). “Ripple” in power production is

not important if all you are doing with the generator is charging a battery, but if the generator is used to directly drive a mechanical device it can be problematic.

Finally, the advent of modern electronics means that the AC and DC worlds need not be so separated. AC generators can in fact also be used to produce DC, since rectification can now also be done electronically using diodes that allow current to pass in only one direction. The alternator in your car is an alternating-current generator whose output is rectified via a set of diodes. The output of small home wind turbines, which drive AC generators, is often rectified to DC by the same means. By using the wind turbine for DC, one can avoid the need of controlling its speed to produce 60 Hz power and allow the turbine to turn at whatever speed gives maximum efficiency of power production.

We don't have a generator to show you in class - commercial generators tend to be large and expensive - but we do have several small, inexpensive electric motors that will run in the Electric Motors II lab. Since a generator is essentially an electric motor run backwards, these motor should give you some insight into generators.

Questions you might still have at this point include:

- Given how much trouble AC current is, why is that the world standard for electrical power? Why not DC?
- How are generators all over the country kept rotating in perfect synchronicity?
- Why 3-phase power?
- What happens if everyone shuts their lights off at the same time - if there is no demand for electricity?
- How efficient is conversion of mechanical energy to electrical energy, and what controls that efficiency?

We'll try to hit these topics in lecture.