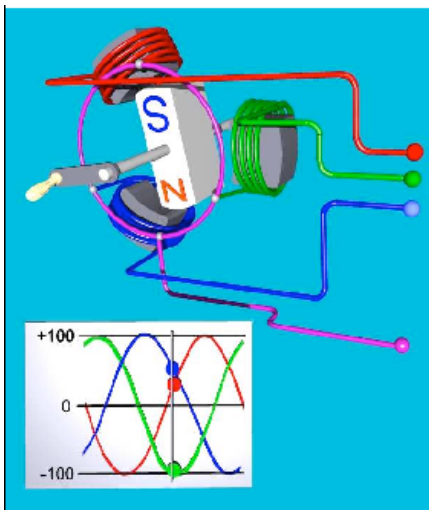
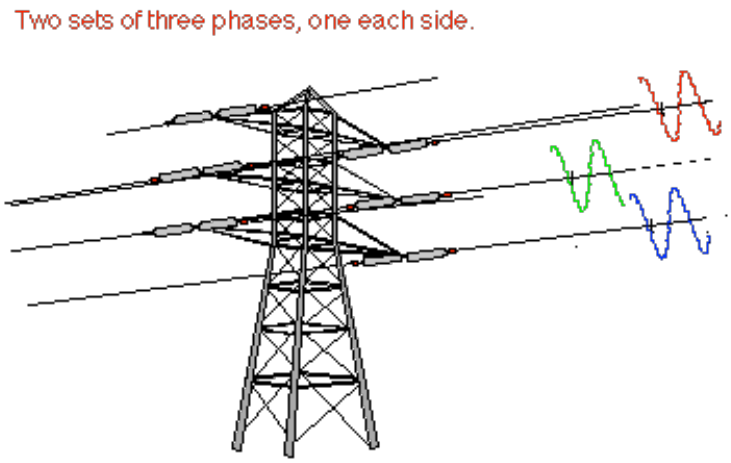
GEOS 24705 / ENST 24705
Problem set #Grid
Due: Tues. May 15

Problem 1: Three-phase power transmission

The standard means by which electricity is generated and transmitted in the U.S. is as 3-phase AC power: three different alternating current and voltage, each with the same frequency but out of phase with each other. That is, each generator carries separate windings that are not connected, and the rotating magnetic field in the rotor generates a different voltage in each one as the magnetic field changes in each set of coils successively. (See the animation previously shown in class if this is not clear: http://www.launc.tased.edu.au/online/sciences/physics/3phase/threeph.htm). Each industrial power generator is essentially three generators in one.



3-phase generation.
Image from koehler.me.uk



3-phase transmission.
Image from Launceton College

The electrical grid is therefore also essentially three grids in one, with three totally electrically separate sets of wires carrying the three phases. You never see high-voltage transmission that doesn't carry wires in multiples of three (except for the very occasional high-voltage DC line). Each wire carries a single phase.

(The three-phase transmission is, incidentally, the reason that a bird whose wings span two lines can cause a blackout. If the lines are connected, a current will flow because the voltages are different on the different lines at each moment. When it touches the bird will experience an oscillating current flowing back and forth, and very quickly you will have a dead bird and a blackout. If the three lines were all in phase, their voltages would be identical, and the bird could touch two at once without harm).

Although all electrical devices you use in daily life use only a single phase, and each plug a residential wall carries only a single phase there are efficiency benefits to using 3-phase power for industrial electric motors, so industrial customers often receive all three phases

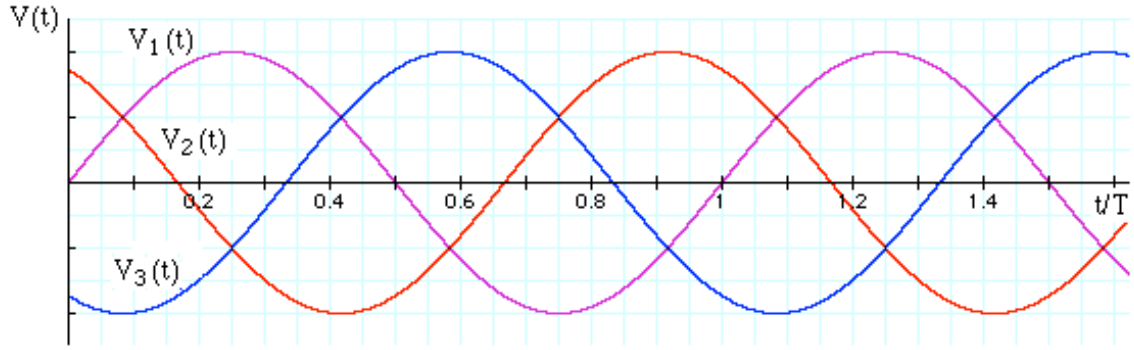
are wire them into special outlets. (The motor being the converse of the generator, you'd expect that if three-phase generation is advantageous then using all three phases in a motor would also be helpful).

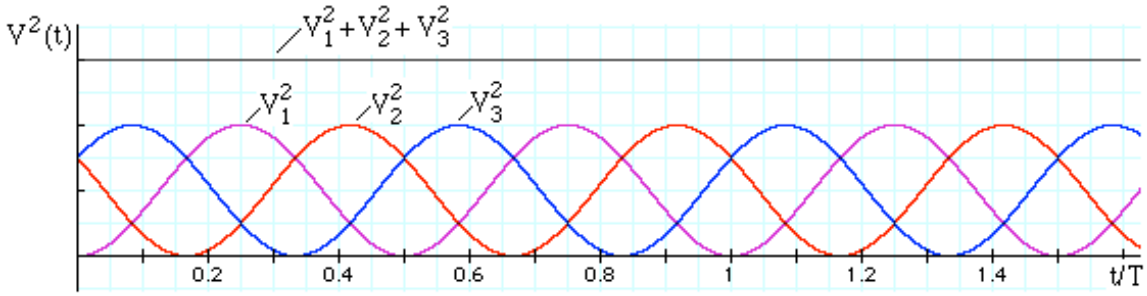
L: Single-phase outlet (a "hot" wire, a "neutral" or "return", and a grounding wire. *(Image source unknown)*.

R: Three-phase outlet (three "hot" wires, one "return", one ground)
Image from Demand Energy

The 3-phase AC power system also two tremendous advantages for transmission. 1) First, the voltages always sum to zero, so there is no net movement of charge. In each circuit the AC current is constantly "sloshing" back and forth, but at every moment the sum of all that current is exactly zero. That means that there is no need for return wire in the transmission system – a huge cost savings. 2) Second, the total power (which is proportional to V^2) carried by all three phases is constant at all times, so that power transmission is smooth, with no jerkiness – the same power is delivered at all times.

The diagram below shows V and V^2 for the 3 phases.





A. **Show from the physics that in each line, current will be proportional to voltage and that power is proportional to the square of voltage.**

B. **Demonstrate that the voltages sum to zero** (and therefore there is no net current in the transmission lines).

   For those who are comfortable with sines & cosines, consider the sum of $V_1=\sin(\omega t)$, $V_2=\sin(\omega t + \phi_2)$, and $V_3=\sin(\omega t + \phi_3)$ and prove that it equals zero. (You need standard trig identities but nothing fancier than that).

   For those who are not comfortable, pick four locations on the top figure above, and at each location measure V_1, V_2, and V_3 by hand and add them to show the sum is constant at all times.

C. **Demonstrate that the sum of the V^2s is constant** (and therefore that power transmission is constant).

   As before, for those comfortable with sine and cosines, show analytically that $V_1^2 + V_2^2 + V_3^2$ = constant. For those not comfortable, pick four locations along the figure and measure and add by hand.

D. **Can you get the same properties if you use only two phases?** Discuss and demonstrate.

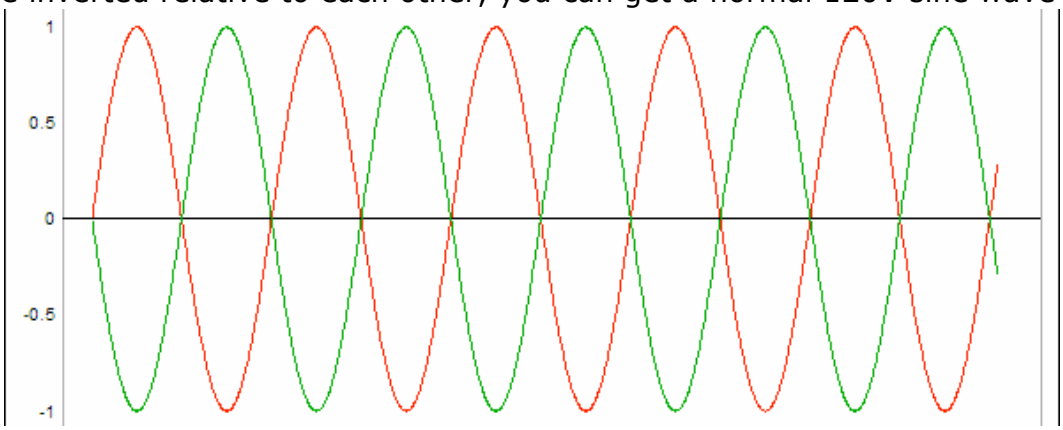
Problem 2: Electricity distribution – a very local field trip.
In the questions below, answer what you can from you local electrical system. If you can't answer a few, don't worry. These are look-see questions, not time-consuming.

The electrical power in your house is at a relatively low 110-120 V. You know from class discussions that resistive losses would be severe if you tried to transmit power at this low voltage for any significant distance, and that all transmission and distribution systems minimize resistive losses by moving electrical power at much higher voltages (and therefore lower currents). That means there must be a transformer quite close to your house. How close? Edison transmitted DC power at 110 V and couldn't extend his lines longer than 2 km, so you are sure to find a transformer within 2 km. In modern systems it is much closer than that. In the U.S., transformers are usually located on power poles.

In the U.S., the transformer not only steps down voltage but it also duplicates and inverts each phase that is fed into it. A single conductor that goes into the transformer is matched with three wires leading out: a "hot" wire that carries the original signal, only now stepped down in voltage to 120V, a "hot" wire that carries that same 120V signal only inverted (180 degree phase shift, for those comfortable with that language), and a return wires, because the system is no longer balanced and certainly there will be net current flow.

Why the inverting? Because 120V was chosen for household wiring to be safe – the lower the voltage, the less dangerous it is if you accidentally span that voltage and shock yourself. But some household appliances actually need higher voltage – things like clothes

dryers and electric stoves that pull a lot of power. (Since P = I*V, too low a voltage would require them to draw too high a current). If your building carries two 120V lines whose signals are inverted relative to each other, you can get a normal 120V sine wave by



connecting either line to ground (0 volts) or you can get a 240V sine wave by connecting the two hot lines to each other. This allows your house to have the best of both worlds (120 V vs. 240 V): most of the wiring in your house can be at a safe low voltage, but the occasional high-power device can still be wired to get the higher voltage it needs.

A. **Go outside and find the transformer that serves your house /dorm / building, photograph the high(er) voltage distribution lines coming in to the transformer, the transformer itself, and the lines coming into your building. Attach the images to your problem set solutions (or make hand sketches if you don't have a camera).**

B. **Label the picture/s of the distribution lines with all interesting /relevant features.** Refer to the Hayes chapter for more information... Be sure to note whether your local distribution lines have a fourth "neutral" or "return" wire, or whether they carry the three phases without a neutral, as do transmission lines. (Both are possibilities – the high-voltage transmission lines always skip the return, but sometimes it's used for local distribution).

C. **Label the picture/s of wires entering the transformer, and again comment on all interesting features**. How many of the primary phase conductors (the 3 "hot wires" of the distribution system) feed the transformer? If only one conductor feeds it, the transformer can only produce single-phase power.

D. **How many buildings are served by the transformer that serves your house/dorm/apartment?**

E. **Label the picture/s of lines leaving the transformer and entering your building and again comment on features.** From the "low side" of the transformer (the low-voltage power leaving the transformer), how many wires leave the transformer? What are those wires carrying? (See explanation above). Look for where those lines go – how many phases are sent to each building served by the transformer? Remember that since each primary phase conductor would normally

become three lines (one phase and its inverse plus a neutral return wire), having 3 wires coming in doesn't mean you're getting 3-phase power. For three-phase you'd need four wires, 3 for the three phases plus a neutral.

F. **Comment on the thickness of the wires leading to your building relative to the distribution lines.** Are they thicker or thinner than the main distribution lines? Explain why. Would they carry more ore less power?

G. **If you can see a max power rating written on the transformer, write it down.** This will be usually written in "kVA", which is essentially kW (as you know if you remember that 1 Volt at 1 Amp = 1 Watt). **Comment on whether that total power is reasonable for the expected number of the people the transformer is serving.**

H. ***(Optional, extra credit)*** **Repeat the above for a different type of building (if you live in an apartment building or dorm, find a single-family home, etc.)**

I. ***(Optional, extra credit)*** **Find and photograph the substation that serves your neighborhood (this is likely a bike ride or even a drive away).** Take pictures of the substation and the high-voltage transmission lines that serve it and discuss the components you see. (You can refer to the Hayes chapter). The substation brings voltage down from the very high levels of long-distance transmission lines (up to > 700 kV) down to ~10s of kV for distribution within a city.

J. **Prove to yourself that if you span one 120V circuit and its inverse, the resultant voltage is a 240V sine wave.** As above, you can do this mathematically or you can do it by hand measurement. For hand measurement: either use the figures from this question or draw out on graph paper two sine waves that are inverted from each other. At some reasonable number of points, find the difference between the two signals. Then graph that difference. It should be a sine wave of the same frequency but twice the amplitude (240 instead of 120V).

K. (Semi-optional) Within your building, **identify *(if you can)* what appliances are requiring 240V, and *(if you can)* photograph their outlets** to confirm that they are 240V. (It's ideal if you can unplug them and photograph the plugs and outlets separately, but even if you can't unplug them, you should be able to observe that the connections look different from, and bigger than, a standard 120V plug).

L. ***(Optional, and may be impossible for most people in apartments or dorms).*** **Find your breaker box, open it (carefully, no touching of anything), photograph it, and identify and label things of interest:** the two bus bars that will carry the two inverted "hot" signals, the neutral bus bar, and the 240 V breaker. (All the 120 V breaker will go from a hot bar to the neutral; the 240 V breaker will span both hot bus bars).

Problem 3: Project reporting

Report on your progress toward finding a project group and topic so far.

Remember that you will need to get approval of your groups/projects before starting. Also that everything takes longer than you think, so you need to be starting now.

The items you'd like to have are below. You should answer A or B with a potential question even if you have not formed a group yet.

A. **Your proposed project question, the question that you're aiming to answer.** (Or a potential problem you might want to answer) Remember that a question ends in a "?" . Your question must be something to which you don't know the answer, and I shouldn't know the answer, and you should be curious to determine the answer, and you should have some reasonable chance of doing so in a few weeks.

B. **Write down two different alternative answers you might find to your project question.** Obviously you don't know the answer yet – or hopefully you don't – but for the sake of thinking through possible outcomes, write down two possible answers that you could imagine finding.

C. **Write down your proposed project group members if you have a group.** Or tell us what you are doing to get a group together.

D. **If you have a group, write down your proposed initial workplan broken down by person for your current planning horizon, and that horizon.** That is, list who is in the group and what in your upcoming planning horizon each person is doing. That horizon can vary by group. You could say "Our planning horizon is zero, we don't have a plan yet and therefore are still meeting all together to decide how to break out responsibilities." Or you could say "Our horizon is about one week, John Doe is going to be investigating X, Jane Doe is looking into Y, Jane Roe is phoning people to get information about Z, and we'll all meet together in about a week to decide on next steps." There is no wrong answer other than that you're going to do separate things til the day before the project is due and then just staple them together.