Final Technical Report
COVER PAGE

Project Title: Advanced Offshore Wind Energy – Atlantic Consortium

Federal Agency to which Report is submitted: DOE EERE – Wind & Water Power Program

Recipient: University of Delaware, Newark, DE 19716 - DUNS #05-900-7500
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Executive Summary

This project developed relationships among the lead institution, U of Delaware, wind industry participants from 11 companies, and two other universities in the region. The participating regional universities were University of Maryland and Old Dominion University. Research was carried out in six major areas: Analysis and documentation of extreme oceanic wind events & their impact on design parameters, calibration of corrosivity estimates measured on a coastal turbine, measurment and modeling of tower structures, measurement and modeling of the tribology of major drive components, and gearbox conditioning monitoring using acoustic sensors. The project also had several educational goals, including establishing a course in wind energy and training graduate students. Going beyond these goals, three new courses were developed, a graduate certificate program in wind power was developed and approved, and an exchange program in wind energy was established with Danish Technical University. Related to the installation of a Gamesa G90 turbine on campus and a Gamesa-UD research program established in part due to this award, several additional research projects have been carried out based on mutual industry-university interests, and funded by turbine revenues. This award and the Gamesa partnership have jointly led to seven graduate students receiving full safety and climb training, to become "research climbers" as part of their wind power training, and contributing to on-turbine research. As a result of the educational program, already six graduate students have taken jobs in the US wind industry.

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Introduction

This project was proposed in response to EERE's request DE-FOA-0000090. That RFP required that the recipient work with both industry and academic institutions in the region, and that it install a utility-scale wind turbine. Our original proposal was declined, but we were invited to prepare a second proposal with a smaller budget. We responded with a second request that reduced the amount of research and that did not use the grant to help fund a utility-scale wind turbine. Whereas the original proposal aimed to accomplish "Top-to-bottom redesign of offshore turbines", the revised and downsized SOPO proposed to work in smaller set of six specific areas:

1. Curriculum Development
2. Extreme wind events and design parameters
3. Corrosivity Estimates
4. Tower Structures
5. Gearbox Tribology
6. Gearbox Condition Monitoring

The resulting progress and outcomes of these areas are itemized as sections below. Those are followed by sections with outcomes that do not fit clearly into a single one of the SOPO task areas.

Background

Meeting the US goal of 20% wind electricity by 2030, at least cost, will require 54 GW of shallow-water offshore wind capacity, e.g., over 10,000 turbines of 5 MW. To achieve such an expansion of offshore wind, a working group of scientists, engineers, and industry has developed a prioritized consensus list of R&D needs. The current Consortium proposal was guided by the DOE 20% goal and by that industry R&D consensus process. If successful, the Consortium results would lay the foundation of a new offshore wind industry in the United States. For 54 GW by 2030, this would create 7,182 new manufacturing jobs, plus 3,000 new installation jobs, continuously over 20 years. It would also supply US energy needs from US resources, reduce pollution and carbon emissions, and lower the cost of electricity. (From our proposal to DOE for this award – Kempton et al, 2009.)

Results and Discussion, by Task

Task I – Curriculum Development

Our award SOPO promised to create and offer a "Wind 101" course. When we polled participating faculty at U Delaware, several were interested in offering either 1-hour courses or full 3-hour courses. Therefore, without any increase in budget, we were able to produce an entire wind program. With the number of courses we also grouped them (they are in multiple departments) under a "Wind Certificate Program" which has now been approved by the University. The Certificate program is described in the appendix.
Regarding the constituent courses, we sought individual participation. Then through several meetings with the Board of Industrial Advisors, a number of University of Delaware professors developed courses covering multiple aspects of Wind Power and wind technology. Four new courses were developed as graduate courses, however most are available to undergraduates in their junior or senior years. These included:

Dr. John Madsen – Geological Aspects of Offshore Wind Power*
Dr. Cristina Archer - Wind Power Meteorology*
Dr. Keith Goossen – Electrical Engineering for Wind Engineers*
Dr. David Burris – Wind Drivetrain Engineering*
(* Most recent syllabi attached in Appendix)

The Board of Industrial Advisors was very helpful in detailing topics needed to be included in the courses as well as being helpful in suggesting books and reference materials that could be used by students.

While working with these courses and others already being taught, the faculty members involved saw the possibility of developing a Wind Power Certificate for graduate studies. This would be an interdisciplinary program and could appeal to students already accepted into UD graduate programs looking for formal recognition of their wind power expertise, but also working professionals who need to understand more about the wind industry to more effectively do their jobs or seek advancement. This certificate program has now been approved by the University.

As an offshoot of professors working on this grant, a graduate student exchange program has been set up between the University of Delaware (College of Earth, Ocean and Environment and College of Engineering) and the Danish Technical University in Lyngby, Denmark, near Copenhagen. The exchange is for graduate students studying or researching either wind power or electric vehicles. Students can spend a semester at the other University, learning in areas not necessarily being taught at their home institution. Two Danish students studied at the University of Delaware campus just prior to the formal program start, and since then one

Delaware student has gone to Denmark for a semester. Ms. Bonnie Ram, a UD researcher, will be in Denmark from June 2014 through December 2015, and it is hoped she will encourage more Danish students to visit and study in Delaware.

Some student thesis/dissertation work was conducted through funding from this grant and Gamesa. See Task 4, Tower Structures by DeAnna Sewell. Heather Thomson did cost benefit analysis on the Lewes wind turbine. Without this grant, and the building of the turbine in Lewes, this work would not have been possible.

Task 2 – Extreme Wind Events & Design Parameters

Extreme wind events like hurricanes and northeasters and, at a smaller scale, fronts and thunderstorms create extreme stress on offshore structures and sub-sea power cable systems. Consortium experts have prepared reports and held workshops to support those developing offshore wind resource estimates as well as designing, operating and constructing wind facilities offshore. The two reports include: Professor Larry Atkinson at Old Dominion University (under sub-contract to this award), *et al*, on the climatology and meteorological events in the Mid-Atlantic offshore region, and Bruce Williams' report on design parameters for wind turbines in the Mid-Atlantic (funded by DOE grant, Wilmington Canyon Integrated Design, DE-EE0005484).

Dr. Atkinson's complete report can be found on our website: http://www.ceoe.udel.edu/File%20Library/Research/Wind%20Power/ODU-final-report-28-June-2013.pdf .

Unfortunately there are limited data stations offshore of the coastal area of MAB and the length of the record is no longer than 25 years.

In general, wind speed is higher in the winter and lower in the summer. Wind speeds in the fall and spring are somewhere in between. Winter wind speed is flat throughout the day. Summer wind speed is at a minimum in the morning hours, between 8 am and noon and at a maximum in the evening hours between 8 pm and midnight. The low frequency of calms, the high frequency of wind class 3 and above, the low impact of hurricanes and the shallow of the coastal ocean, make the Virginia, Maryland and Delaware coastal ocean a unique place for offshore wind energy development.

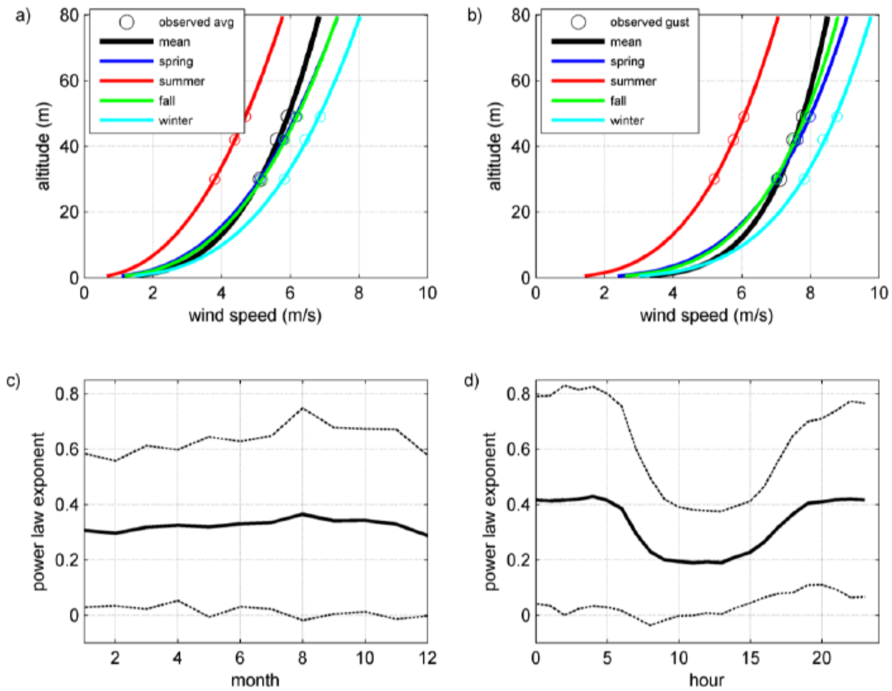


Figure 11.- Annual and seasonal mean (circle) of Lewes met-tower wind profile (lines are power law best-fit curve): a) 10 minutes average; b)10 minutes maximum (gust); c) monthly mean of the power law exponent; and d) hourly mean of the power law exponent, plus and minus one standard deviation (dotted line).

The power law predicts 5-15% higher wind speeds at a 75 m hub height than the log law starting with a 5 to 30 m measurement height. The power law exponent for the entire dataset was obtained to be 0.294 and this value was used to create the profile as indicated in blue in the figures. Similarly, the roughness length was calibrated for the entire dataset and was obtained to be 1.26 m which indicates a sub-urban terrain.

Wind shear exponent using the power law calculated to understand their behavior in different months. The exponent has the lowest level in winter, increases in summer and has its maximum in fall. It behaves the trend in the unstable conditions that prevailed in the winter and stable conditions prevail in fall. As a reason, the wind speed gradient decreases in unstable conditions (heating of the surface, increasing the vertical mixing) and increased during stable conditions (surface cooling, suppresses vertical mixing). Diurnal variation of the exponent of the power law has its maximum late in the evening to early morning, while the lowest was observed at midday.

The wind rose (Figure 3) shows that during the 17 years of data analyzed, the predominant wind direction in the area is along the coast from N-NNW and from SSW with a frequency of 63% of the time with wind over 6 m/s. The long-term average for buoy 44014 was 7.1 m/s and calms are present only 0.78% of the time.

The values of extreme wind speeds are similar at all stations in the MAB area, increasing towards the south, due to the greater prevalence of land falling hurricanes along the North Carolina Outer Banks. At CHLV2, the extreme wind values at 50 m height for 25, 50 and 100 years return period are 35.4, 37.5 and 40.0 m/s respectively for mean wind speed and 40.0, 42.4 and 44.9 m/s for wind gust.

Some summary and conclusions could be better reported in Bruce Williams' paper done for the Wilmington Canyon grant. This full report can be found at: http://www.ceoe.udel.edu/File%20Library/Research/Wind%20Power/WC---Extreme-Metocean-Williams-25-Jul-2013-copy.pdf .

1. **Average, one year peak current velocity** – Based on the literature search, annual average estimates range from 15 to 20 cm/s, which is slightly higher than found by Kuang et al due to the inclusion of winter months when winds are higher. A reasonable estimate for the average current velocity in the study area is 15 to 20 cm/s at the surface and 10 to 15 cm/s depth averaged. Peak one-year return surface velocity is estimated at 40 cm/s, with about 25 cm/s depth averaged.

2. **50 year event** – The storm investigated by Miles et al (Nor'Ida of 2009) produced peak 10 min. avg winds of 20.5 m/s at NDBC 44025, which is about half of what the 50 year event (a Cat 2 Hurricane) would produce at the buoy (NHC 2013). As a rough approximation, this could be expected to produce 50% higher depth averaged and surface velocities. Since the peak surface vector velocity observed by Miles et al was about 1.0 m/s, the 50 year event could be expected to produce surface currents of around 1.5 m/s for several hours at least[1]. Based on the shear profiles observed in CMO 2007, this could be expected to produce depth averaged current of about 90 cm/s. Based on the literature survey in the Levitt scour study, this would attenuate to about 40 to 50 cm/s at the seabed.

   These findings are summarized in the table below.

	Average Current	One Yr Event Peak	50 Yr Event Peak
Surface Velocity(cm/s)	15-20	40	150
Depth Average Velocity (cm/s)	10-15	25	90
Nearbed Velocity (cm/s)	5-10	10-20	40-50

[1] Rough estimate was validated as reasonable by Bruce Lipphardt formerly of UD- CEOE /POSE in phone conversation of 4 March 2013.

The full Williams report is available on our offshore wind webpage: http://www.ceoe.udel.edu/File%20Library/Research/Wind%20Power/WC---Extreme-Metocean-Williams-25-Jul-2013-copy.pdf .

Task 3 – Calibration of Corrosivity Estimates

The original project goals for the corrosion effort were to: a) Calibrate the corrosivity of the atmosphere at the Lewes, DE wind turbine site with the intention of being able to predict the corrosivity of future sites, and b) Monitor the real time corrosion of critical wind turbine systems as one component of a condition based maintenance program. (Note: This final goal, along with Objective d) below, could not be accomplished due to factors beyond our control as explained later.)

Project Objectives. In order to meet the above goals, the original project objectives were to:

a) Deploy corrosivity test panels constructed of plain carbon steel at a range of heights and distances from the water in the vicinity of the Lewes turbine site.

b) Analyze the corrosivity values as measured above to determine the corrosivity of the atmosphere at the Lewes turbine site as a function of distance from, and height above the water over a 2-Yr period.

c) Use the data obtained from objectives a) and b) above to evaluate the corrosivity of the present turbine site in comparison to that at other sites along the US Atlantic coastline.

d) Develop a strategy for condition-based maintenance using electronic sensors for detecting corrosion of real turbine components.

For the complete report by Professor Dexter, please go to our website: http://www.ceoe.udel.edu/windpower/atlanticwindconsortium.html

Conclusions from Professor Dexter's Corrosivity report:

With one exception, the progression of the measured corrosion rates for plain carbon steel with time of exposure, distance from the water and height above the water followed a pattern that was compatible with the historic corrosion database as measured over the past 50 years at Eastern USA coastal sites from Florida through New Jersey.

In accord with expectations from that historic database, the corrosion rates measured at each of the four planned exposure periods during the course of this project were highest at the present Site A, which was closest to the water, and they decreased systematically with distance from the water for Sites B and C.

The numerical value of the 2-year corrosion rates measured in this project also were compatible with those in the historic data base.

The exception mentioned in the first conclusion was for the data taken during the first year on top of the Nacelle (Site D). The data for 6 and 12 months at that location showed elevated corrosion rates. The degree of elevation was highest for the 6 month data, less for 12 months, and nonexistent for the data at 18 and 24 months.

The reason for the accelerated corrosion rates for the first 12 months of exposure on top of the Nacelle was thought to be that turbulence induced by the rotating blades interfered with development of the semi-protective corrosion product film during the first year of exposure.

After the first year of exposure, the corrosion rate became independent of the turbulence induced by the rotating blades.

The "linear bilogarithmic Law" may be helpful in predicting long term corrosion rates for future shore-based wind power systems along the eastern Atlantic seaboard of the USA. Success in doing so, however, will require at least 2-years of corrosion data for the prospective site, with ten years of data being preferable for confident predictions.

During this study there were initial problems on getting approval from Gamesa Corporation for installation of the samples on top of the nacelle. Once this was resolved, the project continued as designed. There was also a problem with placing samples inside an electrical cabinet with the turbine tower. This option was not approved because of safety issues with electric power in the cabinet.

One weakness in the present study was having no detailed information on local air quality, including marine aerosols and time of wetness (TOW). It was assumed at the beginning of this work that such data would be available to the project as part of the historical database for the atmosphere in this area. This would have been helpful in interpreting the measured corrosion rates. However, we have not been able to locate any such data.

Complete report and photographs of Professor Dexter's project are available on the DOE Golden Field Office Sharing Center, U.S. Department of Energy – Golden Field Office – EERE-PMC (Energy Efficiency & Renewable Energy Project Management Center in the Personal Directories section.

Task 4 – Tower Structures

Due to personnel changes this section of the grant changed throughout the project. The original investigator, Dr. Mohsen Badiey, was promoted to Deputy

Dean of the College of Earth, Ocean and Environment at the University of Delaware. His expanded duties did not allow him to continue his work on this project. Deanna Sewell, Dr. Badiey's graduate student, then continued the work. Ms. Sewell used this research in her Master's thesis: Wave loads on multi-member offshore wind turbine sub-structures.

Conclusions from Sewell thesis:

"For offshore wind power to be utilized on a large scale, cost needs to be significantly reduced. Thus, understanding the operating conditions for offshore wind power is key in reducing the engineering factor of safety (over design), in turn reducing the cost of construction and installation. Properly understanding the hydrodynamics - the primary difference between offshore and land-based wind power - is an essential step in this process.

In this thesis, results were presented in an attempt to more accurately model the hydrodynamic loads on multi-member offshore wind turbine sub-structures, a jacket and a tripod. A simple case of a monopile was also presented as a well understood, easier to model reference case. Computational dynamics simulations were set up in STAR-CCM+ to model wave loads with an unsteady Reynolds-Averaged Navier-Stokes equation solver. Two wave cases were simulated, a linear wave and a nonlinear wave. Linear wave loads on each structure were com- pared to results using the traditional modeling method of Morison's equation in the simulation code HydroDyn, these results were provided by the National Renewable Energy Laboratory. During the course of this project, the scope of HydroDyn's development was narrowed to not include the non-linear wave. Thus, results were only presented on the 5th order wave for the RANS models done in simulation code STAR-CCM+.

Several discrepancies were found between the model results. In the simple monopile case, much less differences were found, and were explained with very little uncertainty. With respect to the jacket and tripod, unknowns still remain without data to verify either model. One of the underlying assumptions of Morison's equation is that there are no diffraction effects, that is the presence of the structure does not alter the wave field. For the monopile, this is mostly the case with the exception of the vortices being advected back-and forth within the wake as it reversed. However, it was shown that diffraction effects are very apparent with a complex structure.

These results presented several phenomena that are not accounted for in the basic Morison formulation, specifically wave diffraction and non-linear phenomena such as Stokes drift (mean-drift) and vortex-structure interaction. Thus, the physics of how the flow field was changing, and interacting with the structure cannot be ignored. That is, the flow field is affected by the presence of the structure, changing the flow from being periodic and smooth (as prescribed) to being unsteady and turbulent. The resultant turbulent flow was found to be significant in calculating forces.

Another interesting phenomenon observed was the frequency content within the power spectrum of the forces. Typically, offshore structures are designed such that the eigenfrequency (natural frequency) is placed above or below the wave frequencies within the ocean. The broadbanded nature of the y-direction force power spectrum for all of the structures shows that there could be energy at the resonant frequency of the structure which should be considered prior to installation of the structure. Future work should include a stochastic model of the sea states, for a better understanding of the frequency content in the forces along with a fatigue analysis to assess the risk of eigenfrequency excitation.

In conclusion, Morison's equation cannot be relied on to give accurate load prediction for this jacket or tripod. The primary reason for this being that one of the assumptions for Morison's equation is violated, the diffraction assumption. While the individual members of each structure satisfy this condition, the structures as a whole does not. "

Ms. Sewell purchased, installed and calibrated accelerometers to continue her work for this project. Protocol for the research was also developed by Ms. Sewell with advice from Professor Dave Burris. When her degree program at UD was completed, she went on to a PhD program at the University of Colorado in wind engineering and worked at NREL on the FAST model. Her internship led to ongoing employment at NREL. Some family matters prevented further work on the accelerometers.

Task 5 – Gearbox Tribology

Gearboxes are well known in the wind industry as one of the turbine's weakest links. To achieve the increased reliability and lower cost levels needed to achieve the DOE 20% wind deployment goal, gearbox reliability must be improved. Our gearbox effort includes on-site monitoring of the Lewes turbine as well as controlled laboratory studies of bearing failure. The first step was to coordinate with the NREL gearbox reliability collaborative (GRC) and make use of existing databases and the modeling results to obtain best estimates of the load and speeds encountered under various wind-load conditions. The Consortium experts in gearbox condition monitoring and tribology was led by David L. Burris, an Assistant Professor in the University of Delaware's Department of Mechanical Engineering., and with major contributions by Ben Gould, MA student also in in ME.

Recent studies have suggested that variations in wind-speed with elevation (wind shear) contribute to premature wind turbine drivetrain failure because load imbalances across the rotor increase bearing loads. In this paper, we use accepted momentum-based modeling approaches to investigate the effects of the wind shear on rotor pitch moments and drivetrain bearing loads. The non-dimensionalized results can be used to determine thrust force, pitch moment, and power extracted in any general system under known wind shear conditions. Even in extreme wind-shear (m=1), the actual thrust force and power acting on a typical turbine (R*<0.5) were within 8% and 20% of the nominal values (in the absence of wind shear for a given hub wind speed), respectively. The mean pitch moment increased monotonically with turbine thrust, rotor radius, and wind shear exponent. For extreme wind shear (m=1) on a typical turbine (R*=0.5) the mean pitch moment is 25% the product of thrust force and rotor radius. Analysis of wind shear in a typical 750kW turbine suggests that, although wind shear has a dramatic effect on pitch moments, it is unlikely to contribute significantly to premature failure via bearing fatigue because the induced pitch moments are counteracted to a degree by rotor weight. Analyses of more common low wind speed cases suggest that bearing under-loading and wear is more likely to contribute to premature bearing failure than over-loading and classical surface fatigue. The analysis suggests that larger turbines are more prone to failure by bearing under-loading. (Gould and Burris 20xx)

Task 6 – Gearbox Condition Monitoring

Gearboxes can be monitored effectively using fiber optic sensor arrays mounted to the outer casing of the gearbox. Vibration signatures can be monitored, and used to identify if a fault has occurred and classify gear faults such as tooth cracks, spalling, or other wear or damage that may occur during actual operation. Partner Institution University of Maryland, Gessel Rotocraft Center, assessed the feasibility of utilizing a fiber optic sensor array to measure vibration signatures and to detect gear tooth faults using this data. The University of Maryland's (College Park) Minta Martin Professor of Aerospace Engineering Norman Wereley was the primary contact. The Center's PhD student Joseph Coker have produced a report on gearbox condition monitoring and gear fault detection, using a heavily instrumented small gearbox in order to prove the concept. Their report accompanies this final report.

Task 7 – Project Management and Reporting

The Principal Investigator for the project, Willett Kempton, remained the same throughout the grant. End of 2011 hired Bonnie Ram as liaison to the Board of Industrial Advisors.

Other investigators did change during the duration of the grant. Mohsen Badiey, original investigator for the tower structure task was promoted to Deputy Dean of the College of Earth, Ocean and Environment at the University of Delaware. His expanded duties did not allow him to continue his work on this project. Deanna Sewell, Dr. Badiey's graduate student, then continued the work. When Ms. Sewell completed her Master's degree she went on to a PhD program at the University of Colorado in wind engineering and worked at NREL on the FAST model. Her internship led to ongoing employment at NREL. Some family matters prevented further work on the accelerometers.

Originally there were two trained (student) research climbers for the wind turbine, both graduate students, and an additional two maintenance climbers. Both research climbers completed their programs at the same time and left the University. Then three additional climbers were trained, representing mechanical engineering, electrical engineering, and meteorology.

Regarding schedule, the startup for this project was delayed due to NEPA compliance for the Lewes turbine. Although originally listed as beginning in June 2010, monies for sub-contractors were not available until June 2011.

Board of Industrial Advisors

A Board of advisors from the wind industry was part of the original proposal for this grant.

Board of Industrial Advisors (2010-2014)

NAME	AFFILIATION
Daniel Ancona	Princeton Energy Resources International
Jairo Arias	Gamesa Corporation
David Balfrey	Apex Wind
Daniel Broderick	Gamesa Corportation
Woodrow “Woody” Crouch	AECOM Energy
Donald Evans	ApexWind
Miguel Angel Gonzalez-Posada	Gamesa Corporation
Renee Henze	DuPont Performance Lubricants
Justin Hoeter	DuPont Performance Lubricants
Ben Ingram	Clipper Windpower
Peter Jacobs	ExxonMobil Corporate Strategic Research
Jason Kiddy	Aither Engineering
Peter Mandelstam	Arcadia Windpower
Robert “Bob” Mitchell	Atlantic Wind Connection
Deniz Ozkan	Atlantic Wind Connection
Kevin Pearce	Arcadia Windpower
Gonzalo Palacio	Gamesa Corporation
Avinash Taware	Gamesa Corporation

Updated as of 5/2014

There was high attendance initially from this group, and most were willing to speak with researchers when contacted one on one. As the project ensued, we had board attrition, but a few members persisted to the end of the project – these included Dan Ancona from Princeton Energy Resources International, Deniz Ozkan with Atlantic Wind Connection and Kevin Pearce from Arcadia Windpower. Also, the personnel at Gamesa Corporation changed during the project time period, and although still quite helpful when asked, the new people did not always seem to feel the same commitment to the project as those who had started with us. Several of the individuals will continue involvement through networking and ongoing research and industry initiatives.

Formal meetings of the Board of Industrial Advisors were held as follows:

October 13, 2010, Newark Campus, Introductions, overall proposed scope. Feedback from Advisors.

December 14, 2010, Newark campus, progress report.

June 24, 2011 – Lewes, DE – Advisory Board and researchers – Preliminary discussions on what research was planned – Site visit to Lewes wind turbine – intense discussions on course planning including specific topics to be covered, possible texts

September 19, 2011 – Newark campus – researchers – discussions of research to date and seek input and suggestions from others

February 2, 2012 – Newark campus – Advisory Board and researchers – how is research moving forward – discussions of challenges and results to date

October 25, 2012 – Webcast – Drivetrain and Tower Loads Challenges - Advisory Board and researchers

November 8, 2012 – Newark campus – MET workshop – Advisory Board and researchers

December 5, 2013 – Newark campus – Final Advisors Meeting – Advisory Board and researchers.

Gamesa-UD Collaboration, G-90 Turbine, R&D Committee

The original FOA required that recipients install a utility-scale wind turbine as part of the project, and providing some funding for this purpose. The University of Delaware worked out how to carry this out as part of our original proposal that was rejected. Despite the rejection, we investigated and found that we were able to build a utility-scale turbine based on participant contributions (from UD and Gamesa) and existing tax credits and grants. So as a result of the original FOA but without any support from the FOA, a Gamesa G90 was installed at the Lewes campus. Therefore, we here mention some of the results of this turbine and the resulting collaborative relationships, even though they were not funded by the EERE grant, they are very much a result of the original FOA, and worked with other aspects of this actual reduced-scale award, despite the changes.

As a result of the installation of the wind turbine in Lewes, DE, Gamesa Corp. and the University of Delaware formed an R&D committee to direct, approve, and fund research on this particular turbine. The committee consists of three members from the UD and two members from Gamesa. Gamesa paid a substantial portion of the cost of the turbine, but also recovered tax credit. The agreement between UD and Gamesa also specified that turbine revenues, after covering O&M and repayment of capital cost, would be used for R&D on wind energy. The revenue stream is divided between Gamesa and a UD entity, "Blue Hen Wind". The Gamesa portion of the revenue stream is administered by the R&D Committee. The R&D Committee also reviews turbine-related research that involves contact with the turbine or possible shutdown time. The committee must approve any changes/work done to the turbine, other than routine maintenance.

This has led to a broad and deep relationship with the turbine manufacturer, not only on R&D, but also in the area of climber training. Gamesa has developed a training program for climbers and has allowed UD to train their climbers in this program – stressing the safety of personnel as well as of equipment. This has had value on multiple levels for UD and the US wind industry.

Heather Thomson has been using this turbine as the basis of her PhD work on external costs of energy.

Student training and industry readiness

Student Presentations and Participation in Wind Conferences

This grant allowed a number of graduate students the opportunity to attend the American Wind Energy Association (AWEA) and European Wind Energy Association (EWEA) conferences in order to network with professionals and others from throughout the world. Several of these students presented posters at these events explaining the work they are doing at the University of Delaware. Others attended with specific "assignments" from their professors, and then shared their new knowledge with classmates when they returned.

AWEA Las Vegas – May 2014

- Heather Thomson – Poster: A Comparison of Visual Impacts of Wind Turbines and Coal-fired Power Plants in Delaware

AWEA Providence, RI – October 2013

- Kateryna Samoteskul – Best Student Poster - Changing Vessel Routes to Open Areas for Wind Development Could Generate Significant Societal Benefits

- Allison Bates-Honorable Mention Poster Award in the Business/Permitting/Social Science Category - Accounting for Commercial Fishing Interests in Offshore Wind Planning

- Poster: Electrical Infrastructure of Large-Scale Offshore Wind Energy Development, Authors: W. Kempton, R. McCormack, E. Apostolaki-Iosifidou and P. McCoy

- 4 additional attendees from UD Wind program

AWEA Virginia Beach, VA – October 2012
- 3 attendees

EWEA Copenhagen, Denmark – May 2012
- Bruce Williams attended

EWEA Offshore Wind Amersterdam – December 2011
- Alison Bates – Poster: Marine Spatial Planning in Delaware, Mid-Atlantic United States – nominated for best poster

- Willett Kempton and Jeremy Firestone attended

AWEA Baltimore – October 2011
- 8 attendees

AWEA Windpower, Anaheim, CA – May 2011
- Willett Kempton attended

AWEA Offshore Wind, Atlantic City, NJ – October 2010
- 10 attendees

We have developed a page in the University's Wind Power website specifically for this DOE grant. It can be found at http://www.ceoe.udel.edu/research/affiliated-programs/wind-power-program/research-projects/atlantic-wind-consortium

This site contains links to the complete final reports from the various tasks, as well as supplementary work done by the researchers and graduate students that will enhance the reports for those looking to learn and/or do further research of their own.

Research Climber Training for Wind Graduate Students

Although not an explicitly listed project task, much student learning came about through the work on this grant.

Five carefully-selected graduate students were trained to climb and do work within and on top of the nacelle of the Lewes wind turbine. Leveraging DOE funds as well as funds provided by Gamesa Corporation, one of our major industry partners funded this training. These students were Blaise Sheridan, DeAnna Sewell, Hunter Brown, Ben Gould, and Elpiniki Apostolaki. This training played a part in their resumes for moving on to outside employment and furthering their education. Blaise Sheridan is now a policy advisor in the office of US Senator Christopher Coons (D-DE). DeAnna Sewell went on to an internship at NREL and a PhD program in wind energy at University of Colorado. Benjamin Gould was offered an internship at Argonne National Laboratory in part due to the work he had been doing with Professor David L. Burris on this grant.

DeAnna Sewell and Ben Gould were responsible for the installation and monitoring of equipment in and on the research turbine. Their duties included calibration of equipment as well as development of laboratory protocols.

In 2013, some of these trained climbers were used to evaluate the Cape Wind MET tower and instrumentation. See:
https://www.ceoe.udel.edu/our-people/profiles/carcher/impowr

These research-climber graduate students were responsible for the installation and monitoring of equipment in and on the turbine for several of the other tasks for this grant, including the work of Professor David Burris and Professor Stephen Dexter. Graduate students also managed the lab protocols and calibration work in Professor Burris' tribology laboratory on the UD Newark campus.

Students employed by Wind Industry and related areas

Deanna Sewell accepted a position at NREL in Boulder, CO and was accepted into the PhD program at the University of Colorado.

Regina McCormack and Katya Samoteski are both working at Invenergy, LLC (Chicago) as marketing analysts.

Heather Thompson has completed her PhD work, and accepted a position with Mid-Atlantic Renewable Energy Coalition (MAREC), in Dover, DE.
http://www.marec.us/about.html

Ben Gould is continuing his PhD work on bearings while interning at the Argonne Laboratory as well.

Blaise Sheradon was hired as an aide to the office of Senator Chris Coons. Senator Coons has been a proponent of the wind industry, and Mr. Sheradon had extensive experience both with classes and in his certification and research climbs. To our knowledge, he is the only professional Senate staff member who is a certified climber.

Published Papers, Unpublished Reports, and Theses

Journal publications

Gould, B. J., and Burris, D. L. (2015) Effects of wind shear on wind turbine rotor loads and planetary bearing reliability. Wind Energy., doi: 10.1002/we.1879.

Technical Reports

These reports are available both on the UD web site for this grant, http://www.ceoe.udel.edu/research/affiliated-programs/wind-power-program/research-projects/atlantic-wind-consortium

and on the DOE EERE web site, U.S. Department of Energy – Golden Field Office – EERE-PMC (Energy Efficiency & Renewable Energy Project Management Center in the Personal Directories section.

Joseph D Coker, Darryll J Pines, Paul D Samuel, Jason Kiddy, and Chris Baldwin, 2013, Fiber Optic Sensors for the Detection of Planetary Gear Damage. Technical report.

Bruce M. Williams , 2013, Estimate of Extreme Wind, Wave, Surge, and Current Conditions for the Wilmington Canyon Integrated Design Project.

Larry P. Atkinson, Jose L. Blanco, and Ravi Chekura, 2013, Final Report for Task 2.0 Extreme Wind Events & Design Paramenters.

Stephen C. Dexter, 2014 Final Report 2014, Marine Corrosion Component Task.

Posters and Conference presentations

Many presentations and posters were presented at the AWEA Offshore, AWEA Winpower, and EWEA Conferences listed above, and other conferences.

(AWEA conferences are listed above, AWEA presentations and posters not listed separately)

Student Poster Abstract, Ben Gould, Lauren Kewley, David Burris
Read the full article at http://onlinedigitalpublishing.com/article/Student+Poster+Abstract/1463045/-168720/article.html.

Patent

David Burris has a preliminary patent disclosure based on research under this award, and will file a patent through the University of Delaware. This is a control system that will greatly reduce forces on the nacelle and rotor.

Theses and dissertations

DeAnna M. Sewell – Wave Loads on Multi-Member Offshore Wind Turbine Sub-Structures – Master's degree, December 2012

Gould – Thesis in progress – Tentative title "Mechanisms of white-etch cracking failures of wind turbine drivetrain bearings"
Heather Thompson – External Costs of Energy, Analyzed for Shipping and for Power Generation – PhD, August 2015
Baker - The Atlantic Offshore Wind Power Potential in PJM: A Regional Offshore Wind Power Resource Assessment – MMP, 2011
Blaise Sheridan – The Social Costs of Electricity Generation - MMP, February 2013

Appendices

Wind Certificate program description

The Graduate Certificate in Wind Power Science Engineering and Policy is an interdisciplinary program administered by the College of Earth, Ocean and Environment. Courses are taught by faculty from Marine Policy, Physical Ocean Science and Engineering, Mechanical Engineering, Electrical Engineering, Geological Sciences, and Geography. The program is designed to give a broad understanding of the wind energy industry from multiple disciplinary perspectives. The emphasis is on offshore wind power, however, most courses apply equally to wind power either on land, in the ocean, or airborne. The certificate may be taken in conjunction with a graduate degree in a traditional discipline or as a stand-alone program. For more information, please check this link: http://www.ceoe.udel.edu/research/affiliated-programs/wind-power-program/education/wind-power-certificate.

Course syllabi

This Appendix includes course syllabi for the four wind certificate courses developed as part of this award. They are added to two existing courses on wind power, with the existing and new courses together comprising the offerings of the wind certificate program.

Archer

Burris

Goosen

Madsen

MAST/GEOG 667: Wind Power Meteorology
Fall 2013, 3 credit hours

Syllabus

Instructor: Cristina L. Archer
Email: carcher@udel.edu
Phone: (302) 831 6640

Monday, Wednesday 3:30-4:45PM
Robinson Hall 203

Description: This course explores the fundamental concepts of meteorology that are needed to understand onshore, offshore, and airborne wind power. Topics include: forces affecting winds; terrain and land-use effects; air turbulence; numerical modeling; wind power and energy from turbines; and wind measurement technologies.

Textbooks (not required):

- Ahrens, C. D. (2008): *Meteorology today*. Brooks Cole, 9th edition, 549 pp.
- Jacobson, M. Z. (2005): *Fundamentals of atmospheric modeling*. Cambridge University Press, 2nd edition, 813 pp.
- Burton T., D. Sharpe, N. Jenkins, and E. Bossanyi (2001): *Wind energy handbook*. John Wiley and sons, 617 pp.

Office hours: Monday, Wednesday 9:00-10:00AM, or by appointment.

Grading:

Homework	15%
Midterm	30%
Final exam	40%
Project	15%

Grades:

A	A-	B+	B	B-	C+	C	C-	D
93%	90%	87%	83%	80%	77%	73%	70%	60%

Policies: Deadlines will be strictly enforced and no late turn-ins will be accepted, unless prior arrangements had been made with the Instructor.
Eating and drinking are not allowed in the classroom. You will be asked to remove any food or beverage you bring into the classroom.
Please turn off your cell phones and pagers so that you can focus on the class work.
Any student who has a need for accommodations based upon the impact of a disability should contact me as soon as possible. Contact the Office of Disabilities Support Services to coordinate appropriate accommodations.
All students must be honest and forthright in their academic studies. To falsify the results of one's research, to steal the words or ideas of another, to cheat on an assignment, or to allow or assist another to commit these acts corrupts the educational process. Students are expected to do their own work and neither give nor receive unauthorized assistance. Any violation of this standard will be reported to the Office of Student Conduct. Please read http://www.udel.edu/stuguide/11-12/code.html

End of class: the last day of this class will be Wednesday, December 4.

MAST/GEOG 667: Wind Power Meteorology
Fall 2013, 3 credit hours

Course schedule (tentative)

1. What is wind?
    1. Upper-level winds: Pressure Gradient Force and Coriolis (pressure surfaces, geostrophic flow, wind symbols)
    2. Near-surface winds: add Friction (flow around lows and highs at surface, weather and winds associated with L and H)
    3. Distributions of winds on Earth (synoptic flow near surface, winds crossing isobars, fronts, where are the windiest spots?)

2. How does wind change with time, height, and location?
    a. Global circulation, jet streams, and thermal wind (aloft)
    b. Seasonality
    c. Diurnal cycles
    d. Terrain effects (sea/land and mountain/valley breezes)
    e. Turbulence in the boundary layer (eddies, intermittency)
    f. Power law and log law (in the boundary layer)

3. How do we measure winds?
    a. Anemometers
    b. Remote sensing
    c. Field trip to Lewes tower (to be arranged)

4. Power and Energy in the wind
    a. Wind power density (including temperature and altitude corrections to air density)
    b. Betz limit
    c. Wind speed and power distributions (Weibull, Rayleigh, wind power classes)
    d. Actual wind power curves and capacity factors
    e. Annual energy generated by wind turbines

5. Forecasting wind and wind power
    a. The momentum equation
    b. Numerical modeling (including parameterizations of turbulence)
    c. Wake effects
    d. Array losses (turbine spacing)

MEEG XXX –Wind Turbine Drivetrain Mechanics
Department of Mechanical Engineering
University of Delaware – Spring 2011

Instructor Dr. David Burris
Office: 210 Spencer Lab, phone: 831-2006
Email: dlburris@udel.edu
Course website: http://sakai.udel.edu

Class Time XXX, X:XX-X:XX XM
XXX Hall, rm XXX

Office Hours XXX, X:00-X:00 XM, or by appointment

Text Hau, , ISBN- 9783540242406

Description This course presents basic tools, elements and approaches to mechanical systems configuration and design for wind turbines. Thematically, instruction will cover 1) basic wind turbine elements and configurations, 2) gear train analysis, 3) bearings and lubrication, 4) wind loads and drivetrain design considerations. The students will have opportunities to apply the course content to engineering analysis problems and open-ended design challenges.

Content

Topics Covered
Introduction to wind turbine operation and configuration
Gear trains
Bearings and lubrication
Wind loads and drivetrain design considerations

Outcomes By the end of the course, each student should be able to:

- Know the basic drivetrain layout of modern turbines
- Design and analyze compound and epicyclic geartrains
- Estimate loads in the drivetrain and predict potential failures

Assignments **Homework** – 4 assignments will reinforce the content of the course. 50%

Exam- 1 Exam will test the student's ability to apply the content to a more open-ended system-level design problem. 50%

Electrical Engineering for non-Engineers

This short course will provide non-Electrical Engineers with sufficient instruction to understand the conversion of rotary motion into electrical current and voltage, i.e., the operation of an electrical generator. As it is intended for novices, basic principles of charges and forces will be given, electric circuit elements and analysis, relevant electromagnetic theory, electric power and electric power transmission, and DC and AC electrical generators. A background including differential equations is assumed.

I Charge, Current, Voltage, Electric and Magnetic Fields, and Electromagnetic Forces

Electrical Engineering is all about the controlling the flow of charge, or current, through a circuit, or on the electric power side, producing a current by converting from another energy source. This energy source is usually something that causes the turning of a shaft, that in turn causes the movement of wires and magnets that creates current. The primary energy source could then be wind or water flow that causes the shaft to turn, or the burning of a fuel that then is used to cause mechanical movement through a heat to work engine.

Electrostatics

Here in this lecture, we will learn about charge, current and other basic electrical quantities. While "charge" is a term used sometimes in everyday language, it can be a bit mysterious if one thinks about it too deeply. We should say at the outset that this deep thinking is usually the reserve of physicists, and this is an engineering course. As engineers, we are not required to have the deep understanding of the nature of matter, but rather need to be able to apply certain principles of physics to make something work. That being said, "charge" is a quantity of elementary particles, particularly protons and electrons, just as "mass" is a quantity of them. And, just as gravitational attraction exists between two masses, another type of force, much stronger, exists between two charges, with the difference that the charge can be attractive (between an electron of negative charge and a proton of positive charge) or repulsive (between like charges).

An electron has a charge of $1.6\text{x}10^{-19}$ coulombs. How much charge a coulomb is will be defined below; but here let's begin with an understanding that all electrical units are part of the MKS (meter-kilogram-second) or metric system. Thus, a coulomb is a unit of measurement for charge, just as a meter is a unit of measurement for distance.

To understand how much charge a coulomb is, we can examine one of the first electrical experiments done, by Sir Coulomb. He placed charge on two balls attached to a spring, and noted that the more (like) charge he placed on them, the more the balls pushed apart against the force of the spring. Sir Coulomb noted that the force on the balls went as $1/r^2$, the distance between them; later when forces were quantified, with a force of 1 Newton being the force necessary to accelerate a 1 kilogram weight at 1 (meter/second)/second, it was defined that one coulomb is the amount of charge on balls 1 meter apart that result in a force of $1/(4\pi\varepsilon)$, where ε is something called the permittivity. The permittivity of air is $9\text{x}10^{-12}$ farads/meter. Note that later we will learn how a farad, the unit of capacitance, is related to force and charge via force = coulomb^2/farad-meter. For now, let's just plug in and see that the force exerted upon two 1 coulomb charges 1 meter apart is 1/(4x3.14x9E-12) = 8,800,000,000 newtons! This is the same amount of force as the weight of a 900,000,000 kg mass! So, a coulomb is a lot of charge, more than we normally ever experience in our lives.

Mathematically, then, the force between charges is given by

$$F = \frac{q_1 q_2}{4\pi\varepsilon r^2} \qquad (1.1).$$

So far, this is pretty straightforward: an observation is made, the forces between charges, and an equation is written to quantify those forces. Now, we introduce the concept of *field*. We are all familiar with the force of gravity, which causes an object to fall to earth. Scientists also talk of a *gravitational field* which just means that something is there that causes objects to fall to earth, even if there is not an object. The same is true for charges, and this is called an *electric field*. If only one charge is present, there is no force, but there is still an electric field, that is capable of causing any charge that happens to come around to experience a force. The electric field caused by a charge q_1 is given by

$\mathrm{E} = \frac{q_1}{4\pi\varepsilon r^2}$ (1.2).

Thus, we see that the force on a charge q_2 is given by

$\mathrm{F} = q_2\mathrm{E}$ (1.3).

Note that this equation works no matter what the source of electric field, force is always charge times electric field.

Now, we can use the basic principle of energy,

Energy = Force x Distance (1.4),

that is, the energy expended to do something equals the force applied times the distance over which the force is applied. Then, in electrical work,

Energy, electrical = qEh (1.5),

where *h* is the distance that a charge is moved through an electric field. Note that this is completely analogous to the energy expended to move a mass through a gravitational field:

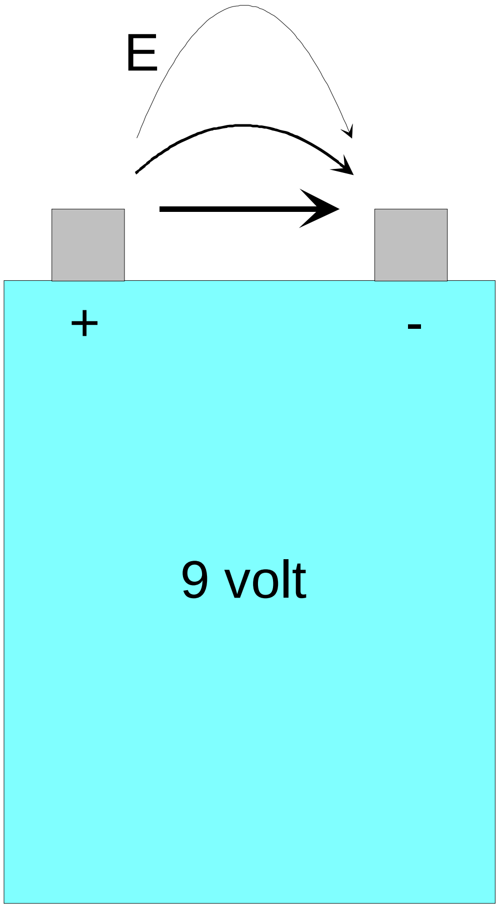
Energy, gravitational = mgh (1.6).

In electrical phenomena, we define a term called the voltage potential,

$V = \mathrm{E}h$ (1.7).

This is the quantity you are familiar with from everyday life, such as a 9 *volt* battery. So, an electric field is determined by the voltage across a distance, volts/meter.

So far, all the equations above have used scalar quantities, that is, having no direction. Of course, we know that forces have a direction, so are a vector quantity, and thus so are electric fields. Furthermore, we can surmise that electric fields are not constant in space:



Thus, the electric field between the terminals of a 9 volt battery are not constant and do not have a constant direction. Now, we must rewrite equation 1.7 as

$$V = \int_{+}^{-} \mathbf{E} \cdot \mathbf{dl}, \quad (1.8)$$

that is, along any path from the positive to the negative terminal, taking the dot product of the electric field with the differential of length, the integration with yield 9 volts. Note that this is for <u>any</u> path taken. This is completely analogous to if you walk up a hill, no matter what path you take, you expend the same energy against the gravitational field, since you have changed the same amount of height. Going forward in this course, we will only be doing electrostatic problems where the electric fields are in straight lines, so we will not have to worry about the vectors, but equation 1.8 is shown so that we understand the vector nature of fields.

<u>HOMEWORK 1.1:</u> A single positive charge exists in space. What is the voltage potential a distance *R* from that charge? Hint: The voltage potential is zero at an infinite distance from the charge.

<u>Current, and Power</u>

Current (*I*) is the movement of charge, or, the charge per unit time that crosses a plane. Now, we know that power is the energy supplied per unit time. If in the 9 volt battery above, we connect the terminals across a load, allowing a current to flow, the power supplied to the load equals the charge per unit time leaving the positive terminal, times the voltage between the terminals:

$$power = \frac{energy}{time} = \frac{charge}{time} x \frac{energy}{charge} \qquad (1.9).$$

Charge/time is current, and energy/charge is given by equations 1.5 and 1.7, so we have that power (*W*) is given by current times voltage:

$$W = IV \qquad (1.10).$$

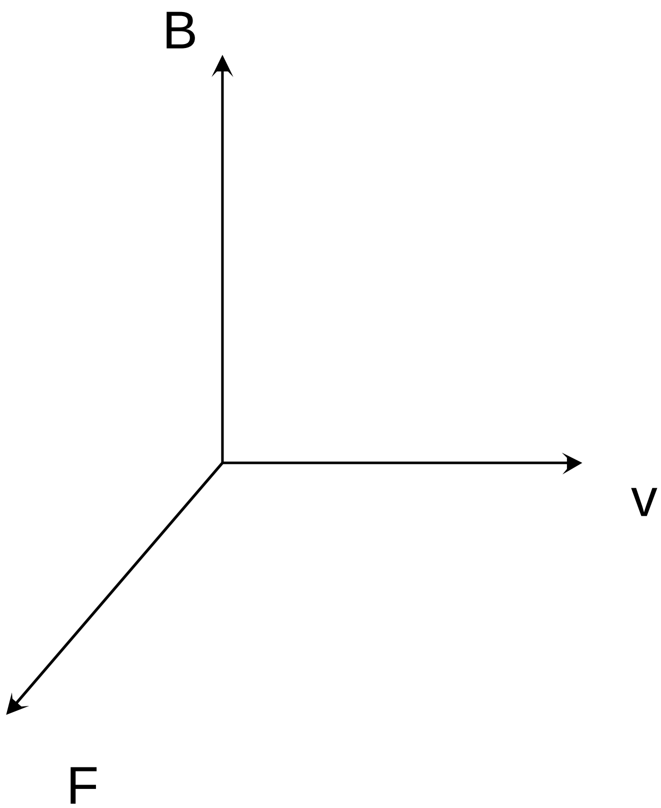
Magnetostatics

Stationary charges produce electric fields. When charges are in motion, they also produce magnetic fields. We are all familiar with magnets. Inside a magnet, the motion of electrons orbiting atoms results in a magnetic field. Since current is the movement of electrons through a wire, it can produce a magnetic field as well. We'll get into that later, but first, let's understand magnetic forces.

Just as magnetic fields only result from charges in motion, so too magnetic fields only exert forces on charges in motion. A stationary charge in a magnetic field will feel nothing from it. But, if the charge has a velocity, a force will be exerted upon it. That force is given by

$$\mathbf{F}_{magnetic} = q\mathbf{v}\mathbf{x}\mathbf{B}. \qquad (1.11)$$

Recall that the direction of a cross product is given by the "right hand rule," and can be found by pointing your fingers in the direction of **v**, rotating them toward **B**; then your thumb points in the direction of **vxB**:



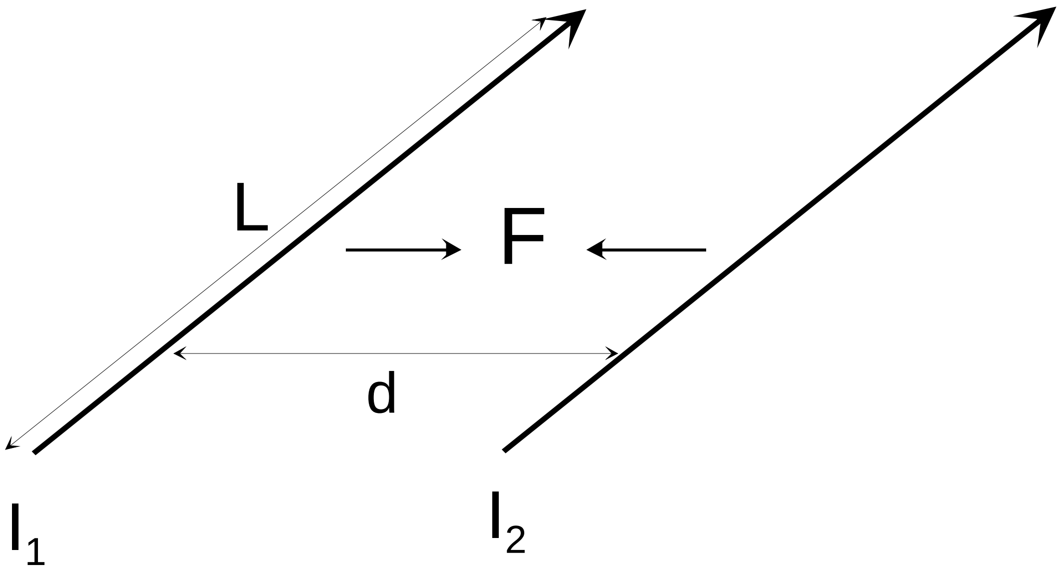
Homework 1.2: A charge is moving straight from left to right in the plane of the paper. A magnetic field is suddenly turned on and points into the paper. What shape path does the charge then take? Hint: think of the direction of force on a satellite in space.

Now, as said, moving charges produce magnetic fields. How do we know this? Well, analogously to Coulomb's experiment with stationary charges, we can discuss the first experiments with moving charges or currents. The current through a wire is the amount of charge moving per unit time across a point in the wire:

$$I = \frac{dq}{dt} \qquad (1.12).$$

Note that while we know that electrons have negative charge, positive current is for positive charges moving through the wire in the direction of current, by definition. This may sound odd, but in fact positive charge carriers exist in electronics, so this is an appropriate definition. The unit of current is an ampere, and is defined as the amount or current in a wire that has 1 coulomb passing a point in 1 second.

It was found, just as charges produce a force on each other, current-carrying wires produce a force on each other:

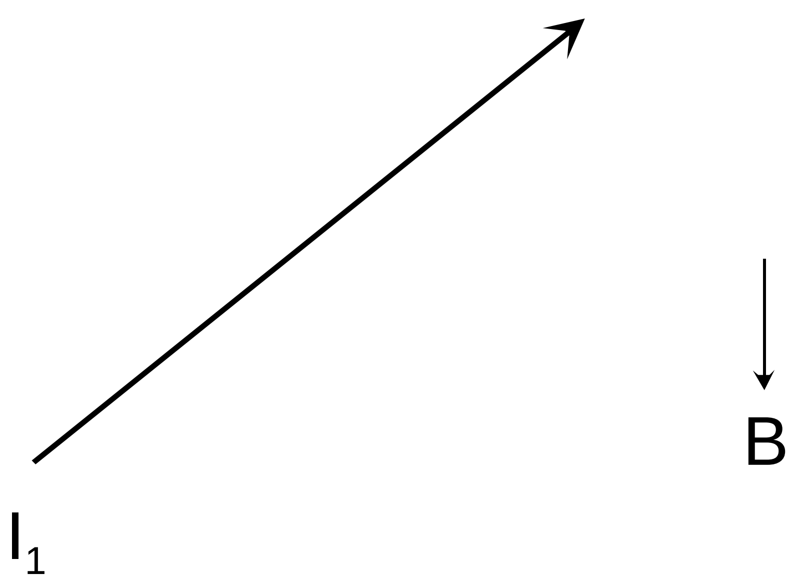


This force was determined to vary as the distance between the wires:

$$\mathbf{F} = \frac{\mu I_1 I_2}{2\pi d} L, \qquad (1.13)$$

where *L* is the length of the wires, and μ is called the *permeability.* For air, $\mu=4\pi x10^{-7}$ henries/meter, where a henry is the unit of inductance. Note here that this looks a lot like equation 1.1 for stationary charges and electric fields. However, it is different in that the force goes inversely as the distance, not distance squared, and also we must multiply by the length of the wire. The reason for this is that the longer the wire, the more moving charges in it, and the greater the force.

Now, just as a single stationary charge in space produces an electric field, as single wire in space produces a magnetic field:



Now, examine the direction of the magnetic field produced by the wire designated 1. It points down. If we replace wire 2, it will experience a force to the left. Does this make sense? Think about it, by convention current as shown is positive charges moving in the direction shown, that is the direction of their velocity. Hence, by the right hand rule of cross product and equation 1.11, the force on wire 2 will be to the left.

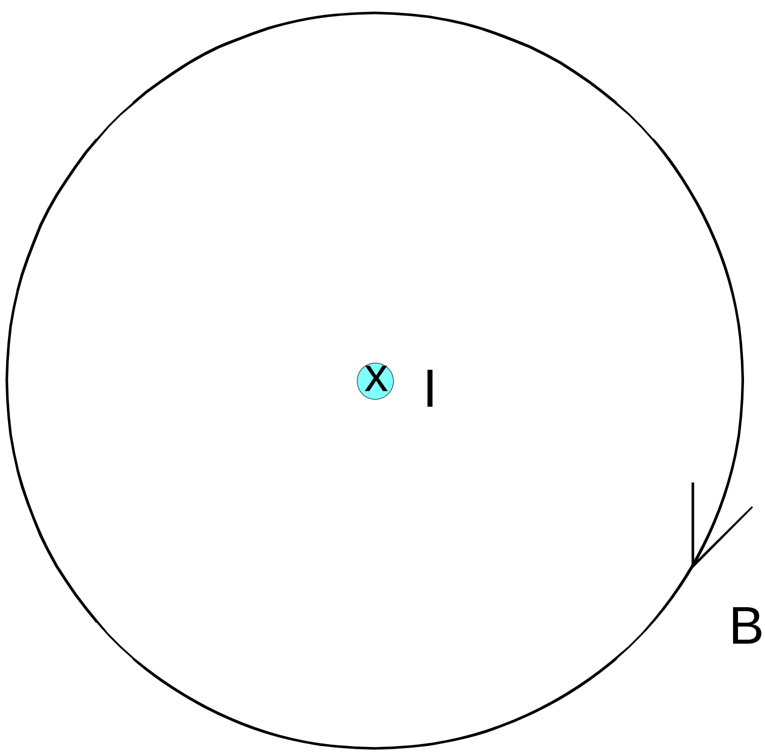
What is the magnetic field produced by wire 1? Well, analogous to equation 1.2, we write that it is

$\mathrm{B} = \frac{\mu I_1}{2\pi d}$. (1.14)

Then, if we place wire 2 back, the force on it will be

$\mathrm{F} = I_2 \mathrm{B} L$. (1.15)

Now, by symmetry, we can reason that wire 1 produces a magnetic field everywhere in space (since no matter where wire 2 is placed, a force will exist), and that also no matter where wire 2 is placed, the force will point toward wire 1. Therefore, the magnetic field is a circle:



Here for simplicity of viewing, the current is shown as a wire directed into the page, and then B is in the page.

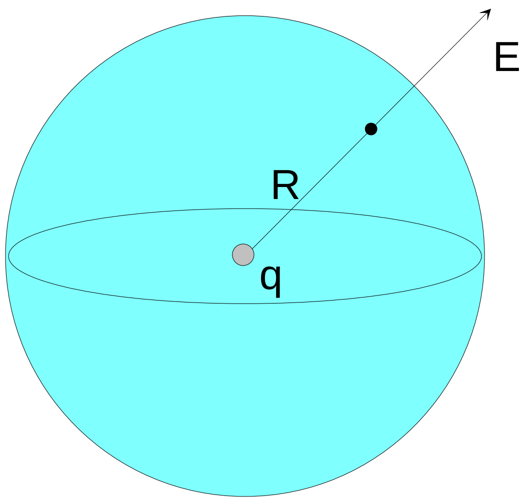
Note here a fundamental difference between electric and magnetic fields: <u>whereas electric fields point from positive to negative charges, and thus have a beginning and end, magnetic fields loop</u>

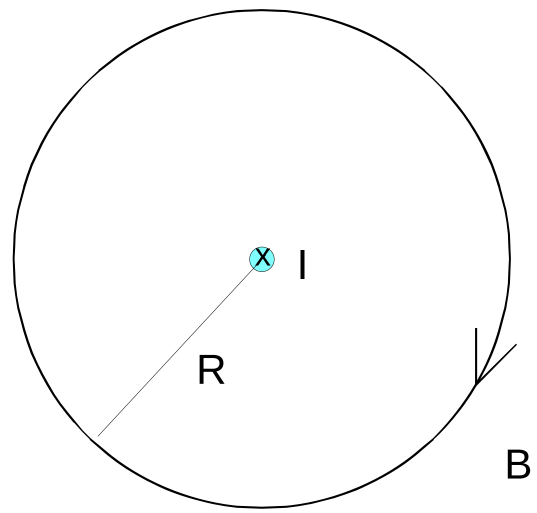
onto themselves, and have no beginning or end. This is true even if magnetic fields are not circular, but have a more complicated shape; they still loop onto themselves.

Homework 1.3: Two wires 0.1 meter apart and 1 meter in length carry 1 ampere each. What is the force in newtons between them?

Statics Mathematical Formalism

We see then that a duality exists between electrostatics and magnetostatics:





$4\pi R^2 E = q/\varepsilon$ $2\pi RB = \mu I$

Now, here is where a postulate is made for both cases. Note for electrostatics that the surface area of the sphere times the electric field equals charge divided by permittivity. For magnetostatics the circumference of the circle times the magnetic field equals current times permeability. It was postulated and found true that for any closed surface, the surface integral of electric field on that surface (that is, over its area), equals the charge/ε contained within, regardless of the shape of the surface or the position of the charges. Likewise, it was postulated and found true that for any closed curve drawn around a current, the line integral of the magnetic field on that curve (that is, over its length) equals the current times μ contained within it, regardless of the shape of the curve or the position of the currents:

$$\iint \mathbf{E} \cdot \mathbf{dS} = \frac{q}{\epsilon} \qquad (1.16)$$

$$\int \mathbf{B} \cdot \mathbf{dl} = \mu I \qquad (1.17).$$

These are respectively called Gauss's Law and Ampere's Law, after the scientists that determined them. In (1.16), S is area, and **dS** points perpendicular from the surface. Thus, for the point charge at the origin, it points away from the origin, in the same direction as **E**. Likewise for (1.17), for a circular path around a wire at its center, B and dl point in the same direction, and hence for both the dot product is simply the product of the magnitudes, and we recover equations 1.2 and 1.14. Equations 1.16 and 1.17 will be used in the next lecture to find formulas for capacitance of parallel plate capacitors, and inductance of solenoidal coils.

II Ohm's Law, Resistors, Capacitors, Inductors, and Circuit Analysis

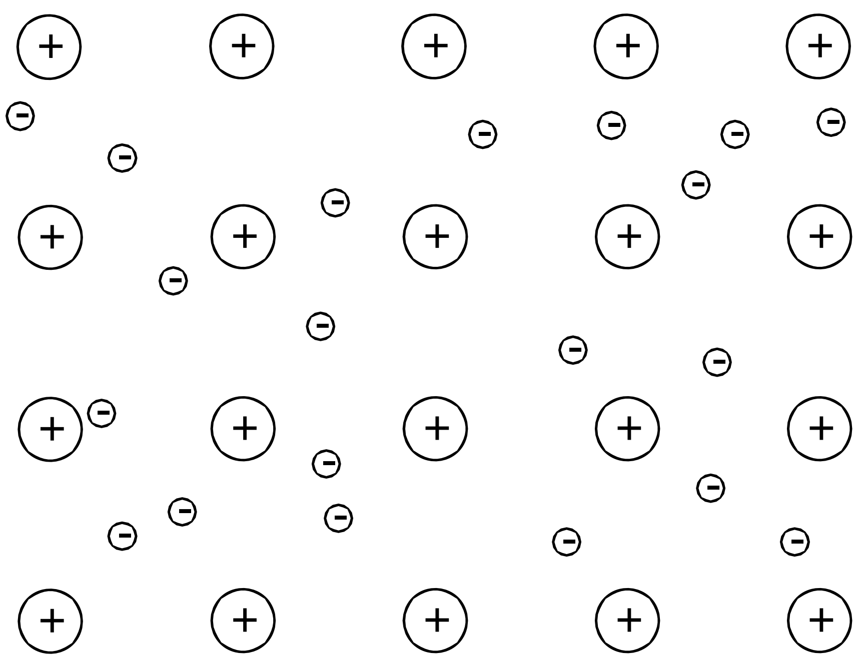
Here we begin the concept of electrical circuits, or connections of electrical elements. A simple electrical circuit may be a voltage source (our 9 volt battery) connected to an element. If the element is a *resistor*, the current flow through it is independent of time. If the element is a *capacitor* or *inductor*, the current flow depends upon how long after the connection is made. The reason for this is that capacitors or inductors can perform energy storage, via the production of electric or magnetic fields.

Resistance

Resistance is defined the ratio of voltage over current for an element that has no inductance or capacitance. Thus, it is just what the name sounds like, an element with higher resistance has more "resistance" to current flow:

$I = V/R$ (2.1).

We see that resistance is in units of volts/amps, termed ohms. What physically is a resistor? Well, most lumps of matter, including me. Upon connecting a voltage supply to my hands and raising the voltage, I was able to observe that the current went up linearly, and my resistance was about 100,000 ohms. To see that for most matter, current goes up linearly with voltage, let's examine what happens microscopically:



Shown here is a conducting solid, consisting of fixed atoms and mobile electrons. If I apply a voltage to this solid, it produces an electric field, via equation 1.7. This electric field in turn produces a force on the electrons, via equation 1.3. If *h* is the length of the solid, then, we have that the forces on the electrons is

$$\mathrm{F} = e\left(\frac{V}{h}\right) = m\frac{dv}{dt} \qquad (2.2).$$

Here we have completed the equation with Newton's Law, F=*ma*. Since the force is constant,

$$v = \left(\frac{eV}{mh}\right)t \qquad (2.3).$$

Now, if this were the complete picture, the electrons would continue to increase velocity forever and the current would also increase. That is not what happens; the reason is that the electrons bounce off the fixed atoms (this is not actually what happens, but to understand what actually happens requires quantum mechanics). So, the electrons accelerate, then hit something, losing their velocity, then accelerate again, etc.; this result in them having an average velocity. Some statistical analysis of this phenomena results in the average velocity of the electrons being given by

$$v_{ave} = \left(\frac{eV}{mh}\right)\tau \qquad (2.4),$$

where τ is called the scattering time.

Now, clearly current is related to the movement of charge, so the greater their velocity, the greater the current. The greater the density of charge (ρ), the larger the current is also. Finally, the greater the cross sectional area of the resistor (*A*), the larger the current. So, we can write that

$$I = \rho v_{ave} A \qquad (2.5),$$

where ρ is the density of mobile charge (charge/volume) in the solid. Combining 2.4 and 2.5, we have

$$I = \left(\frac{\rho e\tau}{m}\right)\left(\frac{A}{h}\right)V \qquad (2.6),$$

and we see that current goes up linearly with voltage. It is seen that resistance depends both upon microscopic quantities and the macroscopic dimensions of the wire.

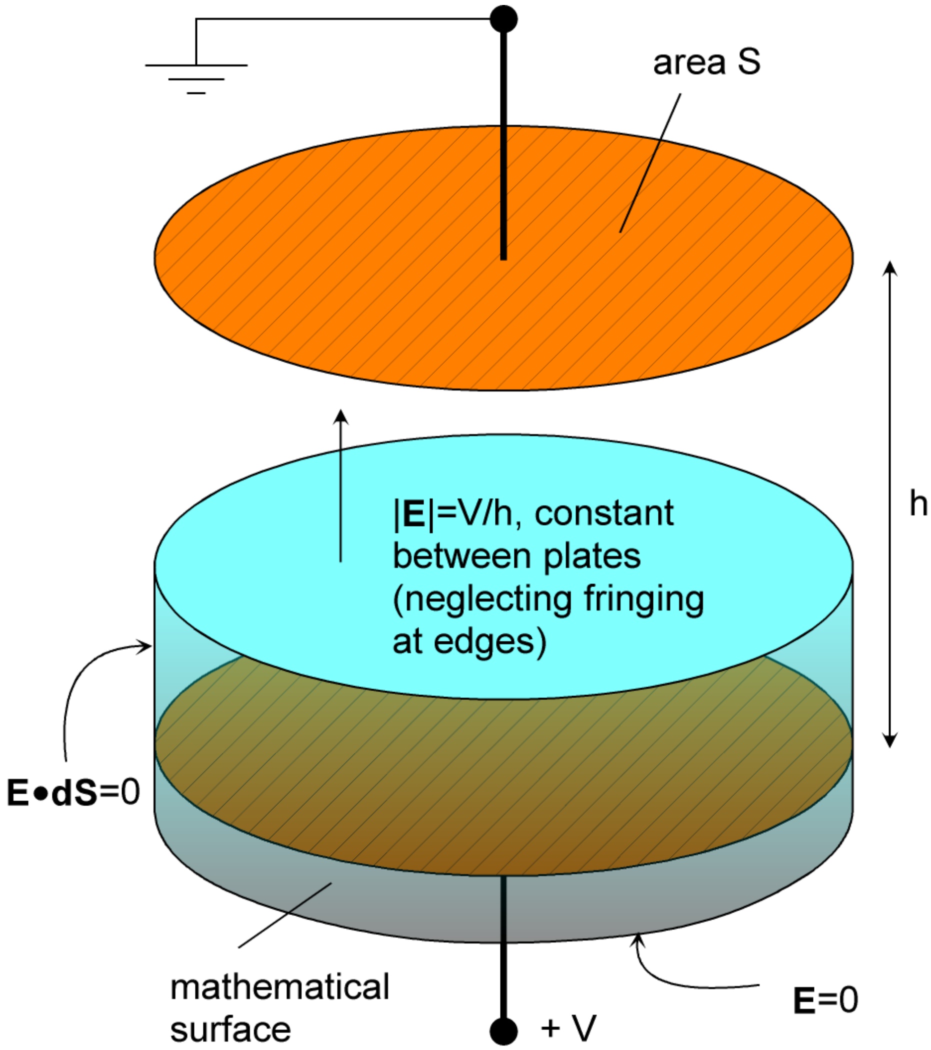
<u>Homework 2.1:</u> Copper has a mobile charge density about $8.5\text{x}10^{27}$ electrons/m3 and a scattering time of about $3\text{x}10^{-14}$ seconds. A power cable has a cross section of 10^{-4} m^2 (1x1 cm) and a length of 10 meters. It is to convey 20 amps. What is the voltage drop across the cable?

Capacitance

A *capacitor* is an element that when a voltage is placed upon it, retains a separation of charge in it. Actually, capacitance (*C*) is a definition, that is what it sounds like, the capacity of an element to store charge at a given voltage:

$$C = Q/V \qquad (2.7).$$

The most common capacitor consists of two parallel plates:



Here, we two parallel plates are shown, one at voltage *V* and the other at zero voltage. This results in positive charge *Q* on the positive plate and negative charge –*Q* on the other plate. To calculate what *Q* is, and hence the capacitance from equation 2.7, we use Gauss's Law (1.16). Shown in the figure is a mathematical surface. Now, the electric field between the plates points from the positive to the zero plate, and by equation 1.7 is given by *V/h*. So, the mathematical surface has no component of $\mathbf{E} \cdot \mathbf{dS}$ on it's sides; also, since E=0 outside the capacitor, there is no component underneath the positive plate. So

$$\iint \mathbf{E} \cdot \mathbf{dS} = \left(\frac{V}{h}\right) A = \frac{Q}{\epsilon} \qquad (2.8),$$

where *A* is the area of the capacitor plates. Hence, we have that

$$C = \left(\frac{Q}{V}\right) = \frac{\epsilon A}{h} \qquad (2.9).$$

As stated above, while for resistors the relationship between current and voltage is not a function of time, here for capacitors (and inductors, below), it is. That can be seen qualitatively from thinking about the sudden hooking up of a voltage source to the capacitor: initially, the current will be high, as the capacitor charges up, but eventually the current will drop to zero, when the capacitor is fully charged. Thus the current is a function of time. The relationship between voltage and current on a capacitor is therefore a differential equation, and can be easily derived from equation 2.7:

$Q = CV$ (2.10),

$\frac{dQ}{dt} = I = \frac{d(CV)}{dt} = C\frac{dV}{dt}$ (2.11).

Thus there is non-zero current going into a capacitor when the voltage across it is changing.

We will use eq. 2.11 below in analyzing circuits with capacitors. Before we leave capacitors specifically, it is helpful to understand that a capacitor is an energy storage device, and we can use these equations to determine the amount of energy stored. We can employ equation 1.5 to write

$energy, capacitor = \frac{QEh}{2} = QV/2$ (2.12).

Why the ½? Because, if the charge on both sides of a capacitor "drops" to the midpoint, the pluses and minuses annihilate each other and the energy is released. So, each charge only has to move across half the distance separating the plates. We can use equations 2.10 and 2.12 to rewrite the energy stored as

$energy, capacitor = CV^2/2$ (2.13).

Homework 2.2: You make a capacitor by rolling up a sandwich of two metal films separated by a 0.01 mm thick insulator. The insulator has a permittivity 10,000,000 times that of air. The capacitor area is 20x500 cm. You place 100 volts on the capacitor. What is the energy stored in kWh? (A kWh is equivalent to 1000 watts or 1000 joules/second running for one hour.)

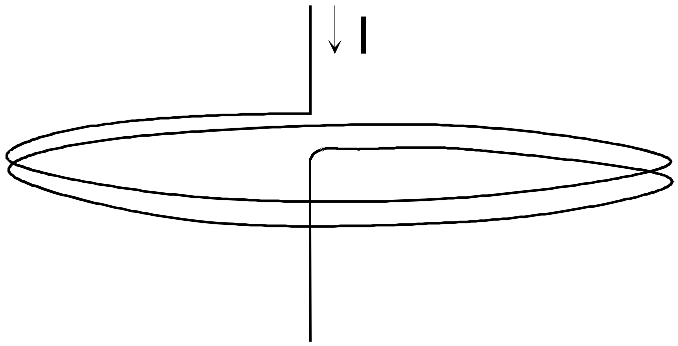
Inductors

For inductors, there is no easy definition like eq. 2.7. To a certain extent, the easiest definition for an inductor is the analog to equation 2.11 for capacitors, switching *I* and *V*:

$V = L\frac{dI}{dt}$ (2.14).

Thus, an inductor is an element where the voltage across it is proportional to the time rate of change of current. The proportionality constant, *L*, is its inductance.

For circuit analysis, 2.14 is all we need to know about inductors. But, we can delve into them a little more, and understand why they obey 2.14. First, as you may know, the classic inductor is a coil or wire:



Now, from what we know about magnetic fields, think about what is happening as we put current through the coil. As the charges move through the wire, they will produce a magnetic field as we found in the first lecture. If the current is constant and therefore the magnetic field is constant, everything is fine, and the voltage across the inductor is zero. Now, we must understand that, just as in a capacitor energy is stored via the production of an electric field, also when a magnetic field is produced, energy is stored. How do we know this? Because, we know that a magnetic field can induce forces on charges that happen to be moving by. So, the magnetic field can deliver energy to the charges. Therefore, the magnetic field has stored energy. If the current to the inductor increases, thus increasing the magnetic field, power must be supplied to the inductor, since the stored energy increases. Now, from section 1, we learned that power=current x voltage. Therefore, a voltage must be supplied to the inductor. So, we have that when current is changing across an inductor, and thus the magnetic field and energy storage is changing, voltage must also be supplied to it, and we have equation 2.14.

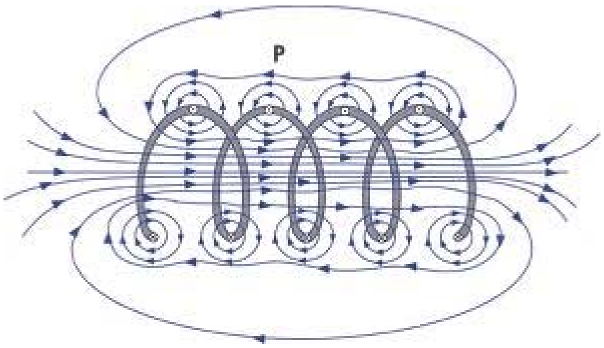
How do we determine the inductance *L*? Well, clearly, if a coil produces a larger magnetic field, *L* is larger. So, we can define inductance as the ratio of magnetic field to current. It's a little different than that,

$$L \approx \frac{BS}{I} \qquad (2.15),$$

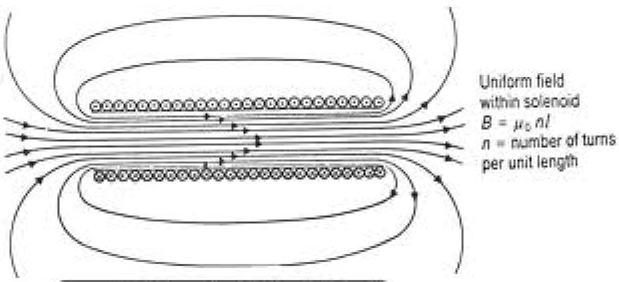
where *S* is the area of the coil (note that if you put *I* on the left, you get a nice mnemonic). Now, this equation is not quite correct, as the magnetic field is not always constant across the coil area. In addition, for the classic coiled inductor with *N* coils, the inductance is larger for each coil. So, the correct equation is

$$L = N\frac{\iint \mathbf{B}\cdot\mathbf{dS}}{I} \qquad (2.16).$$

For a many-coiled inductor or solenoid, we can reason out the direction of the magnetic field:

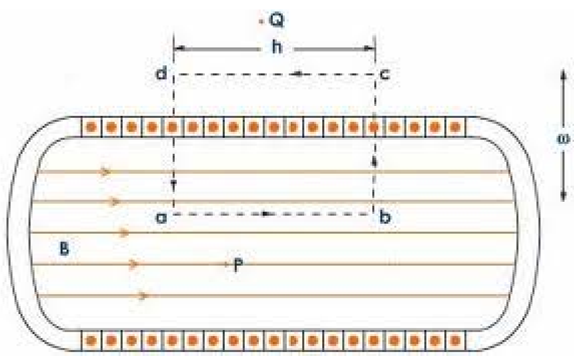


As we know, the magnetic field circles the wires of the winding. It should be apparent that as you move toward the axis of the solenoid, the magnetic fields add up such that they point along the axis of the solenoid. As the winding becomes tighter and as coils are added, this becomes more pronounced:



Magnetic Field for a solenoid (a long helical coil)

Note that the magnetic field outside the solenoid is small and can be approximated as zero. Then, we can use Ampere's law (eq. 1.17), that the integral of B times length along any curve equals the current contained within:



Here, performing the integral of eq. 1.17 along the dotted path shown, there is only a component along line a-b, which has length *h*:

$\int \mathbf{B} \cdot \mathbf{dl} = \mathrm{B}h = \mu I = n\mu I$ (2.17),

where *n* is the number of coils contained within the path. Although we see that the magnetic field becomes "curved" near the ends of the solenoid, we can approximate that

$$B = \frac{\mu N I}{z} \qquad (2.18),$$

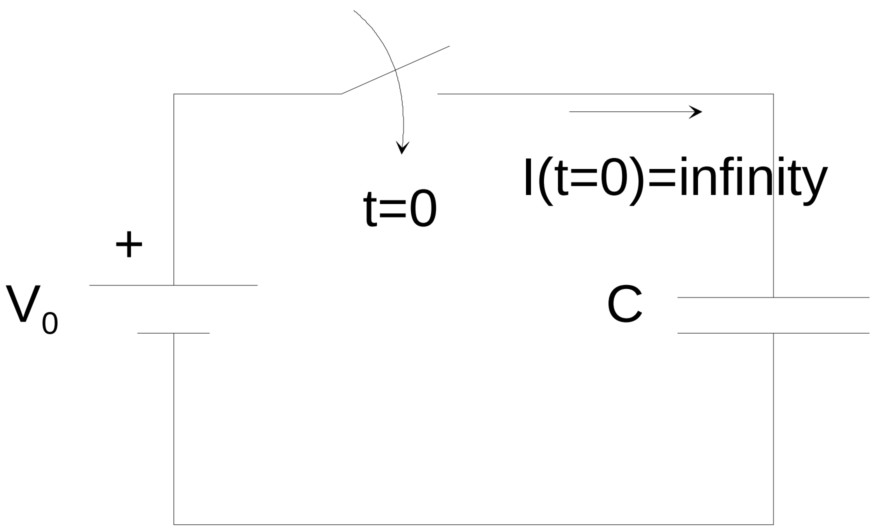
where *N* is the total number of coils and *z* is the total length of the solenoid. Then, using equation 2.15, we have that

$$L = N\frac{\iint \mathbf{B}\cdot\mathbf{dS}}{I} = \frac{N^2 \mu A}{z} \qquad (2.19).$$

So the inductance of a coil goes up as the square of the number of windings, and also with area, and inversely with the length. The latter indicates that very tightly coiled inductors have higher inductance.

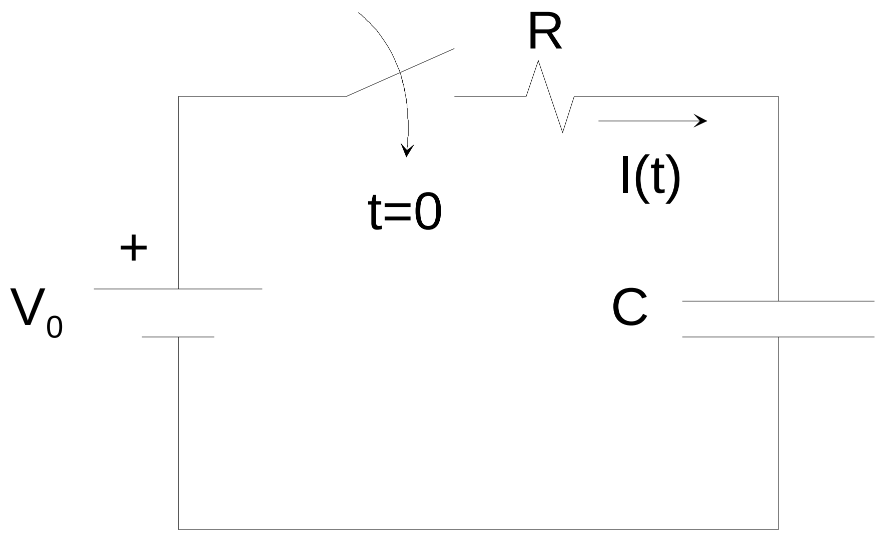
Circuit Analysis

Now, let's place resistors, capacitors, and inductors in a circuit with a voltage source and see what happens. Before beginning, let's examine special cases that illustrate problems to avoid in circuits. First, let's cover the thought problem above of hooking up a battery to a capacitor:



At *t*=0, then, the capacitor, which was uncharged previously, is hooked to the battery. Thus it immediately has a voltage V_0 across it. That implies, by equation 2.11 that, given an instantaneous change in voltage, the current into the capacitor is infinite. Which, of course, it must be since to change voltage instantaneously, it must be charged instantaneously, which implies infinite current. So, if you were to actually do this experiment, you would have a bad day and possibly start a fire!

Rather, the charging must be done with a resistor in series:



Now, since the capacitor's voltage cannot change instantaneously (otherwise we would have infinite current!), at *t*=0, all the battery's voltage initially appears across the resistor. Then, as time progresses, the capacitor eventually charges up to the battery voltage, and current stops. We can formalize this mathematically by writing the differential equation for the circuit at all times. To do this, note that

$$voltage\ across\ resistor = V_R = IR \qquad (2.20),$$

and

$$I = C\frac{dV_C}{dt} \qquad (2.21).$$

But,

$$V_C = V_0 - V_R \qquad (2.22),$$

so, we can write

$$V_C = V_0 - IR = V_0 - RC\frac{dV_C}{dt} \qquad (2.23).$$

Note what we have done here: by reasoning through, and collecting terms, we have written a differential equation for the circuit <u>with one variable</u>, here V_C. Once we solve this differential equation, we can find how the other variables, for example *I* vary with time, for example by using equation 2.21. So, it's a type of algebra, where one wants to eventually write a single equation with a single variable, but having derivatives.

Now, solving 2.23 is just like solving any other differential equation: one knows the answer ahead of time! One can be aided here by knowing that any first order differential equation has an exponential solution:

$$V_C = A + Be^{t/\tau} \qquad (2.24).$$

One plugs our assumed solution 2.24 into 2.23, and if it is correct, can then solve algebraically for *A*, *B*, and τ:

$V_C = A + Be^{t/\tau} = V_0 - RC\frac{dV_C}{dt} = V_0 - RC\frac{d}{dt}(A + Be^{t/\tau})$ (2.25).

Solving,

$A + Be^{t/\tau} = V_0 - RC\frac{d}{dt}\left(A + Be^{\frac{t}{\tau}}\right) = V_0 - \frac{RC}{\tau}\left(Be^{\frac{t}{\tau}}\right)$ (2.26).

Now, examining, we see that in order for the solution to work,

$A = V_0$ (2.27),

and

$\tau = -RC$ (2.28).

So, we have that the solution is

$V_C = V_0 + Be^{-t/(RC)}$ (2.29).

There is a parameter left, *B*. Of course, solving a first order differential equation, there is always a parameter left, which is determined by the *boundary conditions*, which in this case, is a boundary in time: at $t=0$, $V_C=0$. Therefore, $B=-V_0$, and

$V_C = V_0[1 - e^{-t/(RC)}]$ (2.29).

We see that, as stated, the voltage across the capacitor starts at zero, and rises asymptotically to the battery voltage with a time constant *RC*.

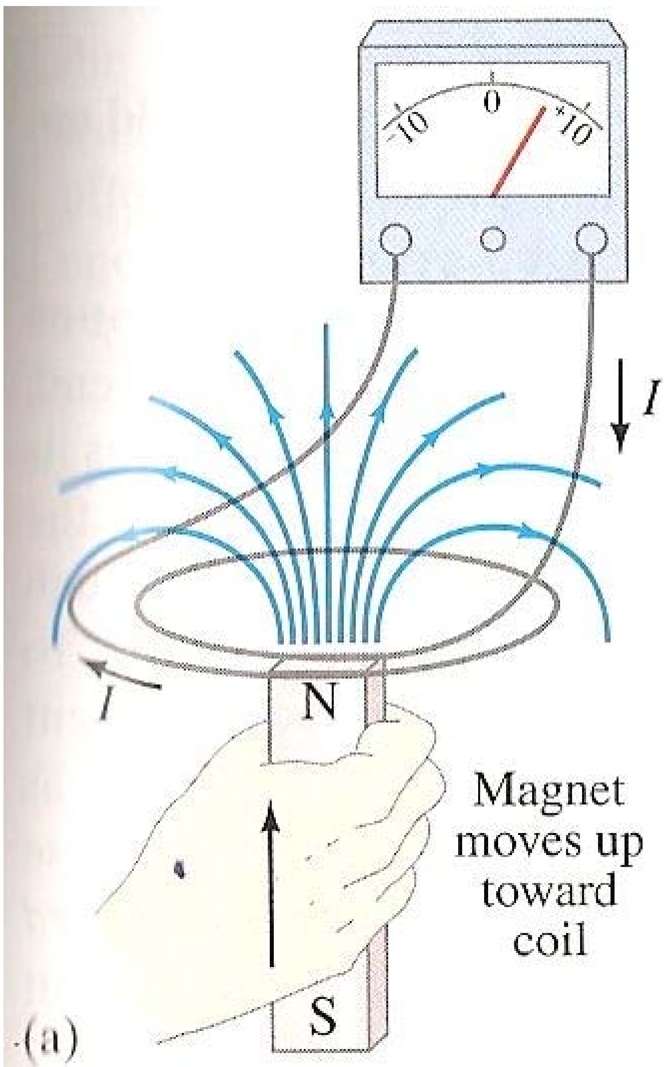
Homework 2.3: You actually could hook a voltage source up directly to a capacitor, because voltage sources always have an internal resistance that is unavoidable and governed by the connections inside, etc. For the capacitor of homework 2.2, assuming the 100 volt source has an internal resistance of 1 ohm, how long does it take for the capacitor to charge to 90 volts?

For circuits with inductors as well as capacitors and resistors, one performs the same operations to solve for the circuit voltages and currents. In lecture 4, we will use such circuit analysis to understand things like power factor in loads with inductance.

III Electromagnetic Theory, Faraday's Law

In the previous lecture, we stated that when the current into an inductor (or any coil) is increased, a voltage must be supplied. The reasoning was that since an increase in current causes an increase in magnetic field, which stores energy, power must be supplied. Since power = voltage x current, voltage must be supplied as well as current to increase the stored energy in the coil.

Here, by corollary, we can also reason that for a coil just sitting there, if it's magnetic field is changed, it must change its stored energy, and current and voltage is developed, passing or taking energy from the circuit it is hooked into. Let's look at some of the original experiments that showed this phenomena:



In the above, as the magnet is moved toward the coil, the magnetic field inside the coil changes and a current is developed, causing the ammeter to register. Actually both a current and voltage are developed, but only the current is shown on the ammeter. If one hooked up a voltmeter instead, a voltage would be shown. If instead a load or resistor was hooked up to the coil, both voltage and current would appear across it, thus supplying power to the load. The power comes from the mechanical power required to move the magnet toward the coil (hey, we made a generator!).

Now, we have danced around this dynamic phenomenon associated with inductors and moving magnets, etc., and made some qualitative remarks about developed voltages, etc. In the last lecture, we quantified part of this with equation 2.14. We supported equation 2.14 with a qualitative remark about how if the current increased into an inductor, increasing its magnetic field, voltage must appear across it as well since power must be supplied to increase the stored energy.

It turns out, that we cannot *derive* equation 2.14. It is a fact of nature, like *F=ma*. Really, equation 2.14 is a result of a more basic relationship, which is: <u>a changing magnetic field will produce a changing electric field</u>. The last statement is true regardless of whether there are any coils or wires or even matter around! With coils and moving magnets (or moving coils), we see the effects of this basic principle of the universe. To ask why this happens is like asking why there is a gravitational field; it is part of the makeup of our universe. Physicists may delve into the basis for this effect, but as engineers we are simply required to understand it and employ the equations that govern it.

So, while we could start with equation 2.14, for example, and try to derive equations that govern the moving magnet experiment above, it is really more appropriate to start with the fundamental equation governing the underlined statement above. Now, I'm going to write it in its complete mathematical form; for those of you that understand vector calculus it may assist you in understanding; for those that don't, do not worry as we are going to quickly go into special cases that get rid of the vector nature:

$$\boldsymbol{\nabla}\mathbf{x}\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad (3.1).$$

Those of you in the know will recognize Maxwell's 3rd equation. Again, <u>this equation, showing how a changing magnetic field produces a changing electric field, is immutable, a fact of the universe.</u> The various experiments including the one showed above, resulted in intermediate equations governing voltages, changing magnetic fields, etc., and eventually led scientists to understand that 3.1 is the basic equation governing all that.

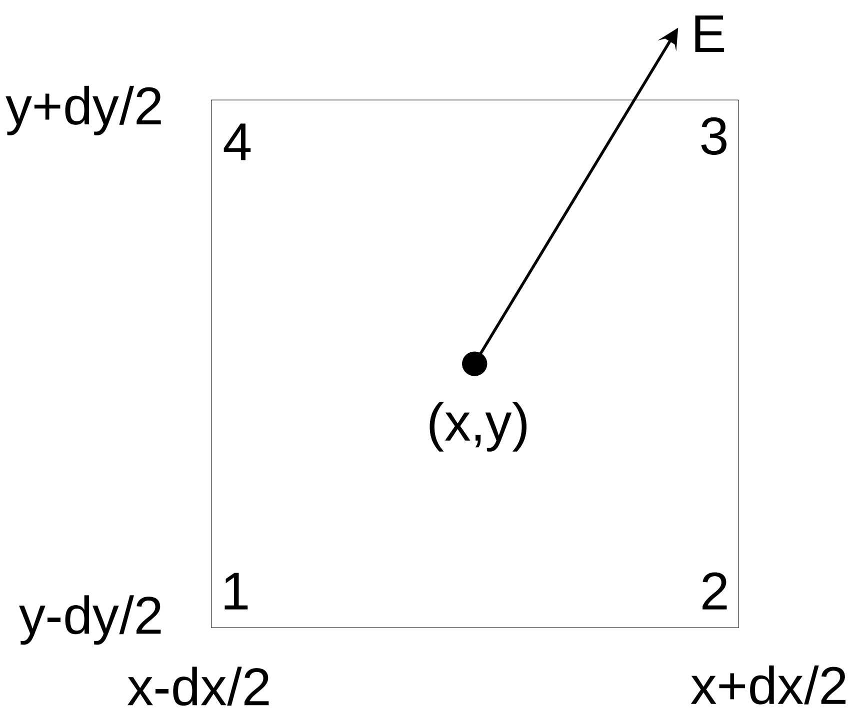
We can find alternate and simpler forms of this equation, for particular cases, for example, the case of a magnetic field only in the z direction. Since

$$\nabla \times \mathbf{E} = \begin{vmatrix} \mathbf{a}_x & \mathbf{a}_y & \mathbf{a}_z \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ \mathrm{E}_x & \mathrm{E}_y & \mathrm{E}_z \end{vmatrix} = (\frac{\partial \mathrm{E}_z}{\partial y} - \frac{\partial \mathrm{E}_y}{\partial z})\mathbf{a}_x + (\frac{\partial \mathrm{E}_x}{\partial z} - \frac{\partial \mathrm{E}_z}{\partial x})\mathbf{a}_y + (\frac{\partial \mathrm{E}_y}{\partial x} - \frac{\partial \mathrm{E}_x}{\partial y})\mathbf{a}_z \qquad (3.2),$$

If only a component of **B** exists in the z direction, this implies that a changing magnetic field will only produce components of electric field in the *x* and *y* directions. So, in the above experiment with the magnet in the coil, if we approximate that the magnetic field is only in the z direction, moving it toward the coil only produces an electric field perpendicular to the magnetic field or in the plane of the shown coil. Thinking about this, we start to get a hint of the behavior, that it is only changes in magnetic field perpendicular to a coil that matter. Writing 3.1 with only magnetic fields in the z direction, we have

$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -\frac{\partial B_z}{\partial t} \qquad (3.3).$$

Now, to proceed, we have to do something complicated mathematically, called Stoke's theorem. I'm going to walk through it; do not worry about having to recreate the following derivation, but simply understand the result. Equation 3.3 says that if a magnetic field is pointing perpendicular to a plane, and it varies with time, it creates electric fields that vary both in time and across the plane. What we are really interested in is what happens to a coil in that plane. So, we have to connect what happens along the length of the coil with equation 3.3. Let's examine a plane with an electric field, zooming in on a very small infinitesimal area:



Now, let's integrate $\mathbf{E} \cdot \mathbf{dl}$ around the loop, going from point 1 to 2 to 3 to 4. This is just the integral of E_x along 1-2, E_y along 2-3, $-E_x$ along 3-4, and $-E_y$ along 4-1. But, for example Ex along line 1-2 does not equal Ex in the center of the loop. Rather, it is given by

Along line 1-2: $E_x = E_x(center) - \frac{\partial E_x}{\partial y}(\frac{dy}{2})$ (3.4)

Along line 2-3: $E_y = E_y(center) + \frac{\partial E_y}{\partial x}(\frac{dx}{2})$ (3.5)

Along line 3-4: $E_x = E_x(center) + \frac{\partial E_x}{\partial y}(\frac{dy}{2})$ (3.6)

Along line 4-1: $\mathrm{E}_y = \mathrm{E}_y(center) - \frac{\partial \mathrm{E}_y}{\partial x}(\frac{dx}{2})$ (3.7)

So, integrating $\mathbf{E} \cdot \mathbf{dl}$ around the loop, we have first for the horizontal lines:

$\oint \mathbf{E} \cdot \mathbf{dl}$**,** 1-2 and 3-4= $[\mathrm{E}_x(center) - \frac{\partial \mathrm{E}_x}{\partial y}\left(\frac{dy}{2}\right)]dx - [\mathrm{E}_x(center) + \frac{\partial \mathrm{E}_x}{\partial y}(\frac{dy}{2})]dx$=$-\frac{\partial \mathrm{E}_x}{\partial y}dxdy$ (3.8).

Along the vertical lines,

$\oint \mathbf{E} \cdot \mathbf{dl}$**,** 2-3 and 4-1= $[\mathrm{E}_y(center) + \frac{\partial \mathrm{E}_y}{\partial x}\left(\frac{dx}{2}\right)]dy - [\mathrm{E}_y(center) - \frac{\partial \mathrm{E}_y}{\partial x}(\frac{dx}{2})]dy$=$\frac{\partial \mathrm{E}_y}{\partial x}dxdy$ (3.9).

And, we have that

$\oint \mathbf{E} \cdot \mathbf{dl}$**,** 1-2-3-4 =$(\frac{\partial \mathrm{E}_y}{\partial x} - \frac{\partial \mathrm{E}_x}{\partial y})dxdy$ (3.10).

Hey, look at equation 3.3!! Without the *dxdy*, equation 3.10 is the left hand side. So, plugging in from eq. 3.3,

$\oint \mathbf{E} \cdot \mathbf{dl}$**,** 1-2-3-4 =$\left(\frac{\partial \mathrm{E}_y}{\partial x} - \frac{\partial \mathrm{E}_x}{\partial y}\right)dxdy = -\frac{\partial B_z}{\partial t}dxdy$ (3.11).

Now, if we make the loop larger, we just add up all the terms of the right:

$\oint \mathbf{E} \cdot \mathbf{dl}$**,** (a large loop) =adding all the $(-\frac{\partial B_z}{\partial t}dxdy)$ in the loop (3.12).

But, adding all the $(-\frac{\partial B_z}{\partial t}dxdy)$ in the loop simply means performing the area integral in the loop:

$\oint \mathbf{E} \cdot \mathbf{dl} = -\iint \frac{\partial \mathrm{B}_z}{\partial t}dxdy = -\frac{\partial}{\partial t}\iint \mathrm{B}_z dxdy$ (3.13).

We define

$\emptyset \equiv \iint \mathrm{B}_z dxdy$ (3.14),

as the <u>magnetic flux</u> enclosed by the coil. Now, from 1.8, $V = \oint \mathbf{E} \cdot \mathbf{dl}$, so the voltage developed across a loop of wire equals the time rate of change of the magnetic flux enclosed by it:

$V = -\frac{d\emptyset}{dt}$ (3.15).

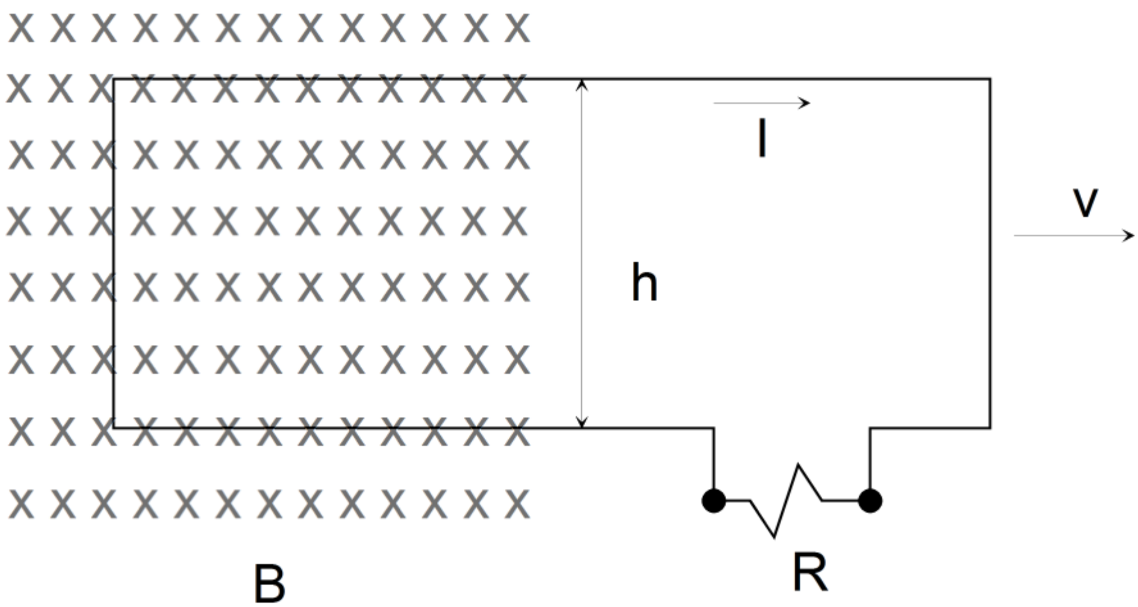
Note that if there are multiple loops in the coil, we simply add the voltages of all the loops:

$V_{N\ coils} = -N\frac{d\emptyset}{dt}$ (3.16).

In lecture 5, we will use eq. 3.15 to calculate the power generated by a rotating coil in a magnetic field. In lecture 4, we will use eq. 3.16 to show how a transformer works. Note that while it is confusing to talk about the voltage developed across a closed loop of wire, as in the experiment above, eq. 3.15 applies to a loop that is coiled, or has a small break in the end to tap current off of.

Homework 3.1: A circular wire is perpendicular to a constant magnetic field B. Its radius r shrinks with time. What voltage is developed in the wire?

We've shown that if a magnet is moved relative to a coil, voltage is developed in the coil. If a resistor is placed across the ends of the coil, current will flow through it, and hence power is delivered to it. Let's examine this "generator":



Here the magnetic field points into the page. The magnetic flux enclosed by the coil is given by ϕ=Bhx, where x is the horizontal distance from the end of the coil to where the magnetic field ends. Therefore,

$$\frac{d\emptyset}{dt} = \mathrm{B}h\frac{dx}{dt} = \mathrm{B}hv = -V \qquad (3.17).$$

Note that whether or not the resistor is connected, the voltage that appears across the coil opening is given by 3.17. Now, since the ends of the coil are connected across a resistor, current will flow, equal to *V/R*.

So far, we have ignored the minus sign in 3.15. It is actually important to know which direction the current will flow in. To see, consider that in our analysis for B pointing in the z direction, we calculated $\oint \mathbf{E} \cdot \mathbf{dl}$ in the counter-clockwise direction. So, if B points in the positive z direction and increases, E points clockwise. Here, B points in the negative z direction but contained flux is decreasing, so E (and hence the induced current) also points in the clockwise direction, as shown.

In our electrical "generator" above, power is supplied to the load resistor. That power must come from that which is pulling the coil to the right, which means, there must be a force opposing that pulling. That force is the force of the magnetic field on the moving current. We know that forces are at right angles to the moving charge or current and the magnetic field. Therefore, the force opposing the pulling is on the coil arm to the left. From equation 1.15, that force is

$F = IhB$ (3.18).

Since energy = force x distance, power = force x velocity. Thus, the power supplied by the agent pulling the coil equals

$P_{mech} = IhBv$ (3.19).

We've learned that electrical power is current times voltage:

$P_{elec} = IV = IBhv$ (3.20).

Thus, the electrical power supplied to the load resistor equals the mechanical power expended pulling the coil through the magnetic field. This is of course what an electrical generator means, the conversion of mechanical power into electrical power. In lecture 5, we will continue to use Faraday's Law to describe a rotating coil generator.

<u>Homework 3.2: In the above generator, one has a 50 ohm load, and wants to supply 200 watts of power. h=20 cm. B=1 tesla. What force is required to pull the coil at? What mass is that equivalent to having to lift in the earth's gravity?</u>

IV Electric Power, DC and AC Power Transmission, and Three-Phase Power

As mentioned, we will cap this 5 lecture series with a description of rotating electrical generators in lecture 5. While perhaps out of order, before we do that we can describe a lot about how that generated electrical power reaches the consumer.

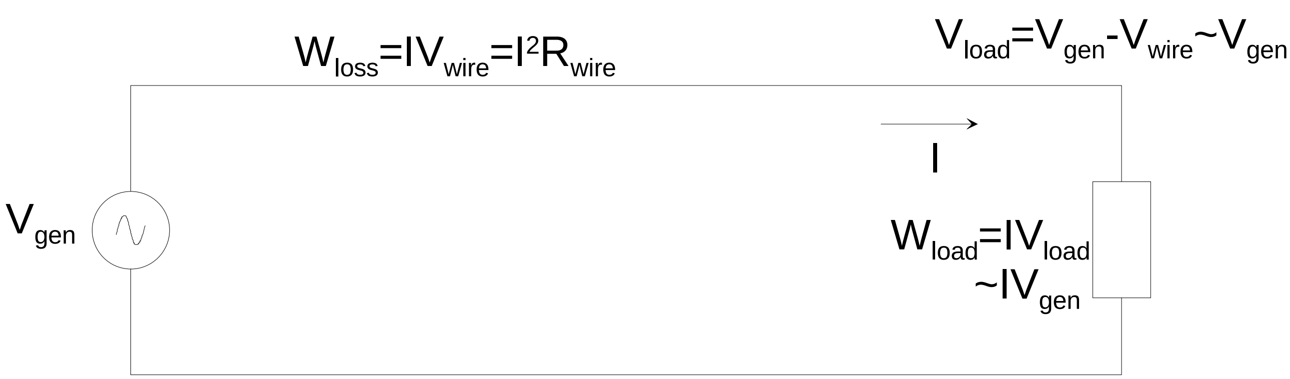
AC and DC electric power

In the previous lecture, an electrical "generator" was described that produces a steady, termed Direct Current or DC electrical output. The word generator is in quotes here, since clearly when the coil reaches the edge of the magnetic field area, it stops working, and must be reset back to the left. Generally, one gets the idea that a rotating device would avoid this problem. Also, generally, one gets the idea that such a rotating device may produce first one polarity than the other, which is called Alternating Current or AC. Actually, one can arrange for a rotating device to produce DC, but the point is that one can produce either.

We generally know that what comes out of the outlets is AC, while not perhaps having a complete understanding of it. Usually, and in the case of our electrical outlets, "AC" implies that the voltage (and current) obeys a sine function:

$$V_{AC} = V_{peak}\sin(\omega t) \qquad (4.1).$$

At this point, we should discuss why electric power is transmitted to us in AC form. It does seem perhaps a bit of a complication, why not just do it DC? This is actually a very interesting historical note on the development of electric power, with Edison promoting DC and Tesla promoting AC transmission. Most of the consideration is the losses in the wires due to wire resistance. Now, it is beyond the scope of this course, but it can be shown that DC transmission at a given voltage has lower wire loss. But, that is only part of the story. What actually governs electric power transmission is that *higher voltages have lower wire loss*. To see this, examine this figure:



As can be seen, the power delivered to load is given by

$$W_{load} = IV_{load} \qquad (4.2).$$

The wire loss is given by

$$W_{loss} = IV_{drop\ across\ wire} \qquad (4.3).$$

Note here that the voltage drop across the wire is very small, so we can approximate that

$$V_{load} = V_{generated} - V_{drop\ across\ wire} \cong V_{generated} \qquad (4.4).$$

But, the voltage drop across the wire is given by

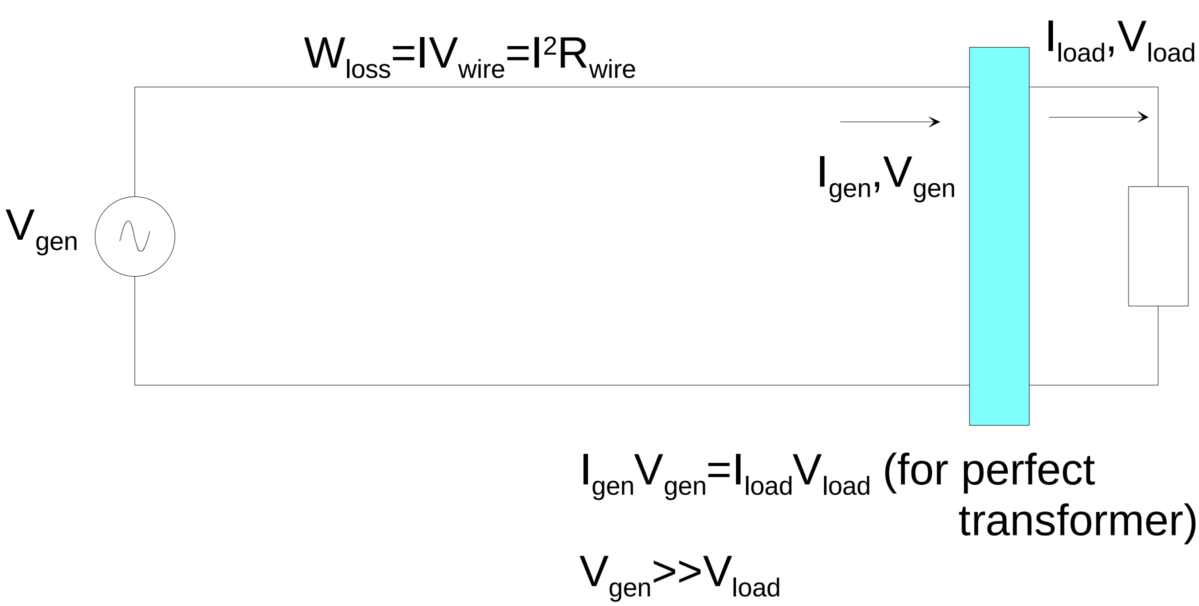
$$V_{drop\ across\ wire} = IR \qquad (4.5),$$

where *R* is the wire resistance. Therefore, the wire loss is given by

$$W_{loss} = I^2R = W_{load}^2 R / V_{generated}^2 \qquad (4.6).$$

Thus we see that the losses in the transmission line goes inversely as the square of the voltage on the line.

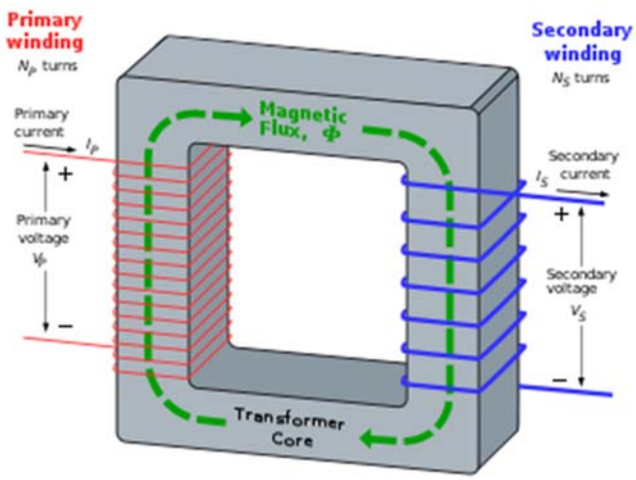
For this reason, transmission voltages are very high, in the hundreds of thousands of volts typically. We still have not explained why this favors AC transmission. The reason is that one does not desire hundreds of thousands of volts at the power outlet! Rather, one wishes to transmit power at very high voltage, but then *step down* the voltage just before the end use:



Note here that equation 4.6 still applies, as when the voltage is stepped down, the current is stepped up, so that the same power is delivered to load. Since the power loss in the wires is determined by the transmission current, which is low since the generation voltage is high, the wire loss is low.

Transformers-

Now, the difference between DC and AC here, is that it is difficult to step down DC, but for AC, there is a very simple device called a *transformer*. You have seen these devices, which are typically cylindrical objects located on telephone poles near your house. Using the principles from the last lecture, we can understand their operation:



Here a simple transformer is shown. It is similar to an inductor, like two coupled inductors. We did not discuss inductor *cores* in the lecture 2; here, just think of the core as "containing" the magnetic field lines. Thus, the same magnetic field strength goes through both windings. So,

$\frac{d\emptyset}{dt}$ is the same in both windings. (4.7)

Now, by equation 3.16, the voltages of the coils are given by:

$$V_p = N_p \frac{d\emptyset}{dt}, V_s = N_s \frac{d\emptyset}{dt} \qquad (4.8),$$

and thus,

$$V_s = \frac{N_s}{N_p} V_p \qquad (4.9).$$

So, we have stepped down the voltage from a high value to a lower value. But, note!: this device only works at AC, since $d\emptyset/dt$ is zero for DC.

So, AC won the engineering battle for electric power transmission, because transformers could be used to step down the voltage, allowing high line voltages (and low line currents and hence low line loss), and low load voltages (so we don't kill ourselves).

Note that today DC-DC voltage converters are available. However, they have higher costs and internal power losses, so we still use AC transmission.

Homework 4.1: As we know, 110 volts is a standard load voltage in our houses. A standard transmission voltage is 600,000 volts. The transmission distance is 100 kilometers, and the cable has the same parameters of problem 2.1, except the area is 10x10 cm. It conveys 10 MW (million watts). What is the loss in the line in watts?

AC power-

Now, in homework 4.1, I allowed you to still use eq. 1.10 to calculate power. But, you may have wondered, if it is AC, what voltage do I use? The voltage is changing in time, so … . Here, we will analyze the power delivered by an AC generator:

$$V_{AC} = V_p \sin(\omega t) \qquad (4.10).$$

Now, later, we will consider that the current is *out of phase* with the voltage, but for now assume the current has the same time relationship:

$$I_{AC} = I_p \sin(\omega t) \qquad (4.11).$$

Then the *time-varying power* is given by

$$P_{AC} = I_p V_p sin^2(\omega t) \qquad (4.12).$$

We see that the power delivered is always positive, but varies in time. We can find the *time-averaged power* by integrating over one cycle, and dividing by the tim

$$P_{AC,ave} = \frac{\omega}{2\pi}\int_0^{2\pi/\omega} I_p V_p sin^2(\omega t)dt \qquad (4.13).$$

Here, we've noted that the *period* of the cycle (*T*), or when it repeats itself, is when $\omega T = 2\pi$, as for any sine function. Noting that

$$sin^2(\omega t) = 0.5 + \sin(2\omega t) \qquad (4.14),$$

and noting that the integral of the sine in 4.14 will be zero over a cycle (up and down), we can easily then write that

$$P_{AC,ave} = \frac{\omega}{2\pi} I_p V_p (0.5)\frac{2\pi}{\omega} = \frac{I_p V_p}{2} \qquad (4.15).$$

We see that if we define something called

$$V_{RMS} \equiv \frac{V_P}{\sqrt{2}} \qquad (4.16),$$

$$I_{RMS} \equiv \frac{I_P}{\sqrt{2}} \qquad (4.17),$$

$$P_{AC,ave} = I_{rms} V_{rms} \qquad (4.18).$$

"RMS" here means "Root mean squared," because

$V_{rms} = \sqrt{< V^2(t) >}$ (4.19),

where <> means taking the time average of, as we did in equation 4.13 for power. Don't worry about that, just remember the result is that it is the peak voltage divide by root 2.

So, when we say that the wall output has 120 volts, what we are referring to is the "RMS" voltage. And, when we use an AC voltmeter, it has been designed to show the RMS voltage. Conveniently then, using an AC voltmeter and ammeter, taking the product of what we see yields the average power.

We can show that Ohm's law (2.1) is true for AC voltages and currents if we use the RMS values. Noting that

$I(t) = \frac{V(t)}{R}$ (4.20)

at any instant of time, then

$I_P = \frac{V_P}{R}$ (4.21), and hence

$I_{rms} = \frac{V_{rms}}{R}$ (4.22).

<u>Inductive and Capacitive Loads-</u>

If the load is an inductor, then on an instantaneous basis 2.14 applies:

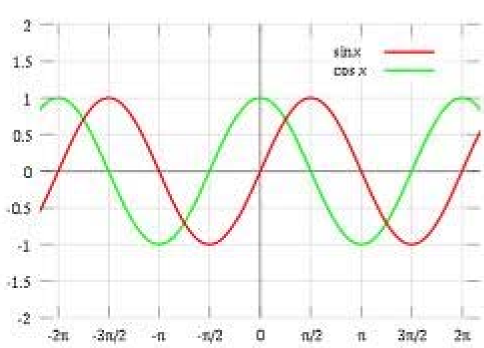
$V(t) = L\frac{dI(t)}{dt}$ (4.23).

And if

$I(t) = I_p \sin(\omega t)$ (4.24), then

$V(t) = LI_p \cos(\omega t)$ (4.25).

We see that current and voltage are then *out of phase* with each other:



Now, instantaneous power is still given by their product, and it

$$W(t) = LI_p^2 \sin(\omega t)\cos(\omega t) \qquad (4.26).$$

Since

$$\sin(\omega t)\cos(\omega t) = 0.5\sin(2\omega t) \qquad (4.27),$$

instantaneous power goes positive and negative, and averages out to zero. This makes perfect sense, as the inductor cannot dissipate power, it can only store it and then give it back to the generator.

For capacitors we see by eq. 2.21 that the same thing happens in reverse, if voltage is sine current is cosine. Since

$$\cos(\omega t) = \sin(\omega t + \tfrac{\pi}{2}) \qquad (4.28),$$

we say that for capacitive or inductive loads, current and voltage are *90 degrees out of phase*, since $\frac{\pi}{2}$ in radians is 90 degrees. For either, there is no power dissipation, rather power is simply cycled to and from the load.

<u>Loads with resistance and inductance and capacitance, and power factor-</u>

While determining the formula for the current when applying an AC voltage to such a load may sound complicated, it is simplified by simply writing that if

$$V_{AC} = V_p \sin(\omega t) \qquad (4.29),$$

$$I_{AC} = I_p \sin(\omega t + \emptyset) \qquad (4.30),$$

where Ø is called the *phase angle* of the load. We see that $\emptyset = 0$ occurs for purely resistive loads, and Ø = 90 or -90 degrees occurs for purely capacitive or inductive loads. For an arbitrary angle, the average power dissipation can be calculated using

$$\sin(\omega t + \emptyset) = \sin(\omega t)\cos(\emptyset) + \cos(\omega t)\sin(\emptyset) \qquad (4.31).$$

If we examine 4.13, we see that only the first term contributes, and

$$P_{AC,ave} = \frac{I_p V_p}{2}\cos(\emptyset) \qquad (4.32).$$

$\cos(\emptyset)$ is called the *power factor* and we see ranges from 0 for purely capacitive or inductive loads to 1 for purely resistive loads. Now, typically, inductive loads are seen since motors, for example, behave more like inductors. Frequently in those situations, a *capacitor bank* is added to the load to compensate for the inductive load and bring the power factor as close to 1 as possible. The reason why, is that from equation 4.32, we see that

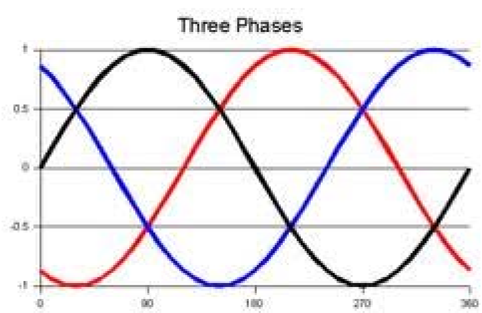
$$I_p = \frac{2P_{AC,ave}}{V_p \cos(\emptyset)} \qquad (4.33).$$

So, for the same power dissipation in the load, the lower the power factor, the higher the current requirement. Since transmission line power loss goes as the square of the current, transmission losses go as the one over the square of the power factor. Thus it is desirable to “correct” for low power factors in a factory, for example, which are usually due to inductive loads, by adding capacitors to the main junction.

Three-phase electric power-

You may have noticed that electric power transmission lines typically consist of three wires:

This is because it is inefficient to generate a single sine wave. While we will not go into the details of three-phase power generation in the next lecture, you should have the feeling that in a rotating generator having just one rotating coil, part of the cycle it is doing nothing. We might as well have at least two coils at right angles, so that when one is at the part of the cycle where it is doing nothing, the other is; engineers settled on three, spaced 120 degrees apart. Thus, the three sine waves look like this:



Mathematically, the voltages on the three lines are given by

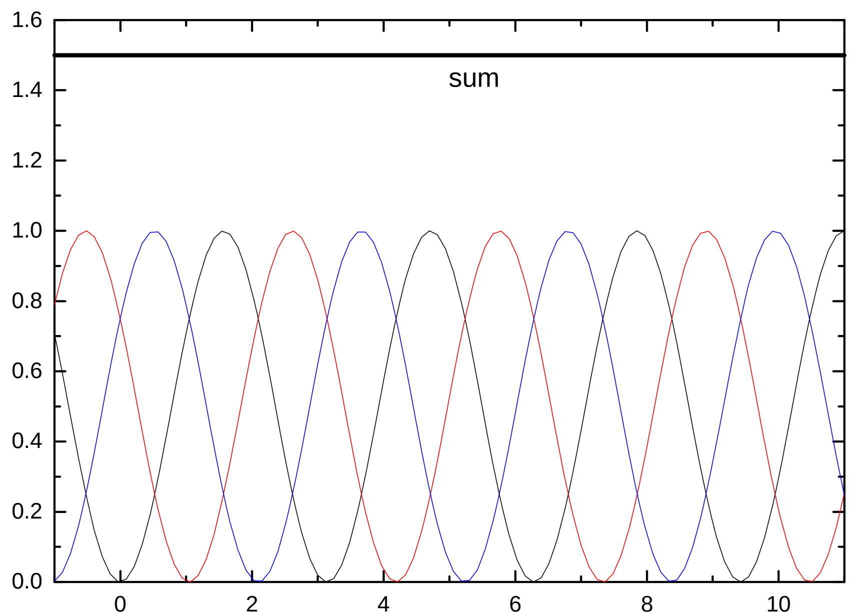
$V_1 = V_p \sin(\omega t)$ (4.34),

$V_2 = V_p \sin(\omega t + 2\pi/3)$ (4.35),

$V_3 = V_p \sin(\omega t + 4\pi/3)$ (4.36).

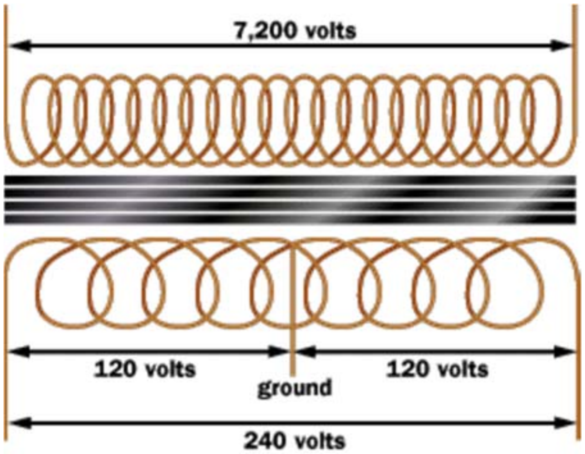
An important property of three-phase power is that one can show the power delivered to a resistive load is constant at all times. We're not going to get into how exactly the three lines are connected to a load; suffice to say there are circuit techniques for doing so. Since the load is resistive, current in each line is in phase with voltage, and the power delivered goes as the sum of the squares of 4.34-4.36:

$$W \propto \sin^2(\omega t) + sin^2(\omega t + 2\pi/3) + sin^2(\omega t + 4\pi/3)\,. \qquad (4.37)$$

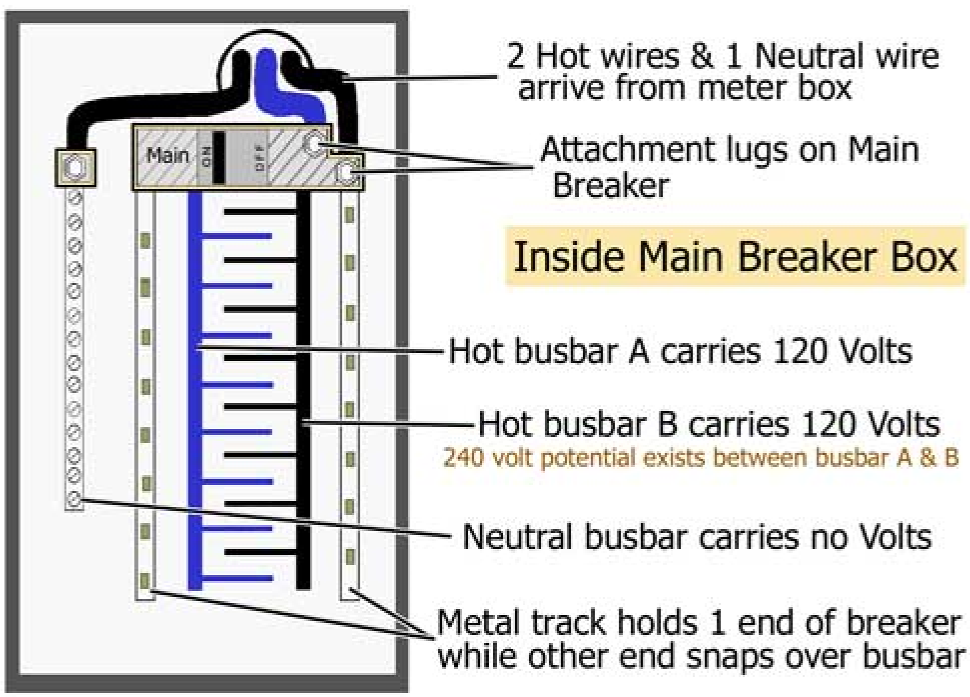


<u>Homework 4.2: Show mathematically that eq. 4.37 equals 1.5.</u>

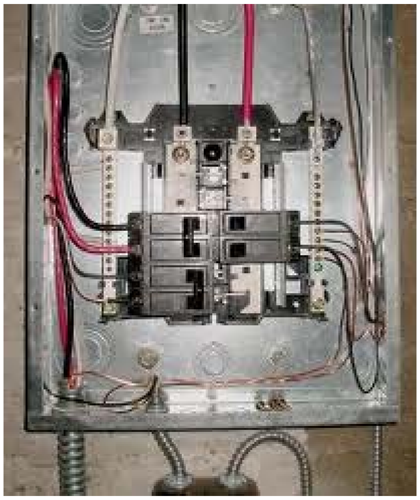
Finally, let's describe how power gets to the outlets in our homes and businesses. What comes out of the outlet is usually *single phase*, that is, one wire is *hot* having a single sine wave, and the other is grounded. Let's show how three-phase becomes single phase in the house. The typical way is just to take one of the phases of the transmission line and put it through a transformer:



Note here that the output coil of the transformer has a *center tap* which is grounded. Thus, what you see going into your house is three wires, one which is ground and two that are hot and 180 degrees out of phase, basically V_{hot}, 0, $-V_{hot}$. The reason for this is that some appliances in your house require higher power and thus higher voltages, and so use the two outside wires. The *breaker box* in your home has this circuit arrangement:

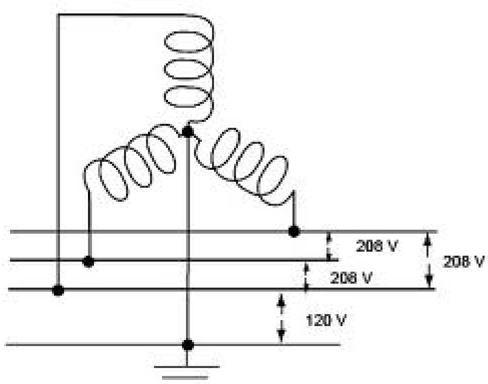


Then, breakers are installed:



You see from above that breakers next to each other get opposite hot phases. Thus, in the picture above, the large red and black wires on the two upper left breakers are going together to the electric range, for example, while the smaller single wires are going to 120 V outlets.

Some commercial places use three-phase step down transformers and three phase distribution inside the facility:



Here only the output coils are shown for brevity. As can be seen, the commercial place then has three-phase distribution within it, allowing powering of three-phase loads, with three hot wires and a ground. Between any of the hot wires and ground, one gets 120 volts, and thus one can also supply ordinary outlets. Thus, each hot line is

$V_1 = 120\sqrt{2}\sin(\omega t)$ (4.38),

$V_2 = 120\sqrt{2}\sin(\omega t + 2\pi/3)$ (4.39),

$V_3 = 120\sqrt{2}\sin(\omega t + 4\pi/3)$ (4.40).

Remember, peak voltage is root 2 times RMS. Then, where a higher voltage is required, one takes the voltage between two of the hot lines:

$V_{208} = 120\sqrt{2}[\sin\left(\omega t + \frac{2\pi}{3}\right) - \sin(\omega t)]$ (4.41).

We can calculate the RMS voltage of this signal:

$V_{208,rms} = sqr\{\frac{120*120*2}{2\pi}\int_0^{2\pi}\left[\sin\left(\omega t + \frac{2\pi}{3}\right) - \sin(\omega t)\right]2dt\}$ (4.42)

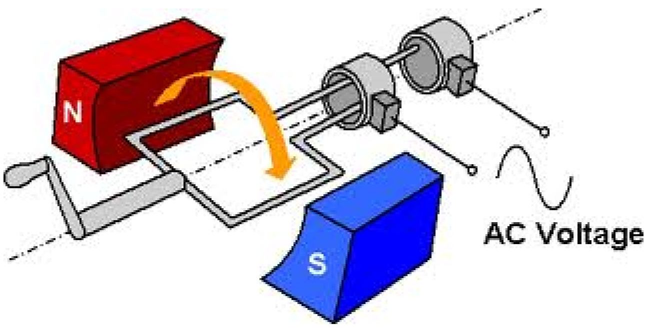
One can show that the integral is (3/2)2π, and plugging in the rest, and thus

$V_{208,rms} = 120\sqrt{3} = 208$ (4.43).

Thus, in a facility with three-phase internal distribution, one may obtain single phase 120 volt for ordinary outlets, but to get higher voltage by using two hot lines, one gets 208 volt instead of 240 volt in a common house with two phases. One must pay attention to this, as some appliances designed for 240 volts will not operate at 208 volts.

V Rotating Electrical Generators

In III, we showed an electrical generator based upon moving a wire coil relative to a magnetic field in a straight line. Of course, such a generator would be problematic in practice, as one would have to go back and forth awkwardly. The solution of course is to rotate a coil in a magnetic field or vice versa rotate a magnet relative to a fixed coil. Now, since the coil must have connections to the load, spinning it would seem problematic and it is, so most electrical generators have a fixed coil and a spinning magnet. However, it is easier to do the math for a spinning coil, so we will treat that first:



Here a moving-coil generator is shown. The magnetic field points from north to south, and the coil is spun as shown. Note the use of *brushes* to make the connection to the coil; basically the brush is an electrical contact that can slide on the spinning rings shown.

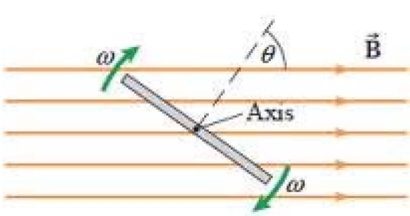
Now, from 3.15, the voltage developed around the coil is equal to the time rate of change of magnetic flux:

$$V = -\frac{d\emptyset}{dt} \qquad (5.1),$$

where the magnetic flux ϕ is given by the integral of the magnetic field across the area of the loop:

$$\emptyset \equiv \iint B_z dxdy \qquad (5.2).$$

Now, here we must think about equation 5.2 a bit. When we derived it, it was for a coil perpendicular to the magnetic field. In the rotating generator above, the magnetic field is not always perpendicular. Thus, the relevant magnetic field is the component perpendicular to the coil. In the picture below, that component is given by $Bsin(\theta)$:



Think about it, when θ=0, the perpendicular component is just B; when θ=90 degrees, the perpendicular component is zero. Thus,

$\emptyset = BSsin(\theta)$ (5.3),

where *S* is the area of the coil. Now, since the coil is spinning at a uniform rate, the rotation angle is proportional to time:

$\theta = \omega t$ (5.4),

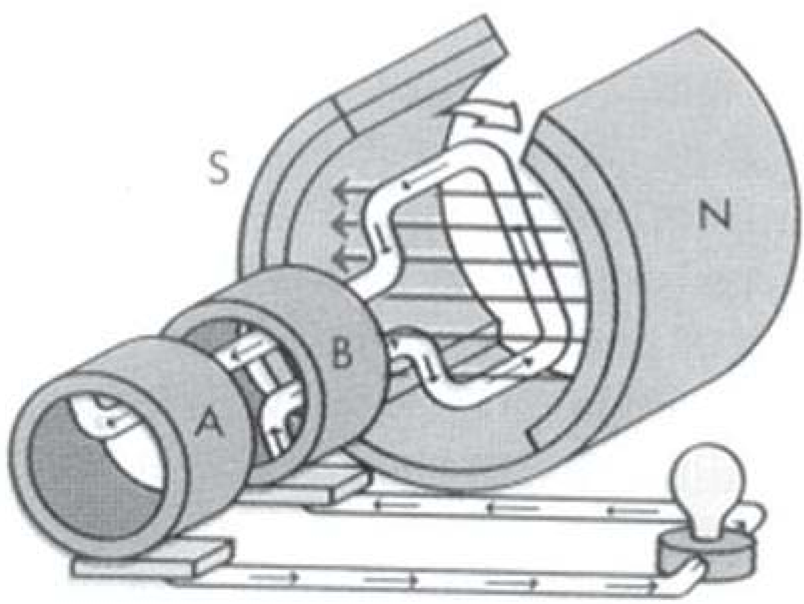
where ω is the radial frequency. Thus,

$\emptyset = BSsin(\omega t)$ (5.5), and

$V = -\frac{d\emptyset}{dt} = -BS\omega cos(\omega t)$ (5.6).

So we see that the voltage generated is AC as shown. Furthermore, the magnitude of the voltage is proportional to the magnetic field, area of the coil, and rotating frequency.

Now, there is a minus sign in 5.6, let's figure that out. Remember in lecture 3, when we did the math, we determined that if B points in the positive z direction and increases, E points clockwise in the x-y plane. Therefore, if we draw the generator at a certain point in time:



We can see in this picture, the current developed is in the right direction since the coil is rotating to the right, and thus the flux is increasing. If we positioned ourselves at the south pole of the magnet (the "z" direction), and looked "down" on the coil, we would see that the current was going clockwise. So, don't worry so much about the minus sign in 5.6; just keep straight which direction the current is in, when a load is attached.

Now, remember that when the coil spins, the voltage developed (equation 5.6) is independent of whether there is any load (current draw) or not. Therefore, the current through the coil is just given by equation 5.6 divided by the load resistance:

$I = \frac{V}{R} = -\frac{BS\omega}{R}\cos\omega t$ (5.7).

Since current flows when a load is attached, then, there is a force on the coil given by equation 1.15:

$\mathrm{F} = IL\mathrm{B}$ (5.8).

By the right hand rule, the force on the up and down parts of the coil in the picture above are along the rotation axis and thus do not affect the rotation. But, the forces on the sideways parts of the coil do experience force that resists the applied rotation. Note that when the coil is at the top of the rotation, the force is perpendicular to the rotation direction and does not affect the rotation. It is only when the coil plane is along the axis of the magnetic field that the force impedes rotation. That makes sense, as when the coil plane is perpendicular to the magnetic field, no current flows. Thus the force impeding rotation goes as $\mathrm{F} = ILBcos(\theta) = IL\mathrm{B}cos(\omega t)$ (5.9).

Remembering that energy is force times distance, and therefore

Power (W) = force x velocity (5.10).

The velocity of the coil is the circumference of the circle described by the sideways part of the coil ($2\pi r$), divided by the rotation period *T*. But, since the rotation frequency (*f=1/T)* is given by

$f = \omega/(2\pi)$ (5.11),

we have that

$velocity = \frac{2\pi r}{\frac{2\pi}{\omega}} = \omega r$ (5.12).

Thus, noting that this force exists on both sideways arms of the coil (x2), the mechanical power that must be supplied to rotate the coil is given by

$W_{mech} = 2ILB\omega rcos(\omega t)$ (5.13).

But,

$2Lr = S$ (5.14), so

$W_{mech} = IBS\omega cos(\omega t)$ (5.13).

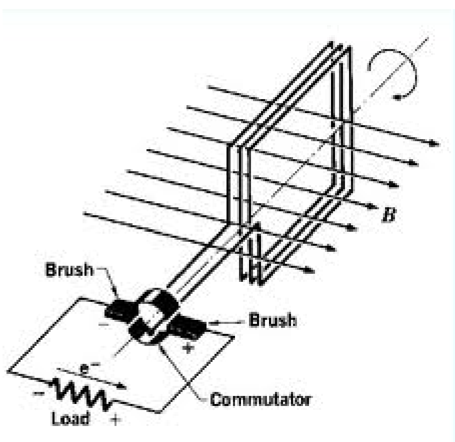
But, note! By equation 5.6 this is just

$W_{mech} = IV = W_{elec}$ (5.14),

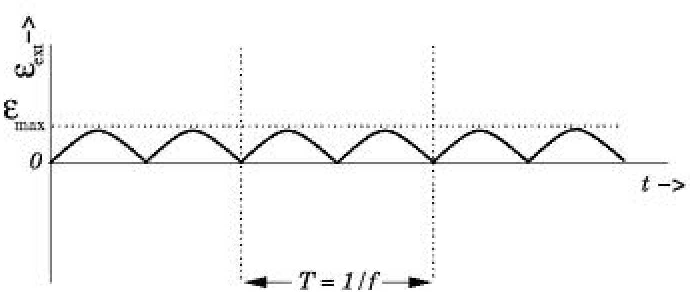
and the instantaneous mechanical power to rotate the coil exactly equals the instantaneous electrical power delivered to the load.

This essentially completes the formal portion of the course. At this point, we can discuss various related aspects without needing to go into mathematical formalism. First, note that in the figure above, if we don't rotate the coil, but supply current in the opposite direction, a force exists on the coil in the direction of rotation. Thus, it is then a motor. Do we need to supply voltage as well as current? Yes!, since the coil will still induce a voltage in the same direction. Thus, current must be supplied in the opposite direction of voltage, and instead of a load, a voltage source must be hooked up. **A motor is just a generator in which voltage is applied and current supplied in the direction opposite to generated current.**

Can we take a rotating coil generator and produce a DC generator? Sure! We install a *commutator* or split-ring contact:

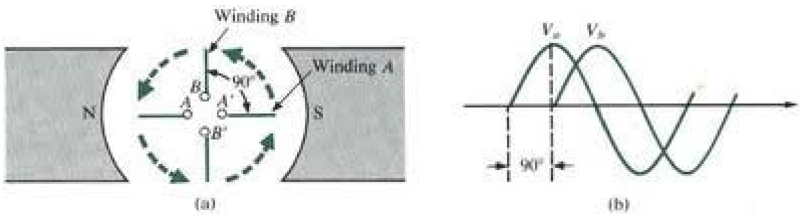


We see that after the coil passes the midplane and current changes direction, the contacts to the load "flip" from one side of the coil to the other. Thus the current supplied is also in the same direction, like this:

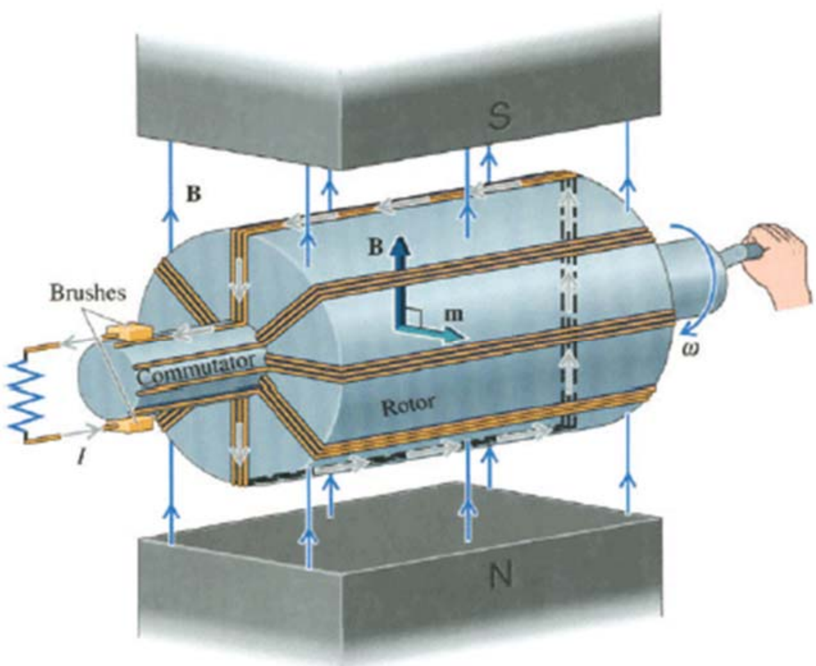


Now, this "DC" current and voltage vary as shown, and further the rings can wear out, so in fact sometimes it is better to make DC if necessary by rectifying and smoothing AC (that is beyond the scope of this course).

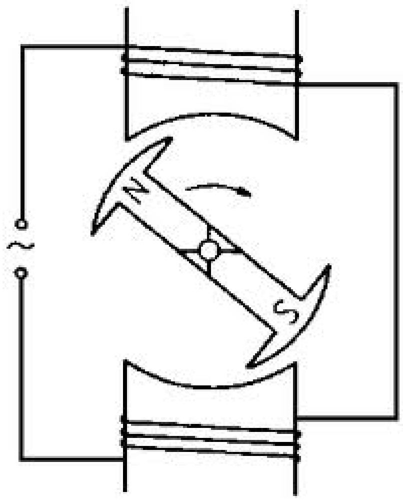
What about 3-phase? As we discussed in lecture 4, and as you can see from above, half the time the generator is doing nothing, so adding coils at different angles would seem to be a good thing. We could make a 2-phase generator:



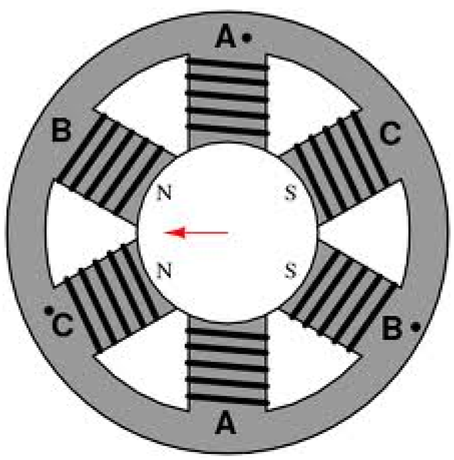
Then, we get power out of coil A when the power out of coil B is zero. Why don't we do this? Well, part of the answer is that as we found in lecture 4, for a 3-phase system the power delivered to the load is constant vs. time. Therefore, the mechanical power that must be supplied to a 3-phase generator is also constant vs. time! And that's nice for whatever is supplying the power. For a 2-phase system, power is not constant vs. time, therefore we use 3-phase, and place three coils at 60 degrees relative to each other:



As we pointed out above, while rotating the coil is easy to describe mathematically, it has difficulties since it requires the brush contacts. In addition, if you think about it the strength of the magnetic field can be higher if it is on the inside rotating:



Looking at this picture, when the magnet is rotated the flux is increasing on the top part of the coil when it is decreasing in the bottom, so the currents add. Going to three phase, it looks like this:



So, as the magnet is rotated, it induces voltage in the coils 120 degrees out of phase.

Finally, it is possible to use multiple rotating magnets, or *multi-pole* generators:

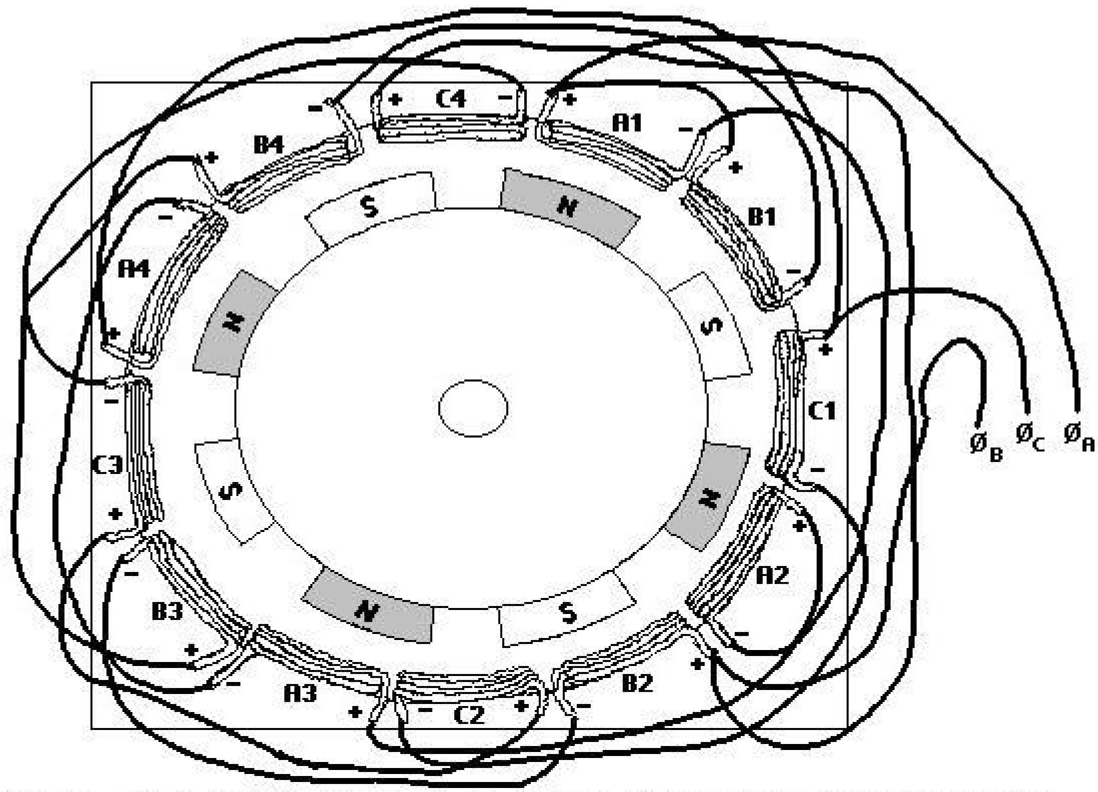


FIGURE 6: Basic construction of an 8-pole, three-phase motor/generator. Cut a circle from the center of a block. Trim the circle to allow magents and coils to clear. Mount coils in the block and wire as shown. Mount magnets on the circle, alternating poles. Mount axle so circle spins in block. Use.

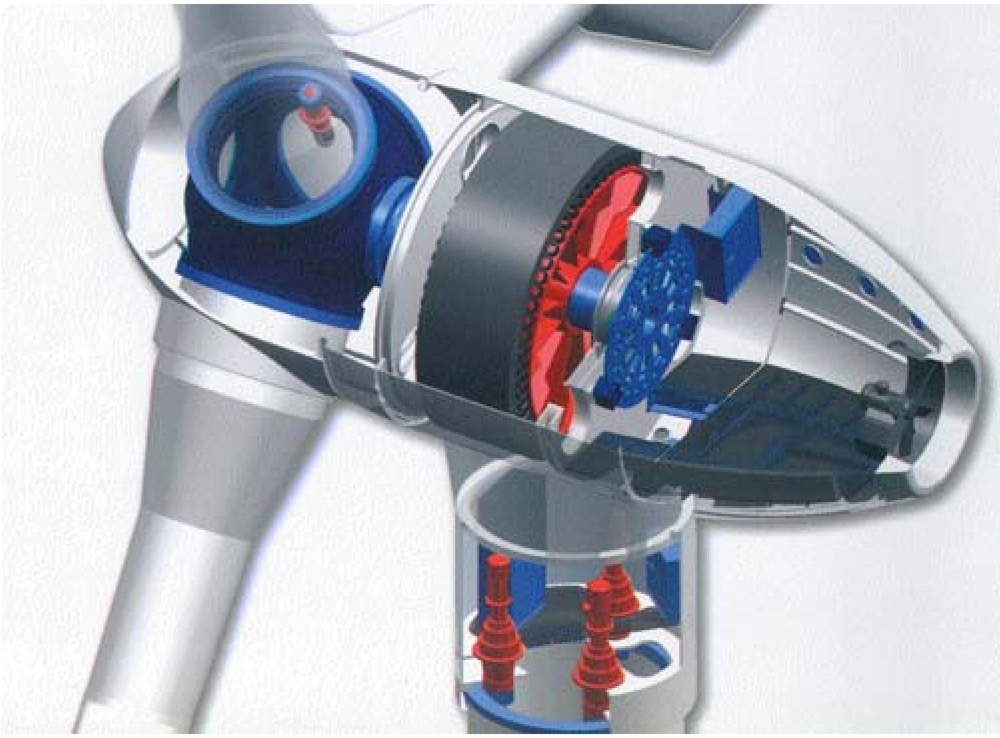
Here each phase has 4 coils (A1, A3, A3, and A4, for phase A). There are north and south magnet poles for each coil, hence this is an 8-pole generator. In the picture above, all the A's have the north poles passing by them, and hence together they generate the same voltage in phase. Now, think about it, in the above picture, a quarter-cycle later, the north poles are again under the A coils. **So, a multi-pole generator generates at a higher frequency, by the number of poles.** Alternatively, if you want to keep the electrical frequency constant (e.g., 60 Hz for US systems), you can use lower rotation speed with multi-pole generators:

Poles	RPM for 60 Hz
2	3,600
4	1,800
6	1,200
8	900
10	720
12	600
14	514.3
16	450

18	400
20	360
40	180

Usually, a 6-pole generator is used in most US power plants, using a rotation speed of 1200 rounds per minute.

In a wind turbine, the main shaft turns at a slow speed, and thus typically in the past a gearbox was used to turn the generator shaft at a much higher speed. However, recently it has been determined that the gearbox is potentially a source of failure, so *direct-drive* wind turbines are being pursued, by using generators with a high number of poles:



Here each of the poles can be seen in the generator; there may be on the order of a hundred to allow slow rotation speeds. As can be perceived in the diagram, having so many poles increases the required diameter of the generator, and results in larger size and mass of the wind turbine, while eliminating the need of a gearbox. The industry seems headed for direct drive, but is still reviewing these design trade-offs.

GEOL 467/667/MAST 667 - GEOLOGICAL ASPECTS OF OFFSHORE WIND PROJECTS

COURSE SYLLABUS

Course Meets – Wednesdays 6:30-9:00 PM; Robinson Hall Room 206
ITV to Lewes, Cannon Lab Room 202

Description: Investigation of the geological and geotechnical aspects of offshore wind projects. Emphasis on influence of geology and properties of sediments and rocks on project planning and construction. Course utilizes problem-based learning pedagogy.

Instructor: Dr. John Madsen
Office: 203 Penny Hall
E-mail: jmadsen@udel.edu
Phone: 302-831-1608 (work) or 610- 299-9757 (cell) Skype: john.madsen59
Office Hours: Wednesdays 5:00-6:00 PM; Thursdays 8:30-10:30 AM
(or by appointment)

Course Web Site: Accessible from UD Sakai https://sakai.udel.edu/portal

Textbook: *Offshore geotechnical engineering: Principles and practice*, E.T.R. Dean, Published 2010 by Thomas Telford Limited, London, UK, www.thomastelford.com, ISBN: 978-0-7277-3641-3

Soil Mechanics, A. Verruijt, Delft University of Technology, 2001, 2010, http://geo.verruijt.net/software/SoilMechBook.pdf

Additional texts and publications will be available at the course web site.

Investigations: The pedagogical approach of this course will be primarily problem-based and inquiry-based learning. Much of the coursework will be done in groups. We will have three major investigations in this course. Each investigation will be designed around geological and geotechnical topics that are relevant to the development of offshore wind projects. The general focus of the investigations are: 1) *Properties of sediments and types of offshore wind turbine foundations;* 2) *A review of existing, or under construction, offshore wind projects; and* 3) *Geotechnical considerations applied to developing an offshore wind project*.

Grading: Grades will be based on:

2 - Content exams, one focusing on sediments, their geotechnical properties and offshore wind turbine foundations and one focusing on the coastal geologic history of a region and its relevance to offshore wind projects, each worth 40 points for undergraduates and 50 points for graduate students. These will account for 31% of your course grade.

6 – Individual problem sets, two within each investigation, worth 5 points each for undergraduates and 8 points each for graduate students. These will account for 12% and 15%, respectively of your course grade.

3 – Group projects, one for each investigation, worth 50 points each. These will account for 57% and 47%, respectively of your course grade.

For graduate students: 1 – Review paper on a topic of interest from the course worth 22 points. This will account for 7% of your course grade.

Course letter grades will be assigned as follows:

Percentage Score (of 260 or 320 total points)	Final Grade
94 and above	A
93.9 - 90	A-
89.9 - 87	B+
86.9 - 84	B
83.9 - 80	B-
79.9 - 77	C+
76.9 - 74	C
73.9 - 70	C-
69.9 - 67	D+
66.9 - 64	D
63.9 - 60	D-
59.9 and below	F

There will be no extra credit offered in this course, your final grade will be based on your scores from the content exams, individual problem sets, group projects, and, if a graduate student, your review paper.

Academic dishonesty will not be tolerated and those engaging in it will be prosecuted. For further information refer to: http://www.udel.edu/stuguide/11-12/code.html#honesty

GEOL 467/667/MAST 667 - GEOLOGICAL ASPECTS OF OFFSHORE WIND PROJECTS

COURSE SCHEDULE

Aug. 31	Course Overview; Lecture Topic: Sediments and their Geotechnical Properties; Introduction of Investigation I: *Properties of sediments and types of offshore wind turbine foundations*
Sep. 7	Lecture Topic: Sediments and their Geotechnical Properties, continued…; Group Work on Investigation I: *Properties of sediments and types of offshore wind turbine foundations*
Sep. 14	Lecture Topic: Offshore Turbine Foundations; Group Work on Investigation I: *Properties of sediments and types of offshore wind turbine foundations*
Sep. 21	Lecture Topic: Offshore Turbine Foundations and Their Installation (Geotechnical Considerations); Group Work on Investigation I: *Properties of sediments and types of offshore wind turbine foundations*

Sep. 28 Presentations and evaluations of Group Work for Investigation I: *Properties of sediments and types of offshore wind turbine foundations*; Group Reports on Investigation I: *Properties of sediments and types of offshore wind turbine foundations* are due; Review of Sediments, their Geotechnical Properties, and Offshore Wind Turbine Foundations

Oct. 5 Content Exam on Sediments, their Geotechnical Properties, and Offshore Wind Turbine Foundations; Introduction of and Work on Investigation II: *A review of existing, or under construction, offshore wind projects*

Oct. 12 Course will not meet – AWEA Offshore Windpower 2011 Conference & Exhibition Oct. 11-13 in Baltimore, MD

Oct. 19 Lecture Topic: Coastal Geology and Geologic Evolution of Coastal Regions; Group Work on Investigation II: *A review of existing, or under construction, offshore wind projects*

Oct. 26 Lecture Topic: Coastal Geology and Geologic Evolution of Coastal Regions, continued…; Group Work on Investigation II: *A review of existing, or under construction, offshore wind projects*

Nov. 2 Poster Presentations and Evaluations of Group Work on Investigation II: *A review of existing, or under construction, offshore wind projects;* Group Reports on Investigation II: *A review of existing, or under construction, offshore wind projects* are due; Introduction of Investigation III: *Geotechnical considerations applied to developing an offshore wind project*

Nov. 9 Lecture Topic: Geologic Evolution of the U.S. Atlantic Continental Margin and Implication for Offshore Wind Projects; Group Work on Investigation III: *Geotechnical considerations applied to developing an offshore wind project*; Review on Coastal Geologic History and Relevance to Offshore Wind Projects

Nov. 16 Content Exam on Coastal Geologic History and Relevance to Offshore Wind Projects; Group Work on Investigation III: *Geotechnical considerations applied to developing an offshore wind project*

Nov. 23 Course will not meet – Thanksgiving Break

Nov. 30 Lecture Topic: Geologic Evolution of the U.S. Atlantic Continental Margin and Implication for Offshore Wind Projects; Group Work on Investigation III: *Geotechnical considerations applied to developing an offshore wind project*

Dec. 7 Presentations and evaluations of Group Work for Investigation III: *Geotechnical considerations applied to developing an offshore wind project*; Group Reports on Investigation III: *Geotechnical considerations applied to developing an offshore wind project* are due