Lightning Risk of Power and Control Systems

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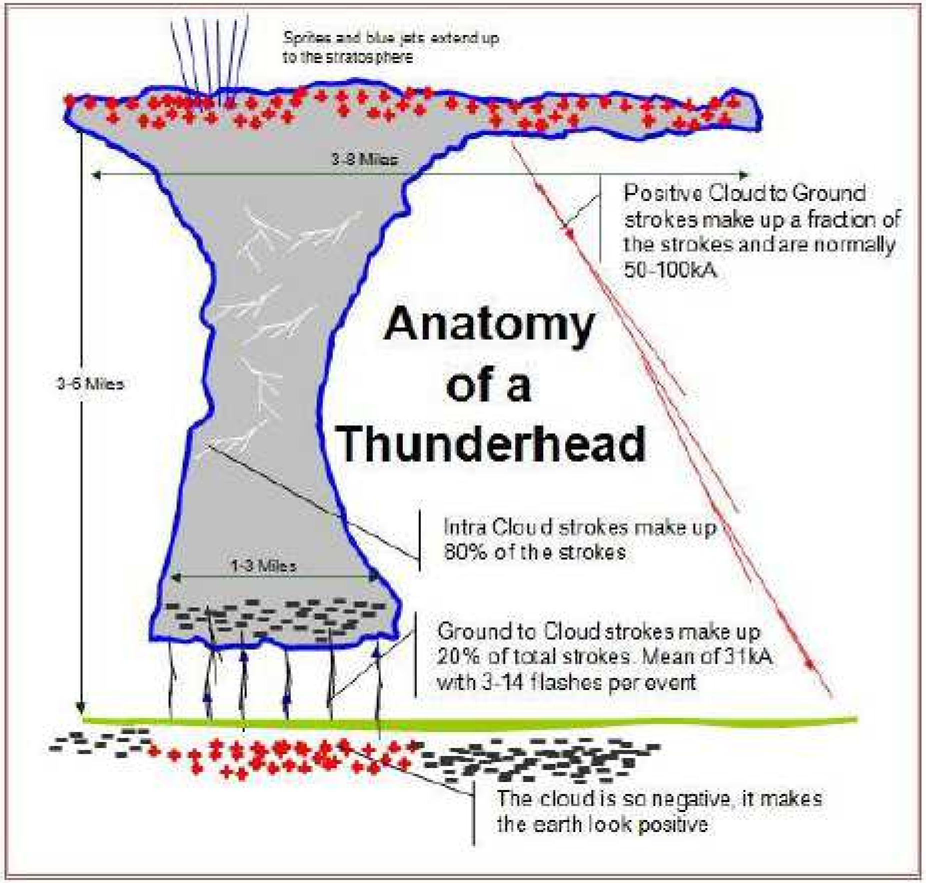
Lightning; Standards Effects; Risk; Mitigation

- **Define Lightning:**
  - Large current which forms as a result of a natural build-up of electrical charge separation in storm clouds where convection and gravitational forces combine with an ample supply of particles to generate differential electrostatic charges.
  - When these charges achieve sufficient strength to overcome the insulating threshold of the local atmosphere then lightning may occur. In thunderstorms, this process results in an accumulation of positive charges towards the top of clouds and an accumulation of negative charges in the cloud base region.
  - In-cloud lightning or cloud-to-ground (CG).

Lightning Formation



Standards

- **IEC 61024-1** series for lightning protection system (LPS).
- **IEC 61312** series for protection against lightning electromagnetic pulse (LEMP).
- **IEC 61622** TR2 for risk assessment.
- In 2006, all these standards documents were substituted by complete multi-parts standard (**IEC 62305- 1 to 4**) providing the general principles of protection against lightning, risk management, protection measures against physical damages to structures and life hazard, and protection measures against damages to electrical and electronic systems within structures.
- **IEC 62305-1** introduces terms and definitions, lightning parameters, damages due to lightning, basic criteria for protection and test parameters to simulate the effect of lightning on lightning protection systems (LPS) components.

- **IEC 62305-2** “Protection against lightning” gives the risk assessment method and its evaluation. It requires a risk assessment to be carried out to determine the characteristics of any lightning protection system to be installed. In order to perform the risk management proposed in [IEC 62305-2, 2006] the CG lightning frequency per kilometer square and per year is needed. This parameter could be achieved with a network of appropriate sensors connected to a computer which is responsible to validate and record data events.
- **IEC 62305-3** is focused on protection measures to reduce physical damages as well as injuries of living beings due to touch and step voltages.
- **IEC 62305-4** considers the protection against LEMP of electrical and electronic systems within the structures.
- **IEC61400-24** focuses on how to apply existing standards to wind turbines in order to achieve effective lightning protection of the entire system. It recommends that wind turbines can be modeled as a tall mast with a height that is equal to the hub height plus one rotor radius.

Lightning Effects

- Direct and indirect!
- Energy spectrum of the lightning current is very wide; lightning current varies from 2 kA (probability 85 – 90 %) up to 200 kA (probability 0.7–1.0 %). Peak currents may exceed 200 kA with 10/350 μs waveshape.
- If the power equipment is not protected the over-voltage will cause burning of insulation. Thus it results into complete shutdown of the power
- Effects may be transferred to consumer service entrances that are connected to the system.

Lightning Risk Tasks

- Risk means probability and "consequences" of loss or damage to human beings or assets.
- Lightning hazard evaluation (LHE) which is based on lightning occurrence frequency, peak values of lightning currents, and energy of lightning.
- Lightning risk assessment taking into account measures to reduce risk or damage and justifying an acceptable risk level.
- Lightning risk management (LRM) including determination of the best measures to protect human life, services, and equipment.

In Engineering, Risk is Anticipated as

$$R = \sum N_i \times C_i \times (1 - P_i)$$

- where *R* is the total risk of an object;
- N_i is the number of damage occurrences of the *i*th kind;
- C_i is the loss when the ith damage occurred on the object;
- P_i is a risk reduction factor, which is 0 if no lightning protection is done and 1 if the perfect lightning protection is carried out.

Power Plants and Substations

- Total number of damage occurrences in a substation facility D_t is the sum of the number of damage occurrences by direct lightning D_d, number of damage occurrences to transmission and/or distribution systems D_l, and number of damage occurrences by the induced lightning to distribution lines or low-voltage circuits of the customer facility and overvoltage through grounding systems D_g.

$$D_t = D_d + D_l + D_g$$

$$D_t = N_d \times P_d + N_l \times P_l + N_g \times P_g$$

- where N_d is the number of direct lightning hits to the system, N_l is the number of induced lightning on the transmission and/or distribution lines, and N_g is the number of lightning that generate an overvoltage on the grounding systems, P_d is the occurrence probability of damage by the direct lightning hits to the systems, P_l is occurrence probability of damage due to induced lightning from transmission and/or distribution lines, and P_g is the occurrence probability of damage due to grounding system.

- If we let the loss to be *L*, the lightning risk of a customer facility is obtained as follows:

$$R_c = D_t \times L$$

- In the lightning risk components, the number of lightning is considered to be proportional to the ground flash density of the region. The number of direct lightning hits to distribution systems N_d may be estimated using electro-geometric models such as the Armstrong-Whitehead model. It is therefore possible to use these results to estimate the number of direct lightning hits that cause damage on a customer facility.

Wind Turbine Systems

- For wind turbine systems, the following three kinds of damage should be considered: damage of wind turbine blades, damage of low-voltage circuits such as control systems, and damage of power systems connected to wind turbines.
- The lightning risk of wind turbine blades is given as follows:

$$R = \sum N_d \times P_s \times C$$

$$N_d = N_g A_d C_d 10^{-6}$$

- where N_d is the number of lightning to the wind turbine blade per year, P_s is the ratio of lightning that causes damage to the blade, C is the cost of the damage, N_g is the annual average ground flash density, A_d is the average collection area of direct lightning strikes and C_d is an environment factor. A_d for a wind turbine placed on a flat ground is calculated to be the area of a circle with a radius of three times the turbine height.

Protection by Air Terminals

- The air terminal concept which is most popular techniques of lightning protection that incorporate sharp rods, horizontal and vertical conductors (Faraday Cage) evolving into the "Cone of Protection" and the "Rolling Sphere" techniques for design of lightning protection.
- Such a lightning protection system consists of collectors (air terminals) to intercept lightning strokes, conductors to conduct surge currents to ground, and the earth interface for dissipation of surges to earth.
- These collector/diverter systems encourage the termination of strikes in close proximity to the "protected" area by providing some form of termination points (collector or air terminals) deployed in a location and manner that actually increases the risk of a strike to that area.

Online Resource

http://www.g9toengineering.com/CaseStudies/MicroHydro.htm

Damage to the concrete might be due to lightning-induced transients. Lightning-induced transients are electrical impulses induced in a conductor by being in the vicinity of a direct lightning strike. These transients may travel considerable distances from the physical strike location especially when conductors are present.

Surge Protection Devices (SPD)

- The SPD or surge arrestor is a device that will ideally conduct no current under normal operating voltages (i.e. have an extremely high resistance) and conduct current during overvoltage's (i.e. have a small resistance). SPDs are used to limit the surge voltage magnitude to a level that is not damaging to **transformers**, **switchgear** or other service entrance equipment.
- SPDs limit surge voltages by diverting the current from the surge around the insulation of the power system to the ground. There are four different classes of SPDs; station, intermediate, distribution, and secondary.
- The functions of a lightning arrester are: 1) to act like an open circuit during normal operation of the system, 2) to limit the transient voltage to a safe level with a minimum delay and fitter, and 3) to bring the system back to its normal operation mode when transient voltage is suppressed.

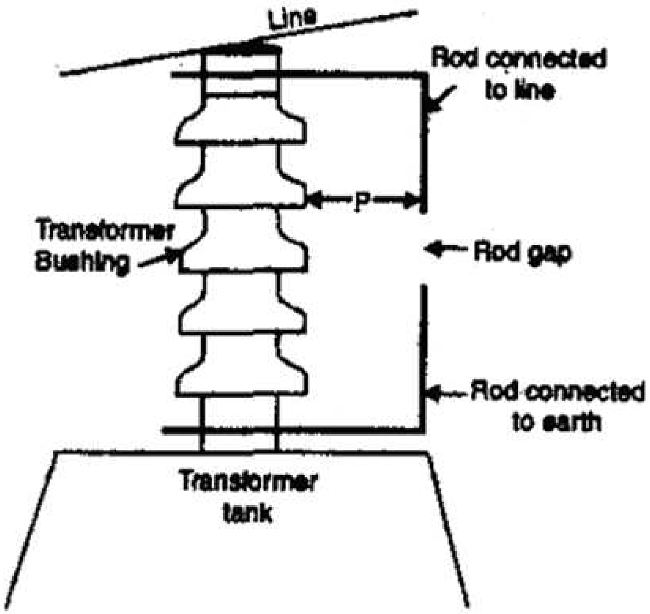
Types of Lightning Surge Arresters

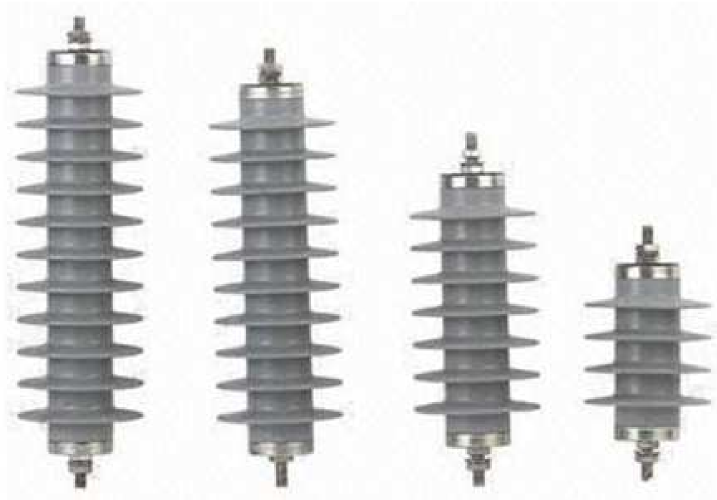
Station: Heavy, high range, best protection.

Intermediate: Moderate (138 kV and less.

Distribution: Low-voltage transformers and lines.

Secondary: Below 1000 V.





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Case Study: Substations

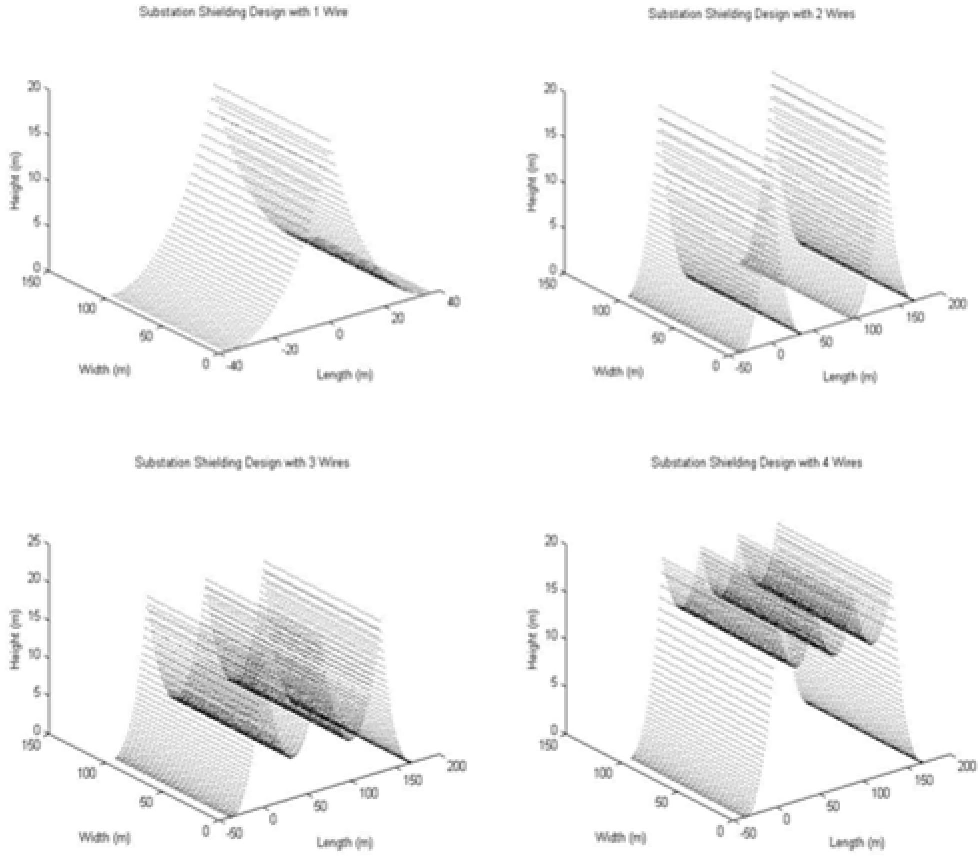
- Various techniques are implemented to protect substations.
- MATLAB can be used to simulate the effectiveness of **shield wires**. This model is based on the relationship of the lightning striking distance to the crest value of the lightning current waveform and the height of the structures.
- Electro-geometric model can be used
- Various equations may be used to calculate the striking distances.

Model	Formula
Love	$S = 10 I_s^{0.65}$
Darveniza	$S = 2I_s + 30\left(1 - e^{0.147 I_s}\right)$
Whitehead	$S = 9.4 I_s^{0.67}$
Suzuki	$S = 3.3 I_s^{0.78}$
Eriksson	$S = 0.67 h^{0.6} I_s^{0.74}$
Rizk	$S = 1.57 h^{0.45} I_s^{0.69}$

S is the striking distance and I_s is the first return stroke current in kA.

1. A. D. Aliabad, and B. Vahidi, "A Software Based on MATLAB for Teaching Substation Lightning Protection Design to Undergraduate Students With an Emphasis on Different Striking Distance Models", Computer Applications in Engineering Education, Amirkabir University of Technology, Dept. of Electrical Engineering, November 19, 2008.

Observe Various Protective Zones as a Function of Shield wires



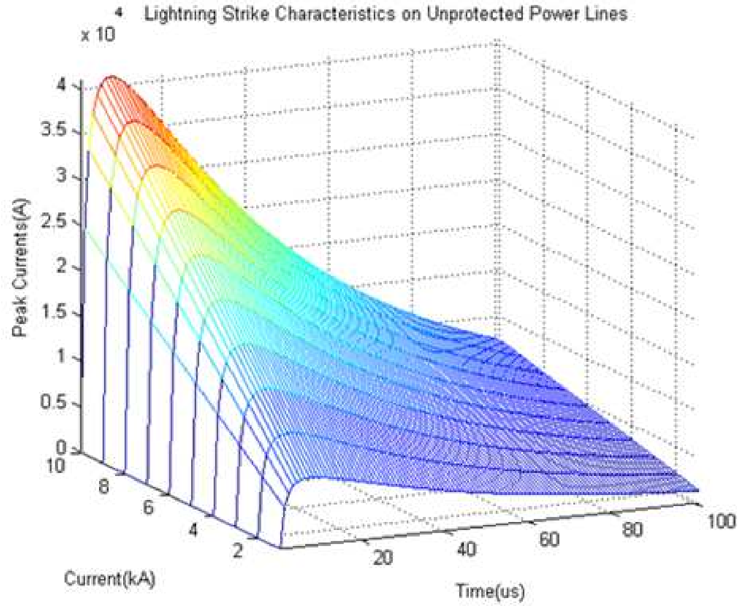
Transmission Lines

- There are two major protective methods against lightning outages on overhead distribution lines: surge arresters and overhead ground wire.
- The following figure shows lightning performance analysis on a transmission line. Basing on electromagnetic transients program (EMTP), students simulated the effect of surge arresters using MATLAB/SIMULINK.
- The other figure depicts the waveform of a concave return stroke. The main parameter used to define this waveform is the peak current magnitude. The impact of protection by using an arrester may be observed.

Transmission Lines

Lightning performance analysis of a transmission line

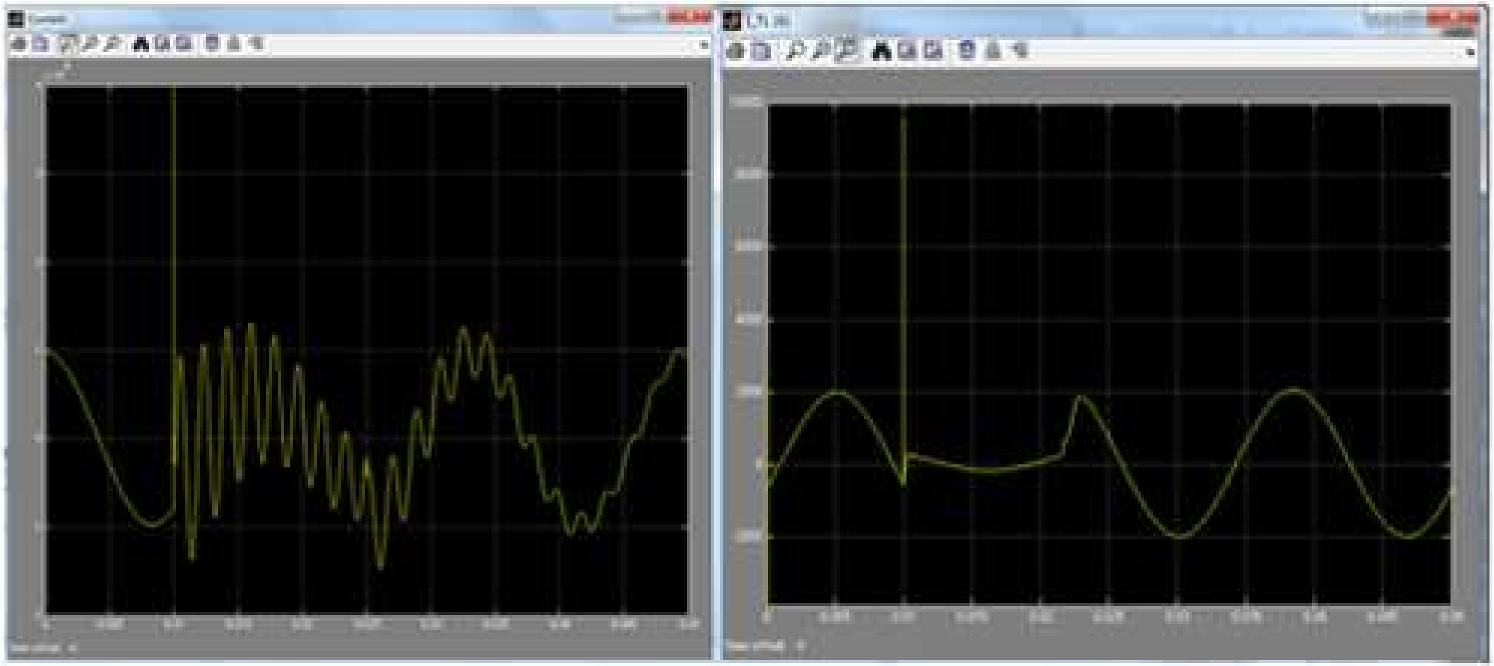
- Surge arresters
- Overhead ground wire.
- Basing on electromagnetic transients program (EMTP) [1], we simulated the effect of surge arresters using MATLAB/SIMULINK.



1. J.A. Martinez, and F. Castro-Aranda, "Lightning Performance Analysis of Overhead Transmission Lines Using the EMTP," IEEE Transactions on Power Delivery, vol. 20, no. 3, pp. 2200-2210, 2005.

Current surge (Left). Protected current surge (Right)

This figure depicts the waveform of a concave return stroke. The main parameter used to define this waveform is the peak current magnitude. The impact of protection by using an arrester may be observed.



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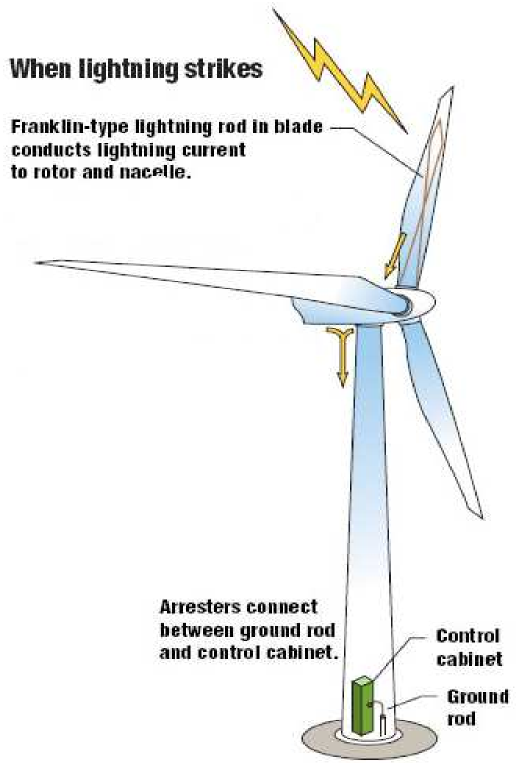
Wind Turbine System

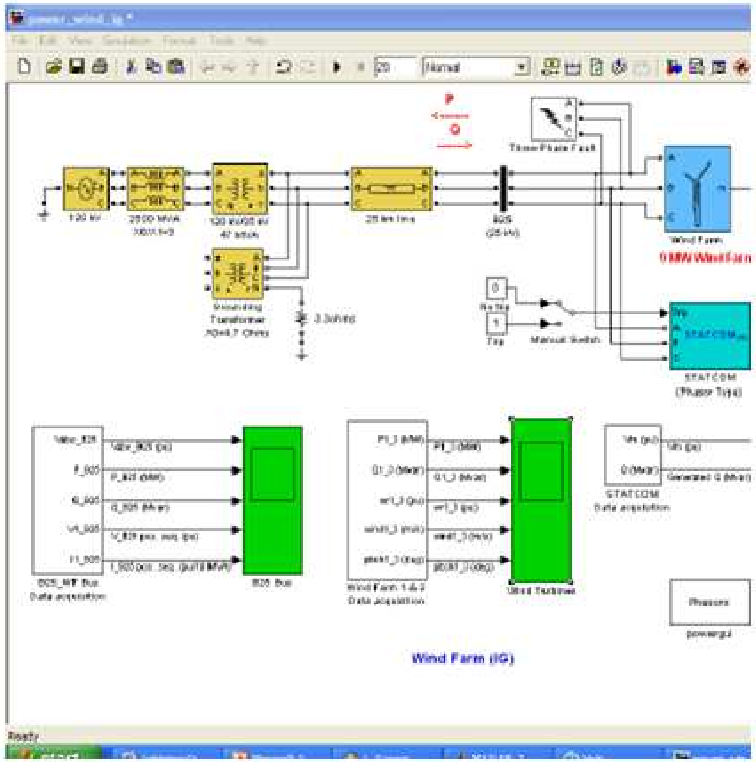
To design and build a wind turbine system or farm, not only must the wind speed be considered, but also the risks derived from the lightning strikes especially on blades, drive train, and tower.

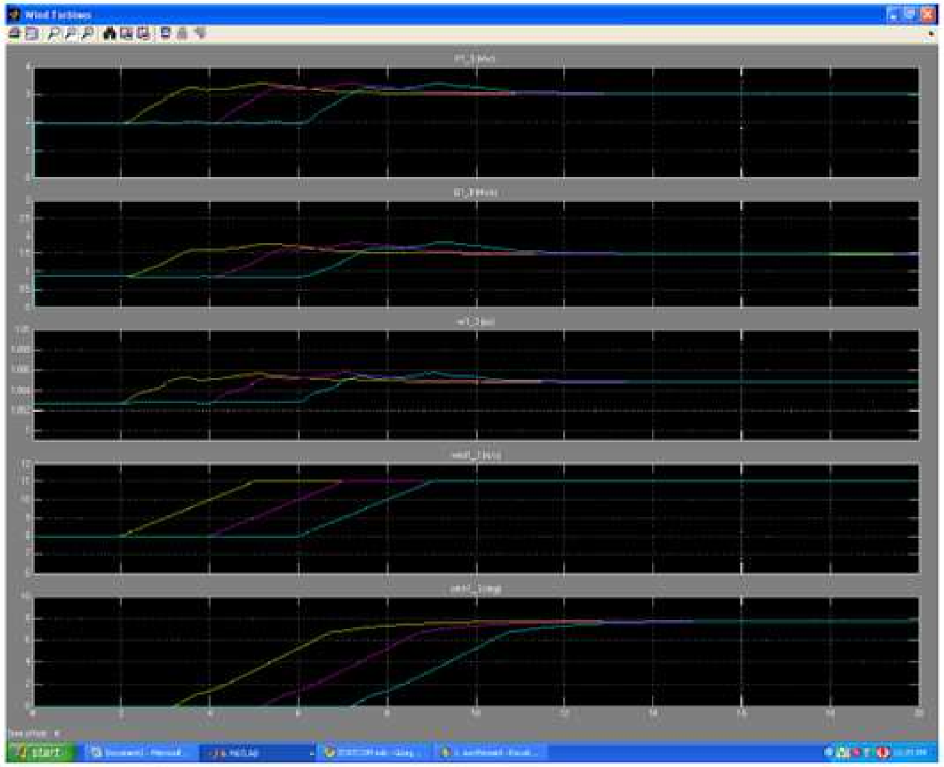
- Surge paths in a typical wind system include rotor caps and blades, bearings, structure, and control system.
- Two simulations have been performed by students:
  - SIMULINK to observe surge faults.
  - CADFEKO EM software to evaluate lightning strike paths of attack.



Wind Turbine System

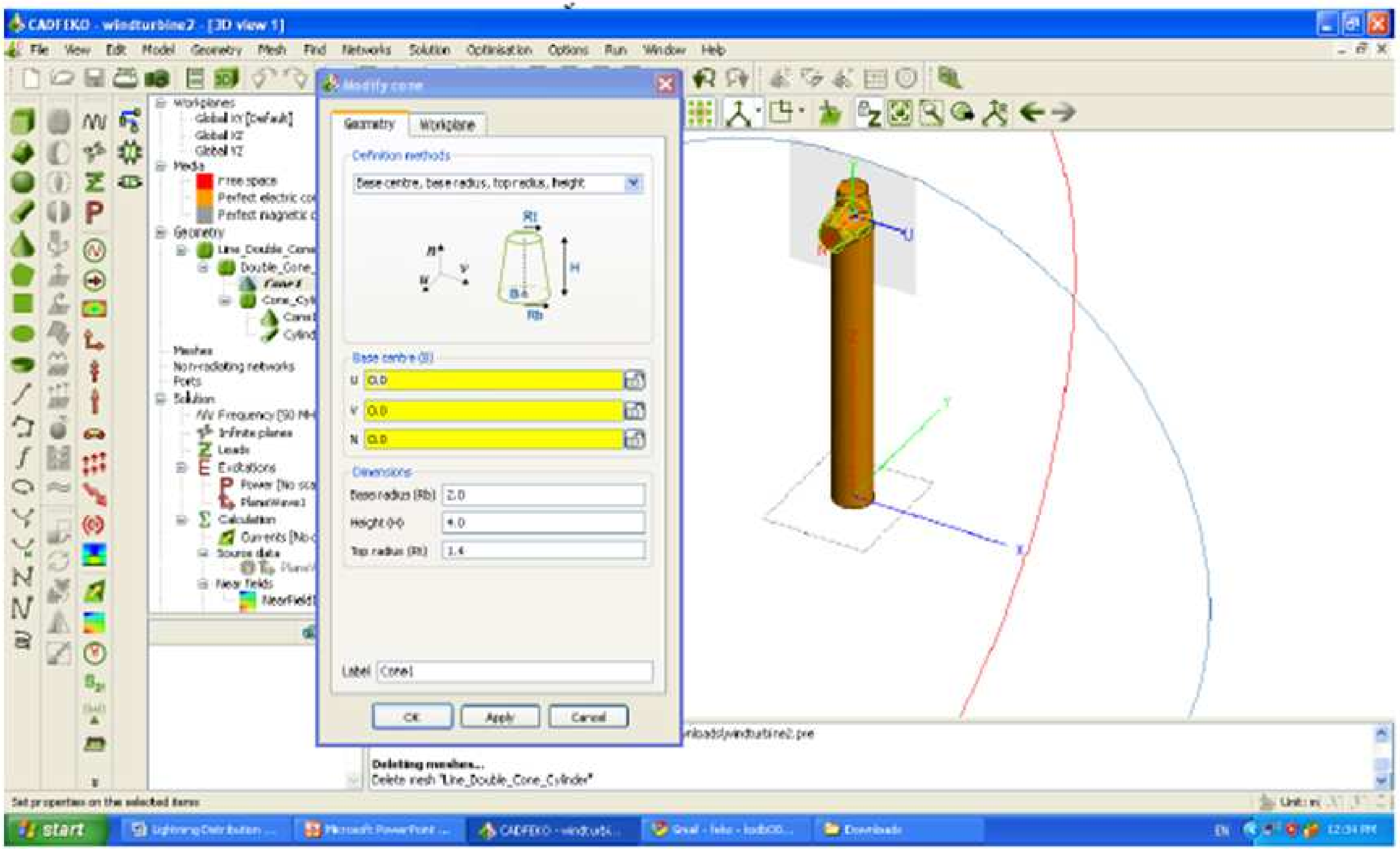
Lightning surges in MATLAB/SIMULINK Environment



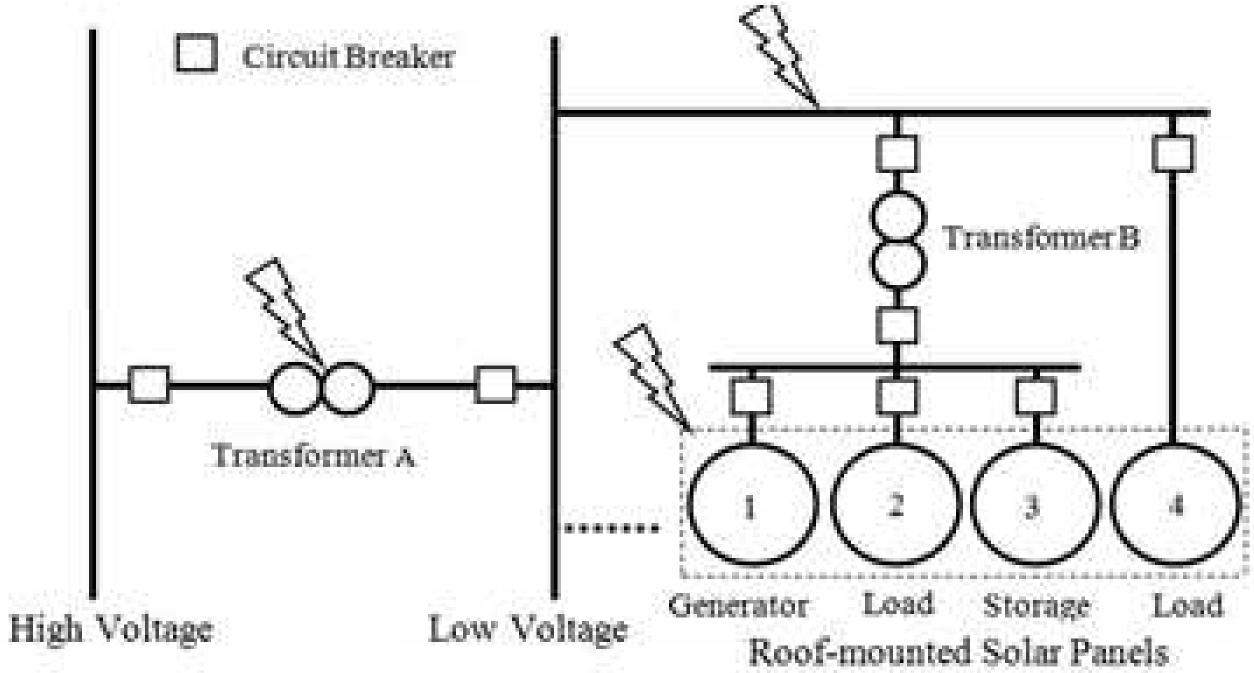


Wind Turbine System

CADFEKO EM software to evaluate lightning strike paths of attack on a wind turbine system



Lightning Possibilities on Microgrid



The Characteristics of the Lightning Locating System and Its Application in Lightning Risk Assessment

- How lightning locating system (LLS) work?
- Method of lightning risk assessment.
- Process of data received from the LLS sensors.

Lightning Detection using NI and LabVIEW: Future Case Study

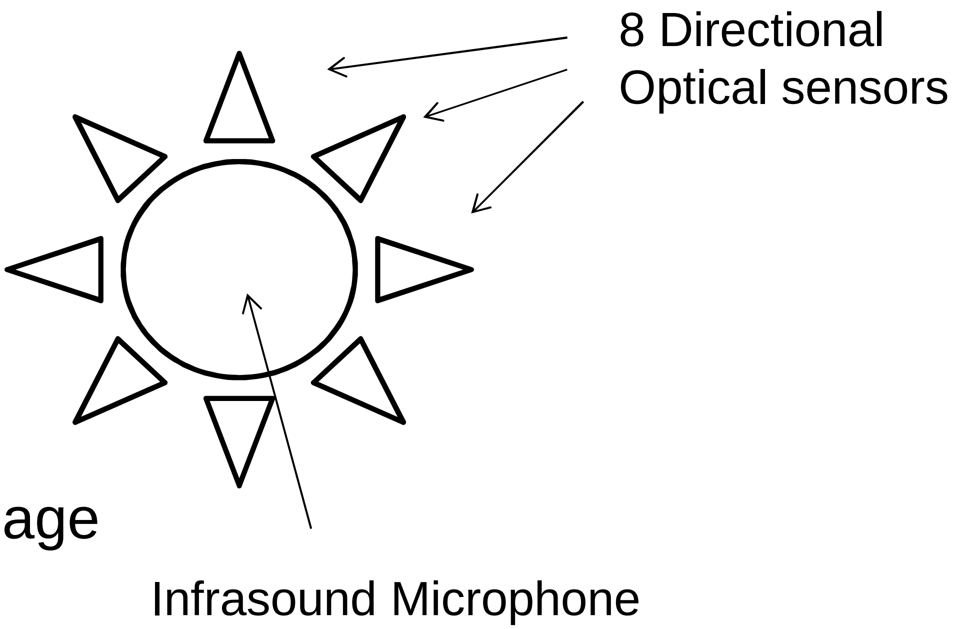
- A theoretical analysis of a possible implementation.
- Virtual instruments, assisted with proper data treatment, can mitigate the cost.
- National Insruments and LabVIEW, connected with DataSocket Technology may become these virtual instruments.

Overview: Observation Station

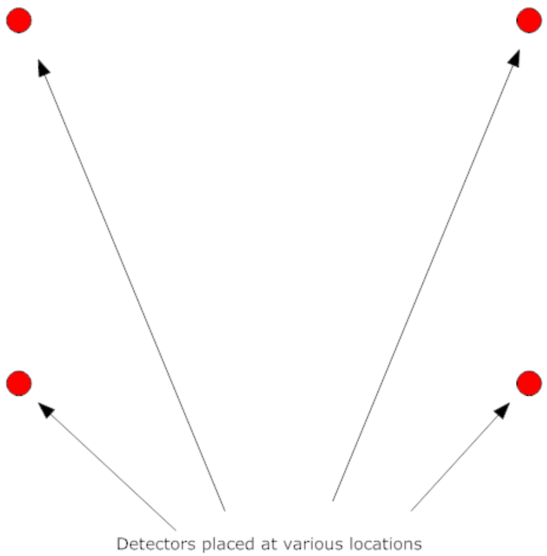
Thunder has an infrasound component, ranging between 1.3 Hz and 6 Hz, most active at 3.5 Hz.

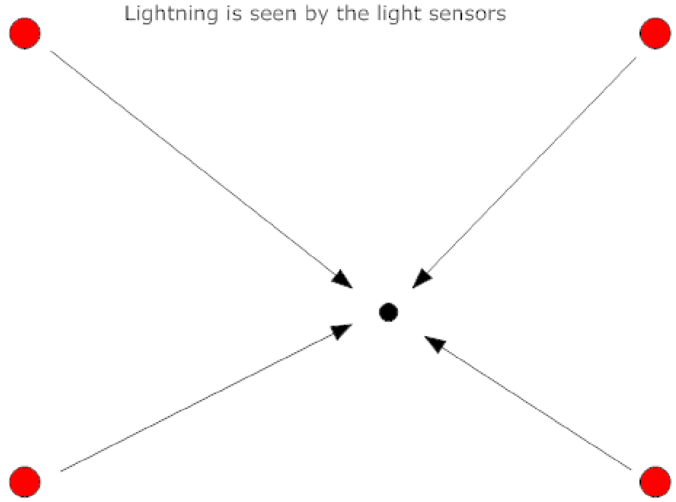
Lightning can be amplified with photomultiplier tubes (PMTs), as to amplify weaker signals.

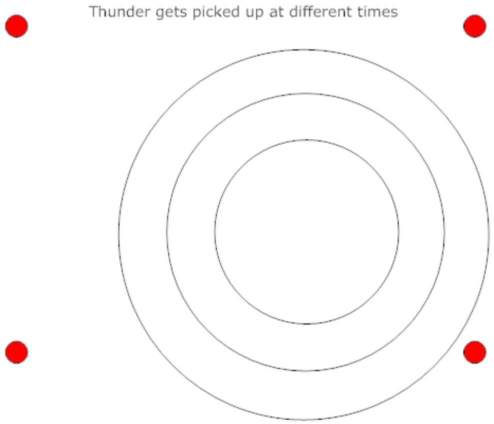
LabVIEW software can manage Incoming analog signals.



Implementation







Stations: Data Transmission

- Upon receiving incoming signals, each station transmits to a central server.
- Time-stamped information can measure proximity of thunder, and equally calibrated PMTs can triangulate lightning.
- Stations can also record data, preparing for possible loss of transmission (not unheard of during thunderstorms).
- According to the reference papers, LabVIEW has the appropriate toolboxes to create the software and manage the information
- National Instruments has the appropriate DAQ boards for such an implementation.

Questions

- Why are circuit breakers and fuses ineffective in protecting against transient over-voltage due to lightning and switching surges?
- Where are surge arresters located in power systems?
- How does one select a surge arrester to protect specific systems?