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College of Engineering

ECE 528 – Understanding Power Quality

http://www.ece.uidaho.edu/ee/power/ECE528/

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Lecture 17

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Today…

- Transient overvoltages
  - Ferroresonance
  - Capacitor switching transients
  - Switching capacitive and inductive loads

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From lecture 16 - lightning detection

- A network of radio receivers in the US can help determine the precise time and location of lightning strikes.
- This can be used to rule-in or rule-out lightning damage.
- This system can also be used when planning new systems to determine the lightning environment in a particular area.

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Ferroresonance

- Symptoms
  - Audible noise
    - Due to "Magnetostriction" – the change in dimensions of the steel transformer core in the varying magnetic field
      - Described by witnesses as a "growling" sound
  - Overheating
    - Stray flux results in heating of the transformer and may lead to damage

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Ferroresonance

- Symptoms continued
  - Significant overvoltages
    - End-user equipment damage
    - Surge suppressor and lightning arrestor damage
  - Flicker
    - Voltage may fluctuate over a wide range, resulting in noticeable light flicker.

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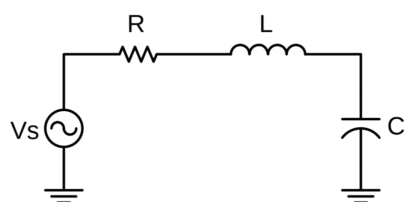
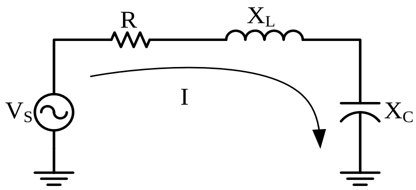
Normal resonance

- The series RLC circuit:



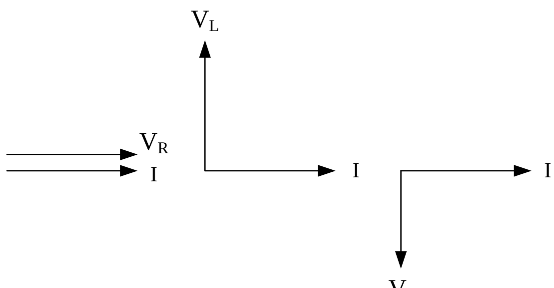
  - In the series circuit, the current through the series elements must be the same
  - The combined voltage across R, L, and C must equal the applied voltage
  - The voltage across individual elements is free to vary
  - For ferroresonance to occur, there must be at least one point in the circuit where the voltage is not fixed

Overvoltages in (nearly) resonant circuits



$$X_L = 2\pi f L \qquad X_C = \frac{1}{2\pi f C}$$

$$V_S = I*(R + j(X_L - X_C))$$



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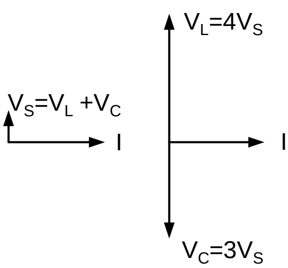
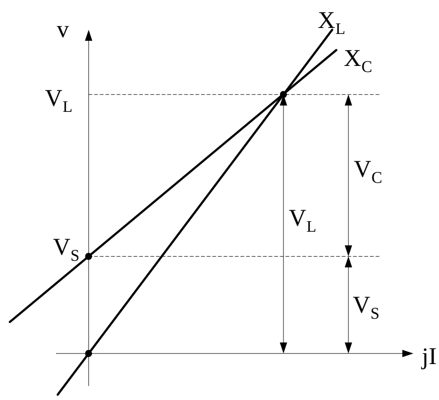
Overvoltages in (nearly) resonant circuits



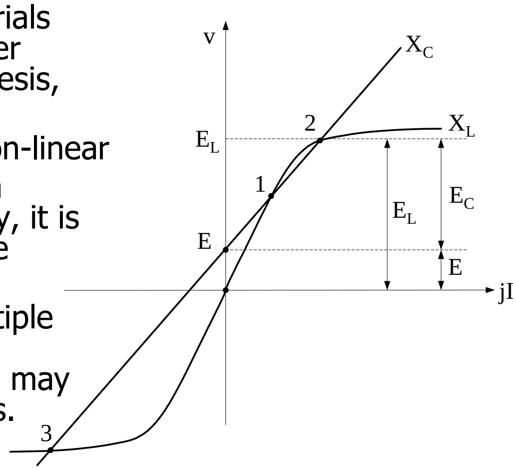
Ignoring the resistance, the applied voltage is the <u>difference</u> between the voltage across the inductance and the voltage across the capacitance.



XL and XC are described by the angles of the lines in the plot. Here each represents a fixed voltage/current relationship.

What's special about Ferroresonance

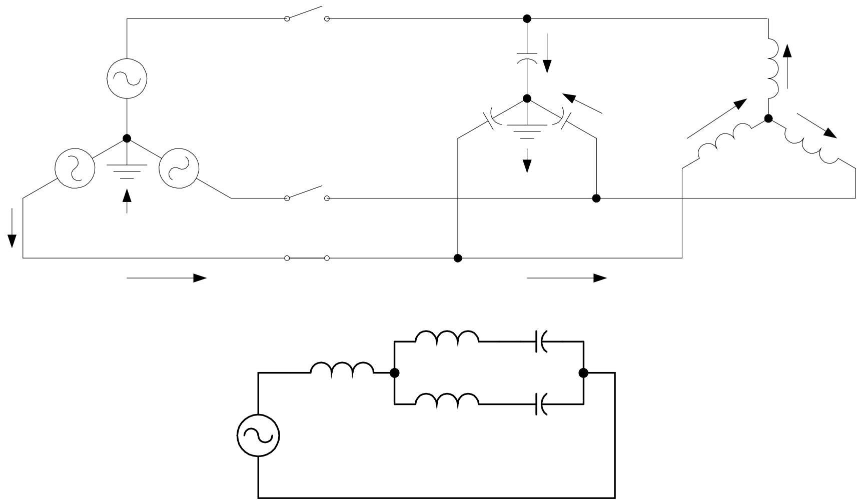
- Ferromagnetic materials (like steel transformer cores) exhibit hysteresis, and can saturate.
- The inductance is non-linear
- X_L is no longer just a function of frequency, it is also a function of the applied voltage
- Circuit will have multiple stable and unstable operating points and may jump between points.



Necessary conditions for ferroresonance

- Capacitance with non-linear inductance
- At least one point where the voltage is not fixed by the external system
- Light loading – minimal damping

Example of ferroresonant condition



Preventing ferroresonance

- Use grounded-wye/grounded-wye systems
- Keep primary cable runs short
- Use three-phase switching and protection
- Place switch/protection directly upstream of the transformer
- Have some load on the transformer when switching
- Surge arrestors may be used to help suppress overvoltages

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A real-world example

- Conditions:
  - Three-phase padmounted transformer
    - 75kVA, 34.5kV grounded-wye primary, 480Y/277V grounded-wye secondary
    - Intermittent fault inside transformer due to manufacturing defect
  - Padmounted vacuum fault interrupter immediately upstream
    - Set for single-phase tripping
  - Approximately 3500′ of three-phase secondary cable underground to an irrigation panel (really!)
    - Irrigation system not operating

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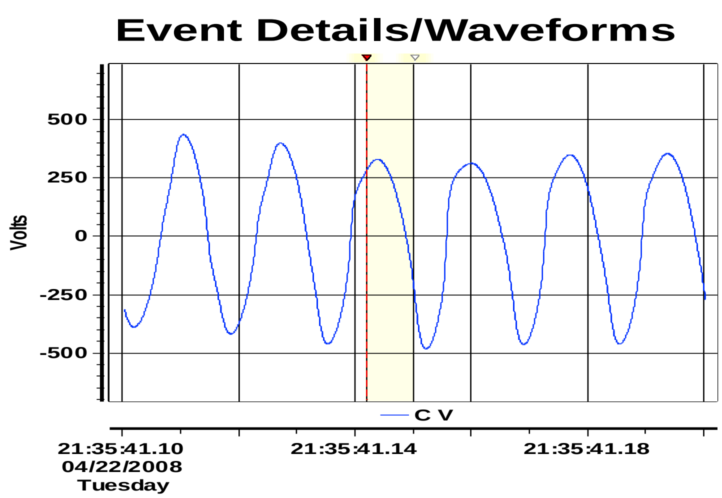
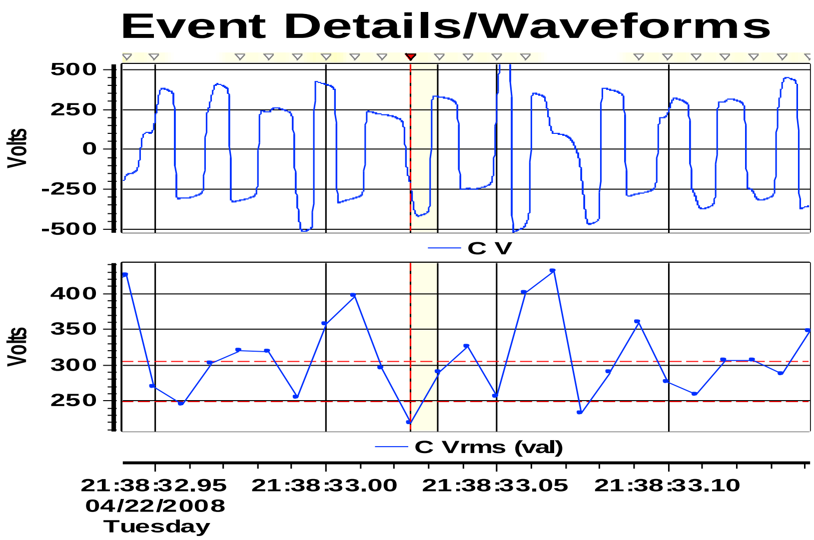
36s after C phase opened on primary



3.5 minutes after C phase opened



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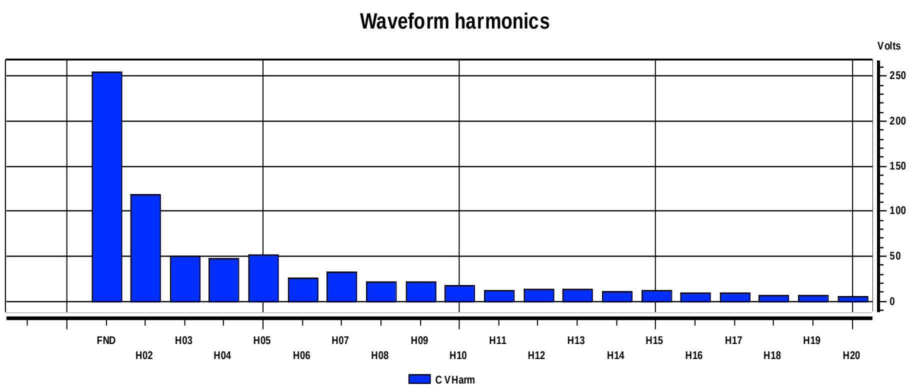
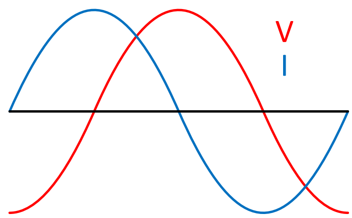
Frequencies in the ferroresonant voltage



	A V	B V	C V	A-B V	B-C V	C-A V	A I	B I	C I
RMS	282.15	284.05	312.55	489.52	549.10	375.47	1.06	1.04	0.95
FND	282.10	284.00	253.88	489.50	517.17	321.95	100.00	100.00	100.00
DC	1.54	-1.28	-3.73	2.83	2.45	-5.28	87.96	81.33	181.06
THD	4.96	5.05	172.09	2.47	173.41	173.26	94.47	100.12	161.52

Switching capacitive and inductive loads

- Capacitive loads:
  - Voltage cannot change instantaneously
  - **Closing the switch** when there is a large voltage across it can lead to a large current inrush transient
  - The current transient results in an oscillatory voltage transient
  - De-energizing capacitive loads is generally not an issue; voltage peaks at current zero, but voltage across switch can still be low



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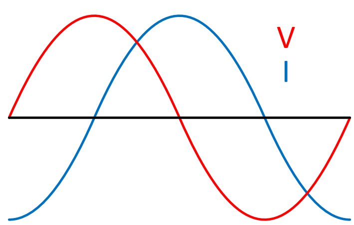
Switching capacitive and inductive loads

- Inductive loads:
  - Current cannot change instantaneously
  - **Opening the switch** when there is a large current through it can lead to a large voltage transient
  - Voltage transient may cause switch to restrike and may impact other equipment
  - Energizing inductive loads is generally not an issue



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Capacitor switching transients

- Symptoms
  - May follow a regular "schedule"
  - Variable speed drives and other rectifier-based loads may trip
  - Theoretical peak is 2 p.u. Damping normally results in transients with peaks of around 1.3 to 1.4 p.u.
  - Over-currents accompany the voltage transients
  - Voltage transient may be magnified at low-voltage capacitors in customer facilities

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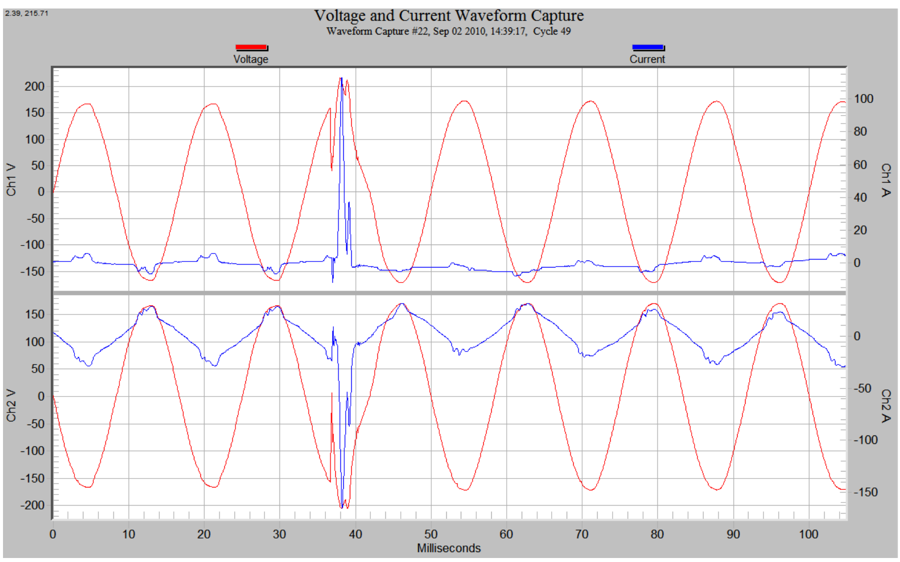
Capacitor switching transient



Capacitor switching transient magnification

Voltage magnification is generally most severe if:

- High voltage (HV) capacitor is much larger than low voltage (LV) capacitor
- Frequency of HV transient is close to resonant frequency of LV transformer in series with the LV capacitor
- Damping is low – LV system is lightly loaded

Capacitor switch restrike

- When opening, a capacitor is left charged to nearly peak system voltage.
- Internal resistors dissipate this stored energy slowly
- If switch restrikes, voltage on capacitor is 180 degrees out of phase with applied voltage, and resulting voltage overshoot is doubled.
- Theoretical peak voltage transient is 3 p.u. on first restrike, 5 p.u. on second restrike.

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Mitigating capacitor switching transients – utility system

- Scheduling – switch at a different time
- Use pre-insertion resistors to damp the inrush and reduce the peak of the transient
- Synchronous switching – usually at voltage zero crossing
- Move the capacitor to provide some system impedance between it and loads

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Mitigating capacitor switching transients – customer system

- Address problem loads only – line reactors on variable speed drives (see PSQ p. 191)
- Use MOVs to clamp the transient peak
- Turn customer capacitors into harmonic filters – inductor in series with capacitors – similar to solution for variable speed drives

Mitigating inductive load switching transients

- Mitigate Electrical fast transient (EFT) with electrical and physical separation (PSQ p. 192)
- Apply "snubbers" at switches to absorb transient energy
- Apply surge suppressors (MOVs).
- Apply a combination of snubbers and surge supressors (see Littlefuse application note)

Next time…

- Switching transients
- Transient protection summary