Identifying and Eliminating Single Points of Failure

Presented by: Thomas King

Course Objectives

- Identifying and Eliminating Single Points of Failure
  - **Training**
    1. Appropriate use of equipment
    2. Fire Prevention
    3. Appropriate use of PPE
  - **Maintenance and Upgrades**
    1. Thermal Scans
    2. Cutting Edge Circuit Breaker Technology
    3. Diesel Fuel and Battery Maintenance
  - **Design**
    1. Sequence of Operation of mechanical and electrical controls
    2. Redundancy of power paths and mechanical and electrical equipment
    3. Transient Voltage Mitigation
    4. Generator loading and paralleling

Training

Emergency Power Off (EPO)

- The “Emergency Power Off” (EPO) button is infamous in the history of IT centers as people sometimes mistake it for a door release button
- The NEC has allowed the EPO to be remotely located (not physically in the IT room) since 2011.
- Legacy installations remain. It is important to be able to tell the difference between the EPO and the Door Release button

Emergency Power Off (EPO)

Fire

- NFPA 75 was created in response to a fire in 1959 which started when magnetic tape was stored too close to an incandescent lamp in a Pentagon Data Center
- NFPA 75 includes requirements for fire alarming and fire protection and includes design requirements for both water and gas based fire suppression

Fire

Pentagon Fire Destroys Air Records and Computers

Associated Press Wirephoto

Firemen pour water through hole cut in floor of Pentagon's main concourse on fire below

Turning the Wrong Handle

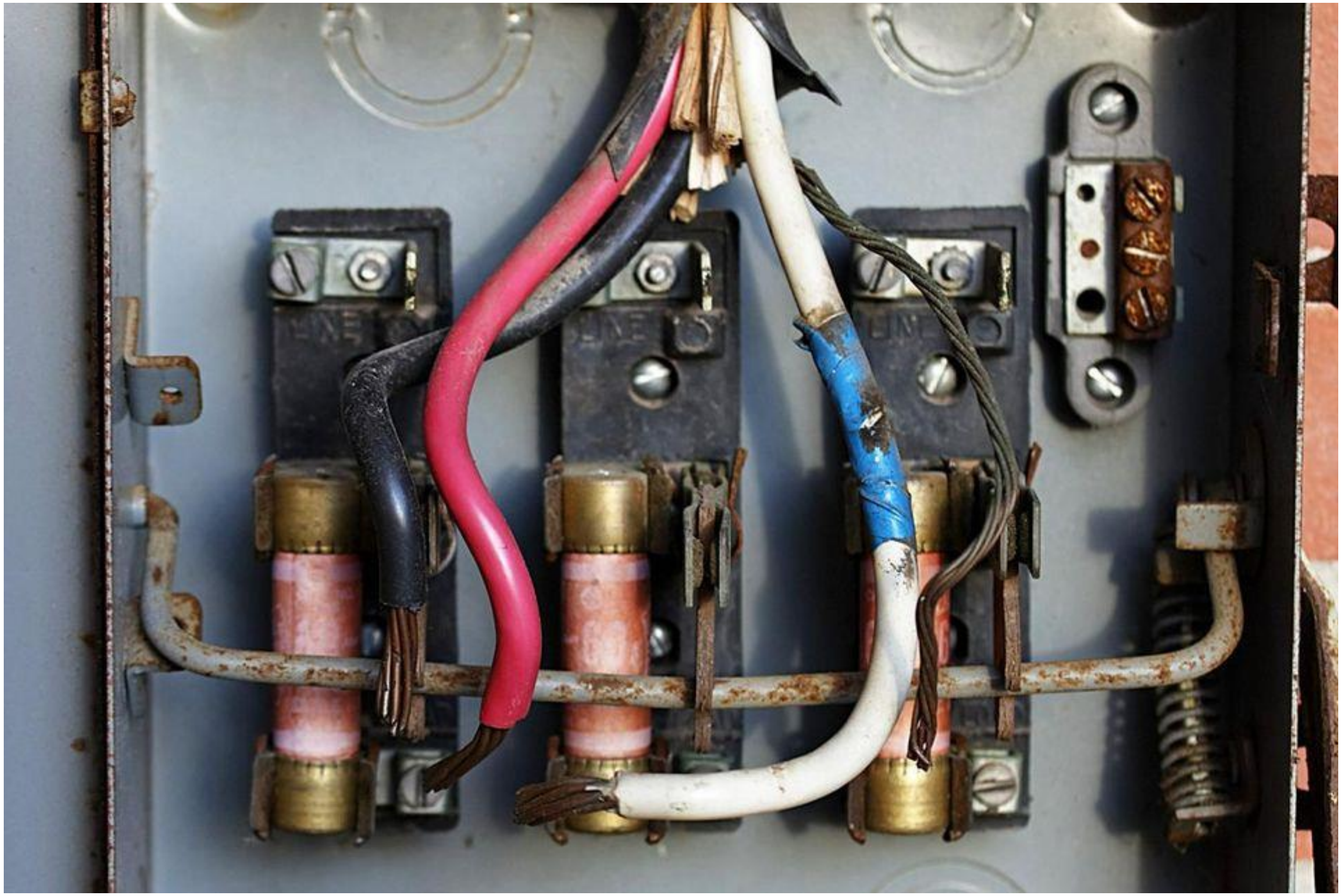
- Critical Facilities are filled with buttons and handles. Turning the wrong one can lead to an outage

Turning the Wrong Handle

Taking Short-Cuts

- It is essential to develop and follow detailed Method Of Procedures (MOPs). Taking short-cuts or using obsolete MOPs could lead to an outage

People Taking Short-Cuts



Jewelry

- OSHA 1910.333(c)(8) prohibits the wearing conductive material where it might come into contact with energized parts

Jewelry

Not Paying Attention

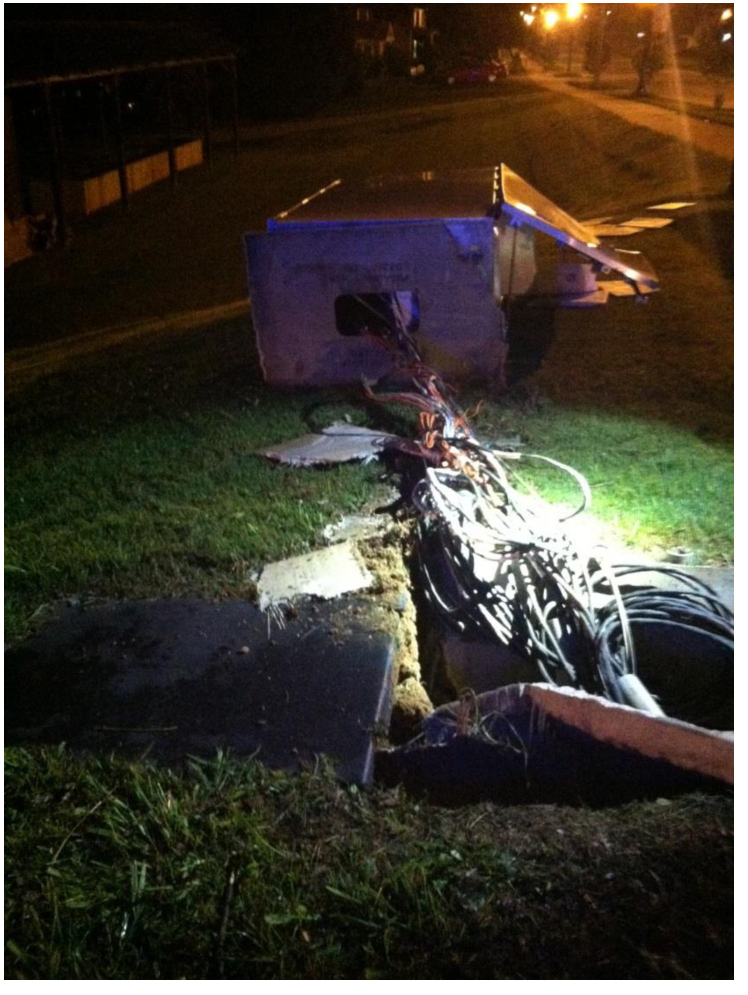
- Situational awareness is mandatory. Leaning on a switchboard or carrying large objects without help could lead to an outage

Not Paying Attention

Driving Poorly

- Car accidents can result in catastrophic damage to utility distribution equipment

Driving Poorly

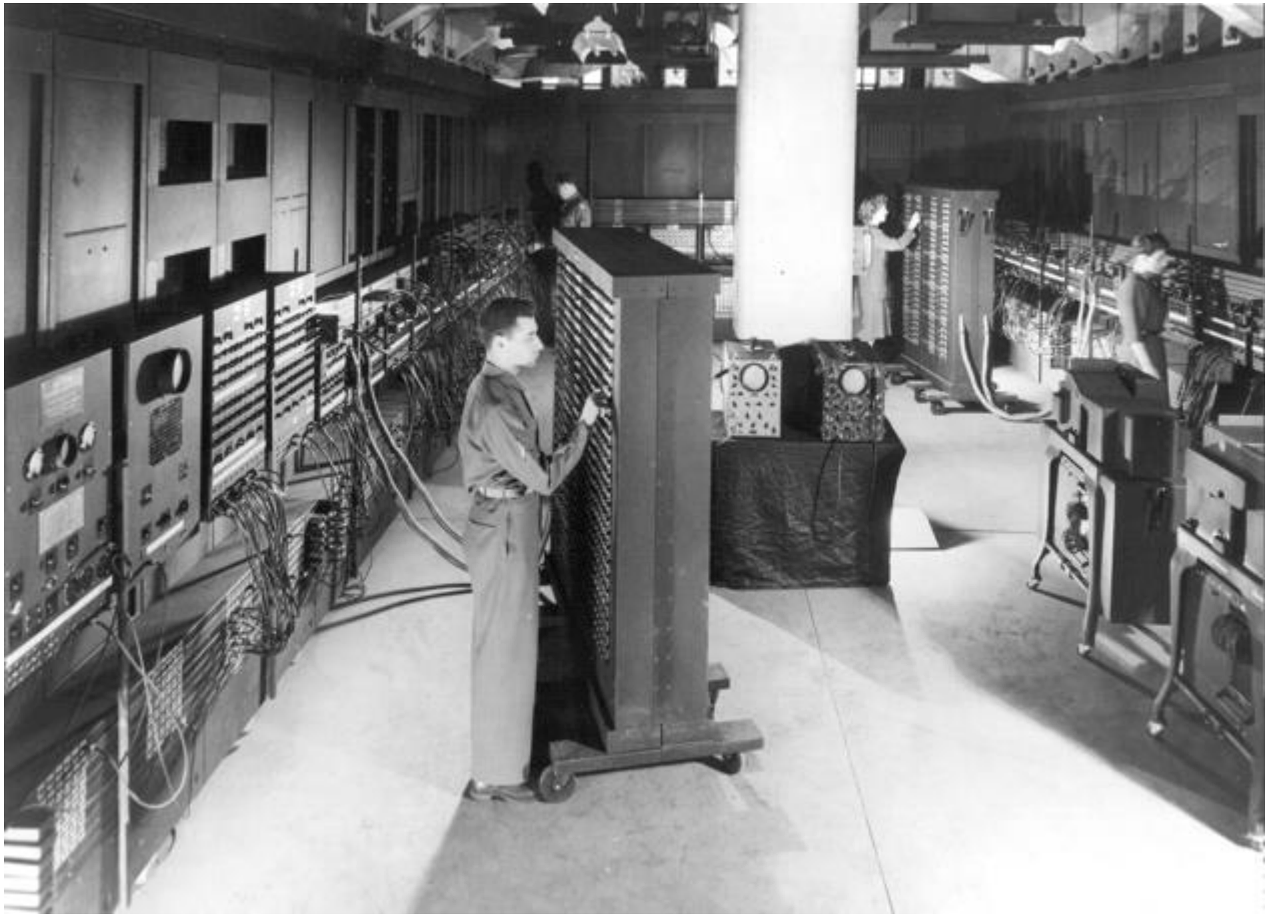


Maintenance

Upgrade Old Equipment

- In 1947, The fastest computer in the world had an up-time of 2 hours a week
- By 1954, this same computer had managed to operate without failure for 116 hours—close to five days
- Solid State equipment has greatly improved the mean time between failure (MTTBF) of IT equipment

Upgrade Old Equipment

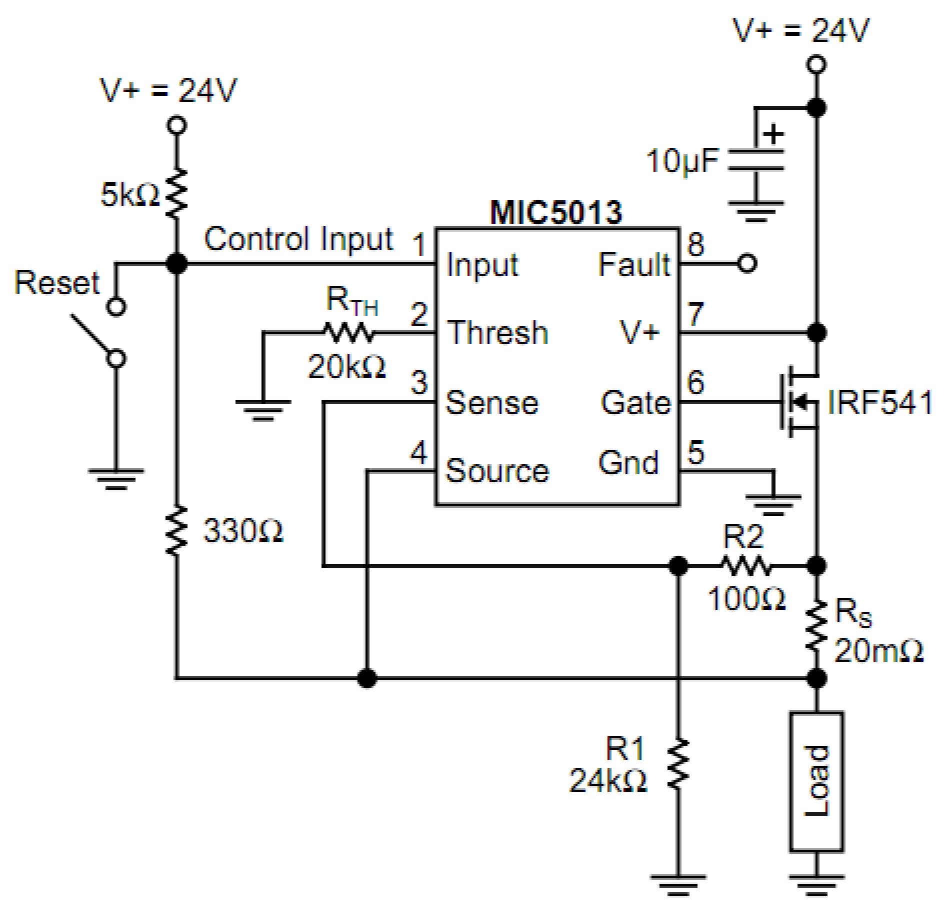


Source: U.S. Army photo

Upgrade Circuit Breakers

- Electronic Trip circuit breakers may provide better selectivity than thermal magnetic circuit breakers
- Solid State circuit breakers provide nearly instantaneous circuit interruption - ensuring selectivity and making Arc Flash a thing of the past

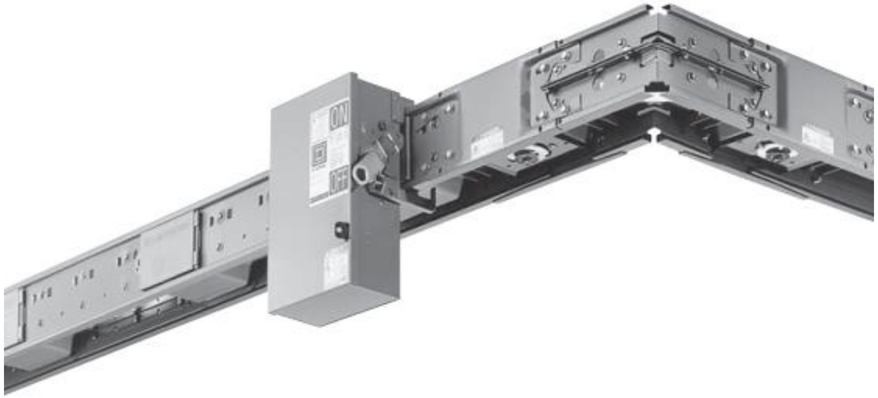
Upgrade Circuit Breakers



Torque

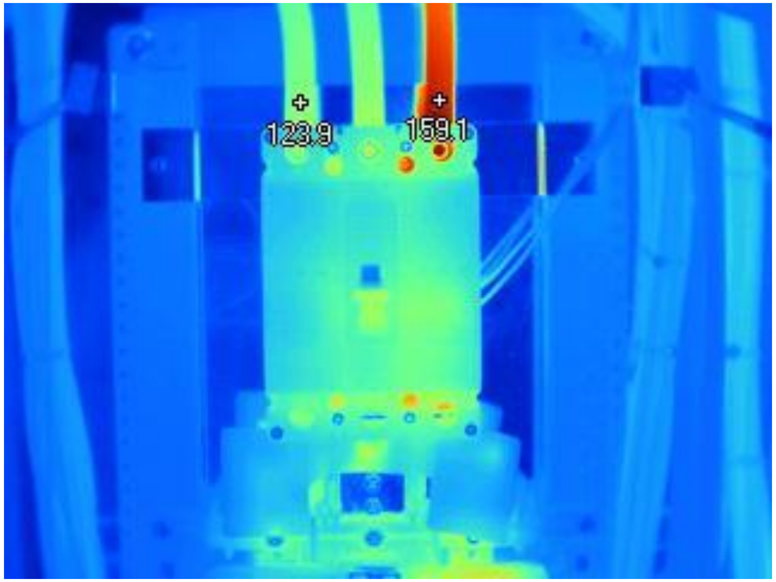
- Infrared cameras allow us to see heat
- Infrared scanning of electrical busway and circuit breaker lugs may indicate hot spots before they become a point of failure

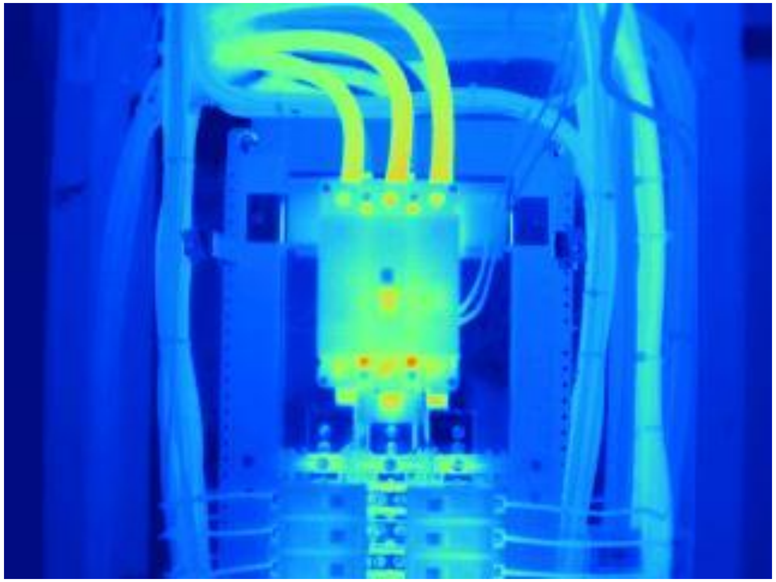
Torque



Source: http://www.fssb.my/buswaymaintainance.html

Torque



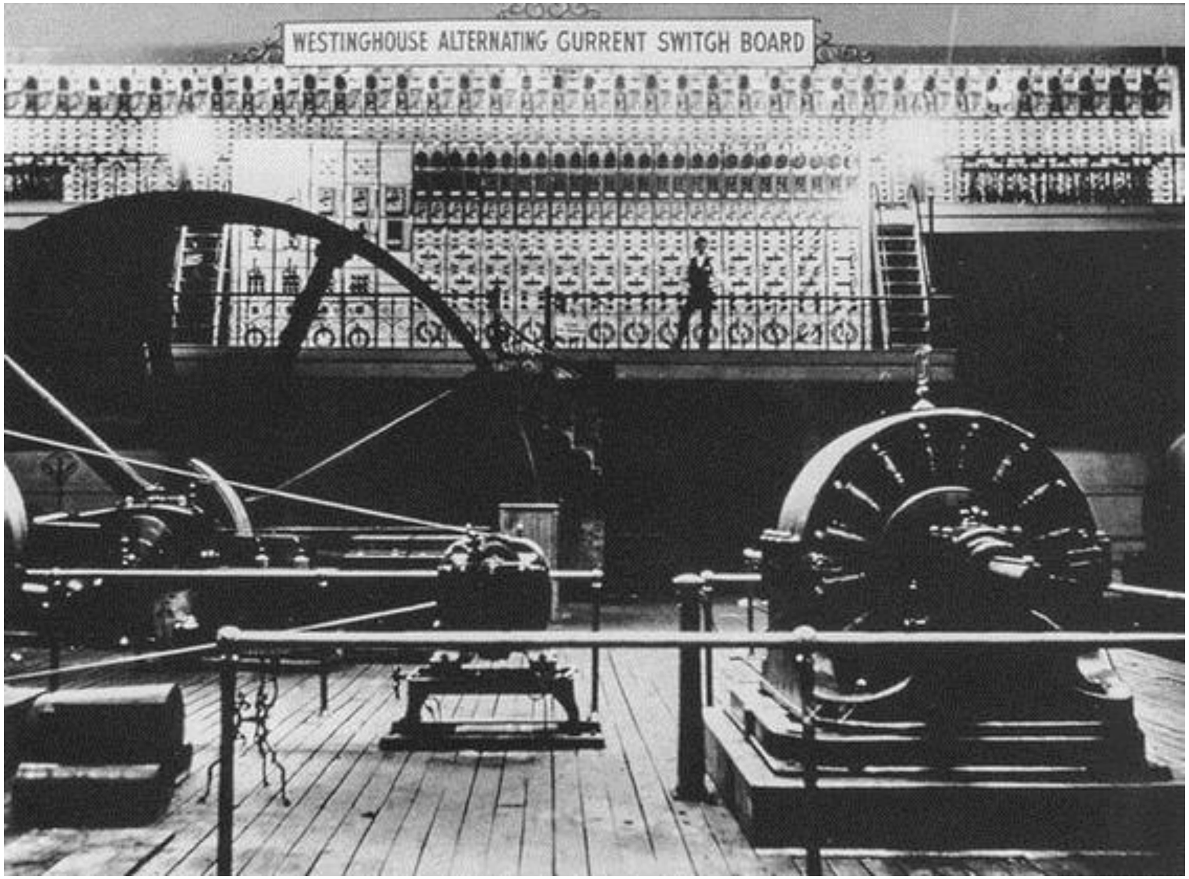


Source: http://www.circuitbreakersblog.com

Replace Existing Equipment

- Some equipment cannot be upgraded and must be replaced in order to improve reliability
- Electrical AC power distribution first gained popularity for lighting in the 1893 world’s fair and has improved in the last 123 years

Replace



Source: https://teslauniverse.com

Maintain Existing Equipment

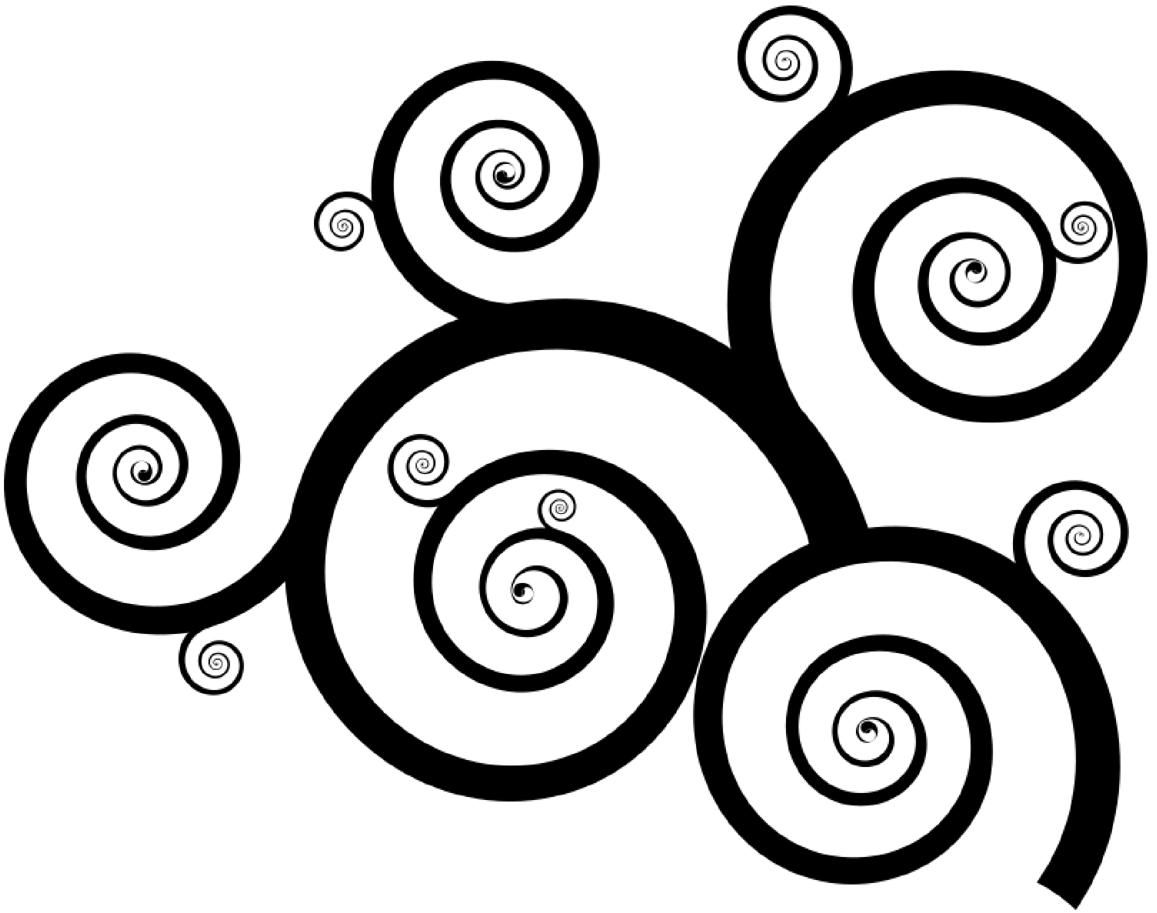
- Regular Maintenance of critical mechanical and electrical systems can prevent outages
- Chemical energy storage such as batteries and diesel fuel requires special regular attention

Maintain Existing Equipment

Source: http://www.eepowersolutions.com

Source: CNBC.com

Design



DCIM/BAS Redundancy

- Consider providing a dedicated BAS for each chiller and its associated pumps and cooling tower
- It may be best if only one controller is required for each chiller system since controller-to-controller communications may degrade redundancy
- Redundant differential pressure sensors are recommended where multiple chillers feed a common loop
- Redundant common control sequences in each controller is recommended for the chilled water pump VFD/pressure controls

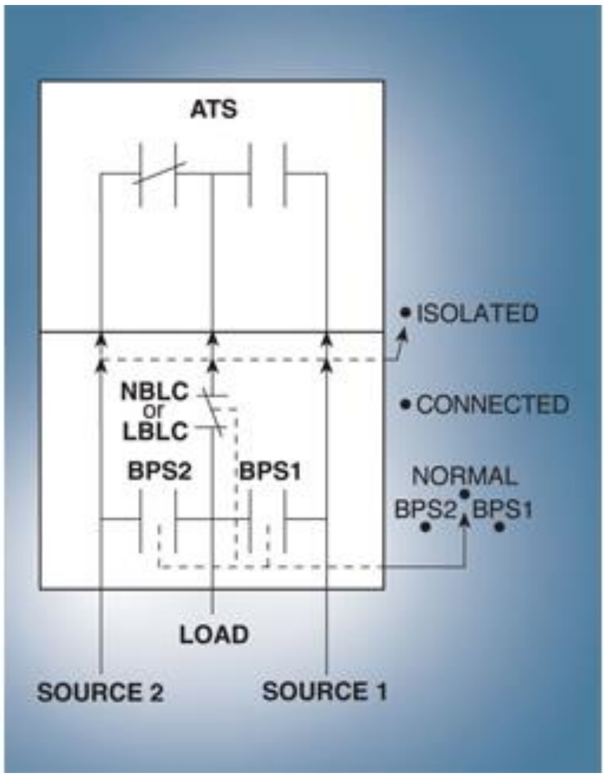
DCIM/BAS Redundancy

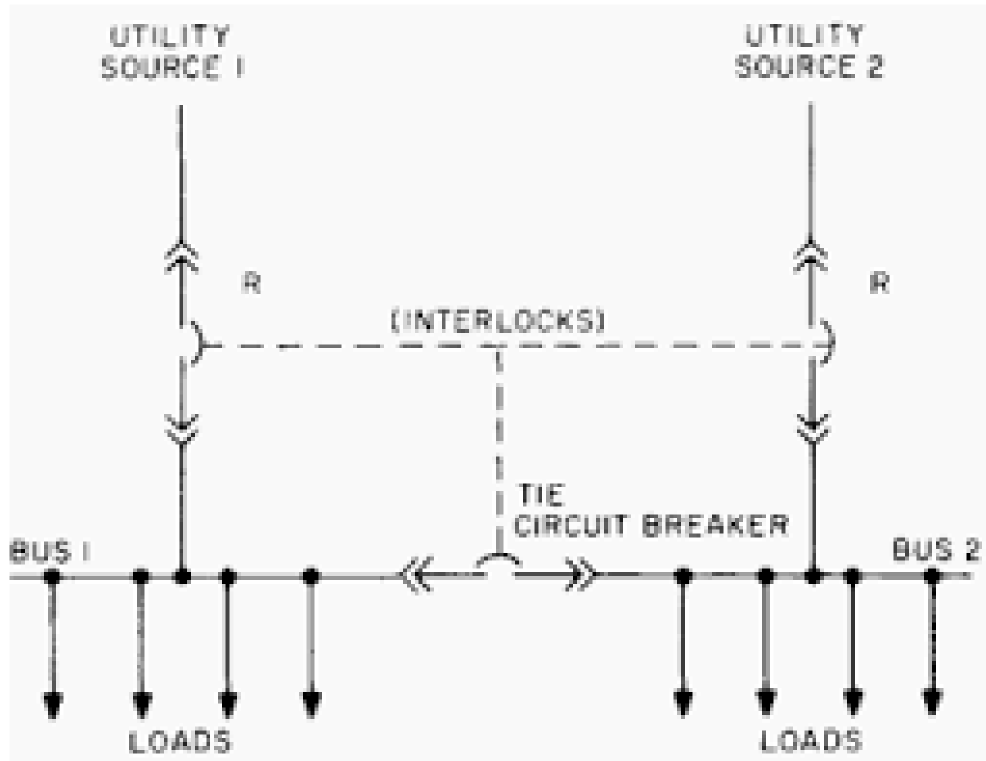
Source: http://berg-group.com

Sequence of Operation

- Where there are multiple sources of power, ensure coordination of ground fault delays to prevent the non-energized source from nuisance tripping
- In Emergency Backup systems, ensure that any engine start delay does not put you outside of the 10 second emergency range
- Coordinate ATS delays with the following considerations in mind:
  - Emergency loads must be stable before standby loads are added
  - All generators must be paralleled and on the bus before adding standby loads

Sequence of Operation



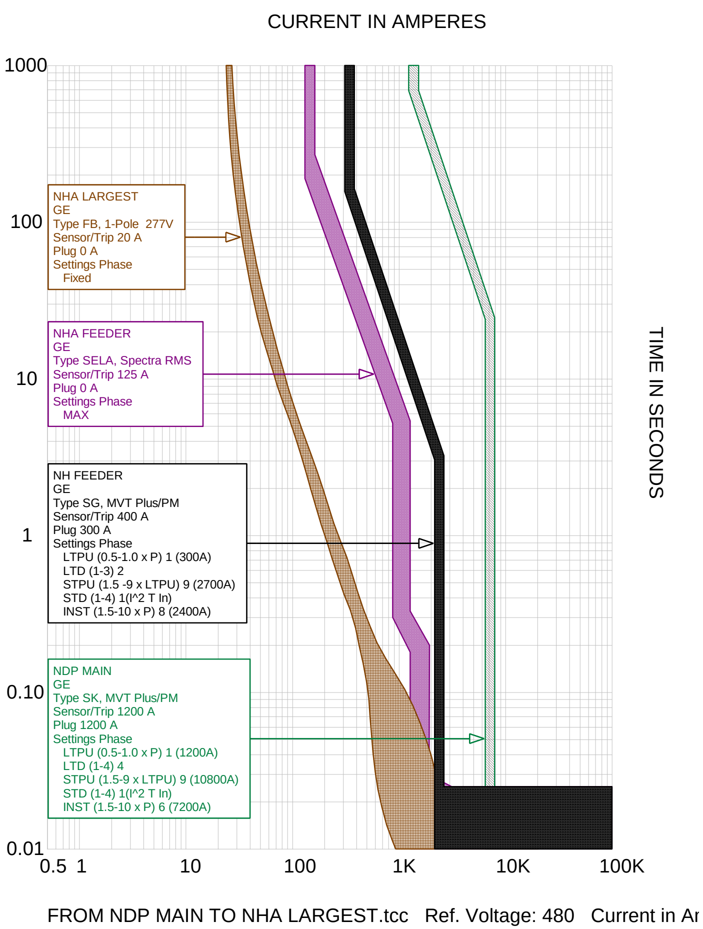


Source: http://www.russelectric.com

Protective Device Settings

- Selective coordination of all protective devices is required in fault tolerant systems
- ATS switching delays need to be coordinated with motor lock-out relays to prevent chillers and other motors from locking out due to multiple transfer operations

Protective Device Settings



Source: http://www.icmcontrols.com

Power Quality Tolerances

- The ATS Sync-Check relay (ANSI device 25) needs to be set with special consideration to both surge current and the practical limitations of the system
- New IT power supplies have improved “ride-through” capabilities as compared to first generation equipment
- Reverse power relays (32R) may be required to prevent back-feeding the utility transformers. Utility network protectors will open on reverse power but do not have sync check capability. If out of sync power is applied to a utility network protector, it may fail catastrophically, leading to a indeterminate power outage.

Power Quality Tolerances

Calculate Out of Phase Voltage and Surge Current

$Delta := 10\ °$ $\quad Motor_{kva} := 3660$

$V_{diff.pu} := 2 \cdot \sin\left(\frac{Delta}{(2)}\right)$ $\qquad V_{diff.pu} = 0.174$

$V_{diff} := V_{diff.pu} \cdot 480\ V$ $\qquad V_{diff} = 83.67\ V$

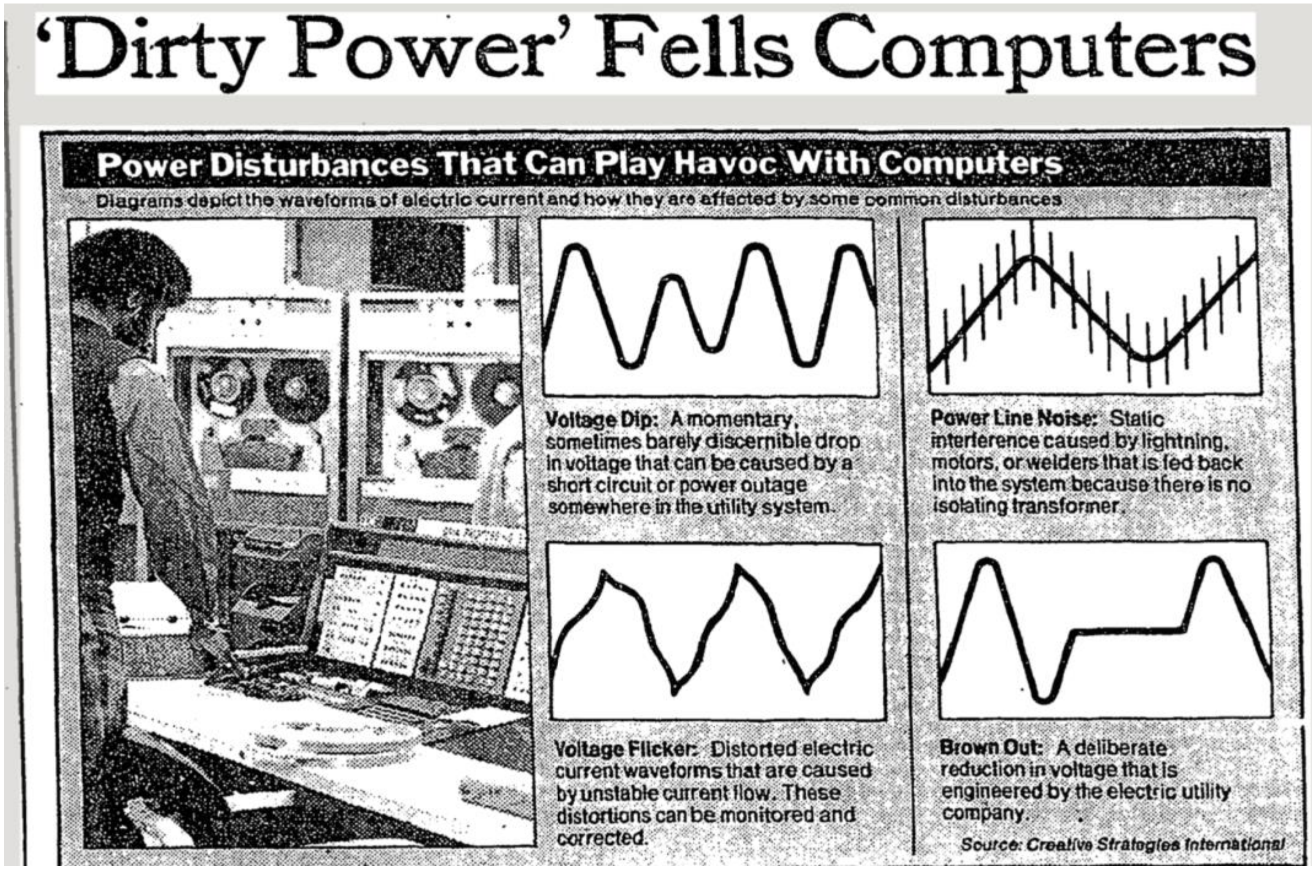
$X_{d''} := .144$

$I_{surge.pu} := \frac{V_{diff.pu}}{X_{d''}}$ $\qquad I_{surge.pu} = 1.21$

$I_{amps} := I_{surge.pu} \cdot \frac{Motor_{kva}}{\left(\sqrt{(3)} \cdot 480\right)} \cdot 1000$ $\qquad I_{amps} = 5.329 \cdot 10^{3}$

Source: "*Managing risks, benefits with closed transition transfer switches*"
Cummins Power Generation

Power Quality Tolerances



'Dirty Power' Fells Computers

Power Disturbances That Can Play Havoc With Computers

Diagrams depict the waveforms of electric current and how they are affected by some common disturbances

Voltage Dip: A momentary, sometimes barely discernible drop in voltage that can be caused by a short circuit or power outage somewhere in the utility system.

Power Line Noise: Static interference caused by lightning, motors, or welders that is fed back into the system because there is no isolating transformer.

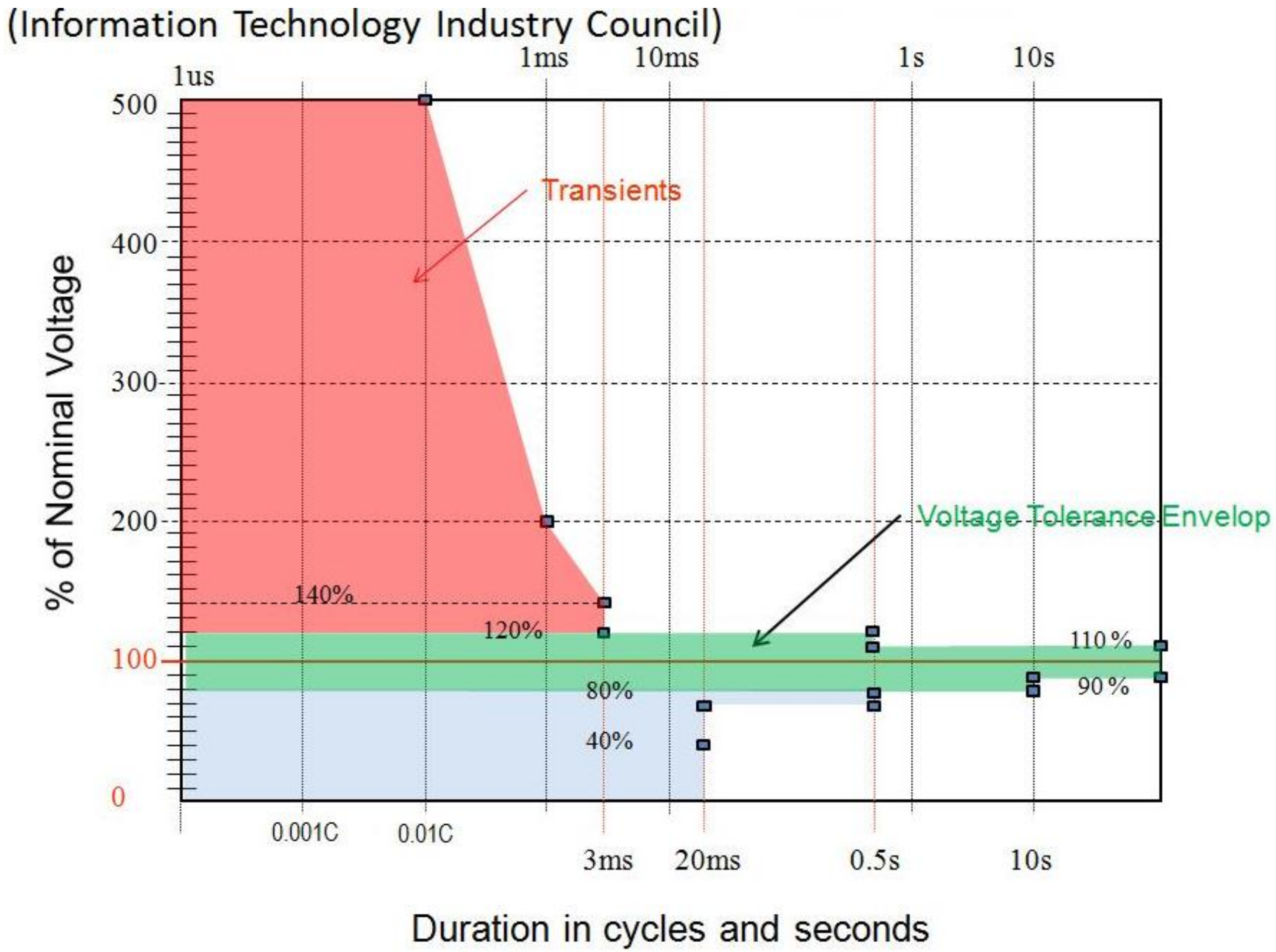
Voltage Flicker: Distorted electric current waveforms that are caused by unstable current flow. These distortions can be monitored and corrected.

Brown Out: A deliberate reduction in voltage that is engineered by the electric utility company.

Source: Creative Strategies International

Source: The New York Times, April 17, 1982

Power Quality Tolerances



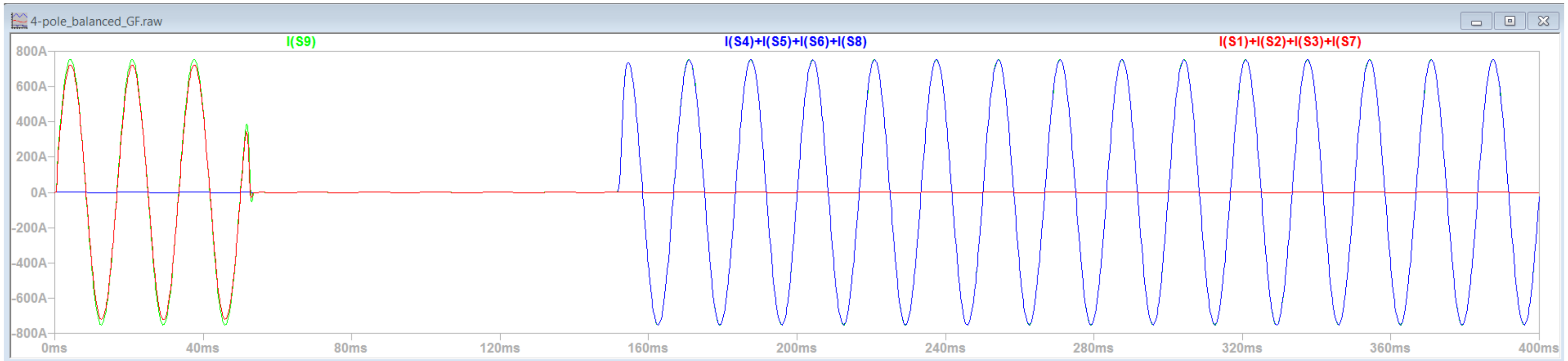
Source: Information Technology Industry Council (ITI)

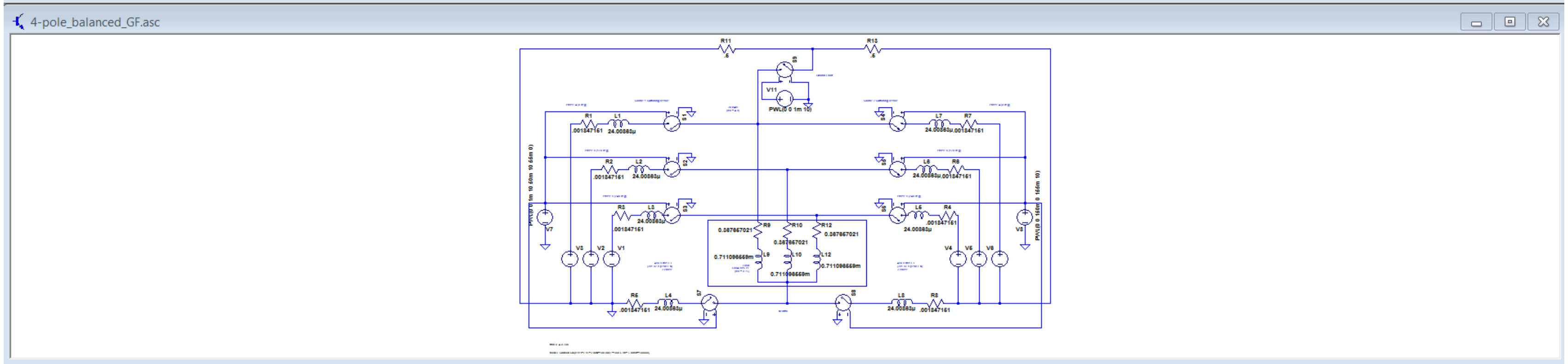
Power Quality Tolerance

4-Pole Open Transition ATS

- The 4-Pole Open Transition ATS prevents the flow of ground fault current back to the de-energized source
- The 4-Pole Open Transition ATS can be specified to include a “delayed off” position to allow the motor contribution to decay
- The 4-Pole Open Transition ATS may experience a transient rise in voltage across the neutral contact if an unbalanced load is being switched

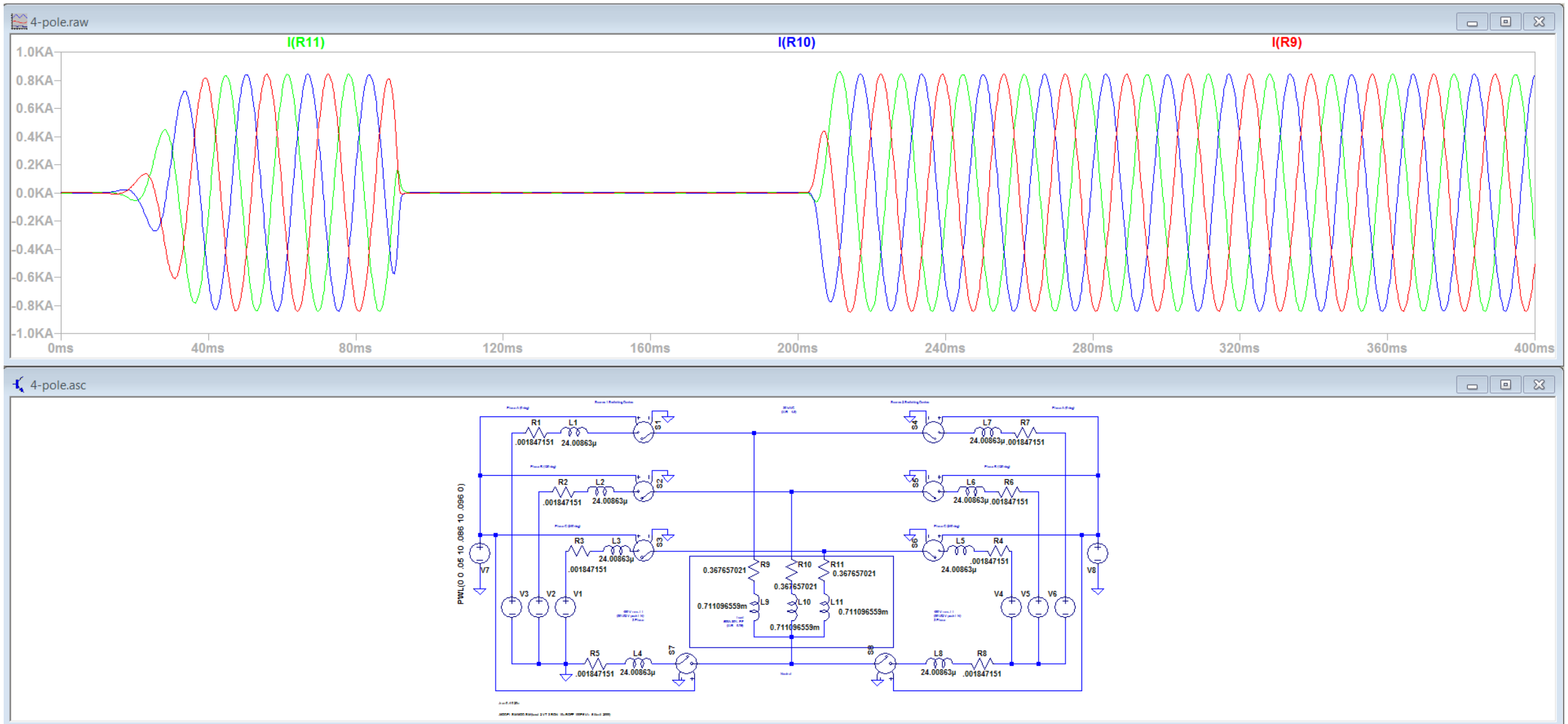
4-Pole Open Transition ATS





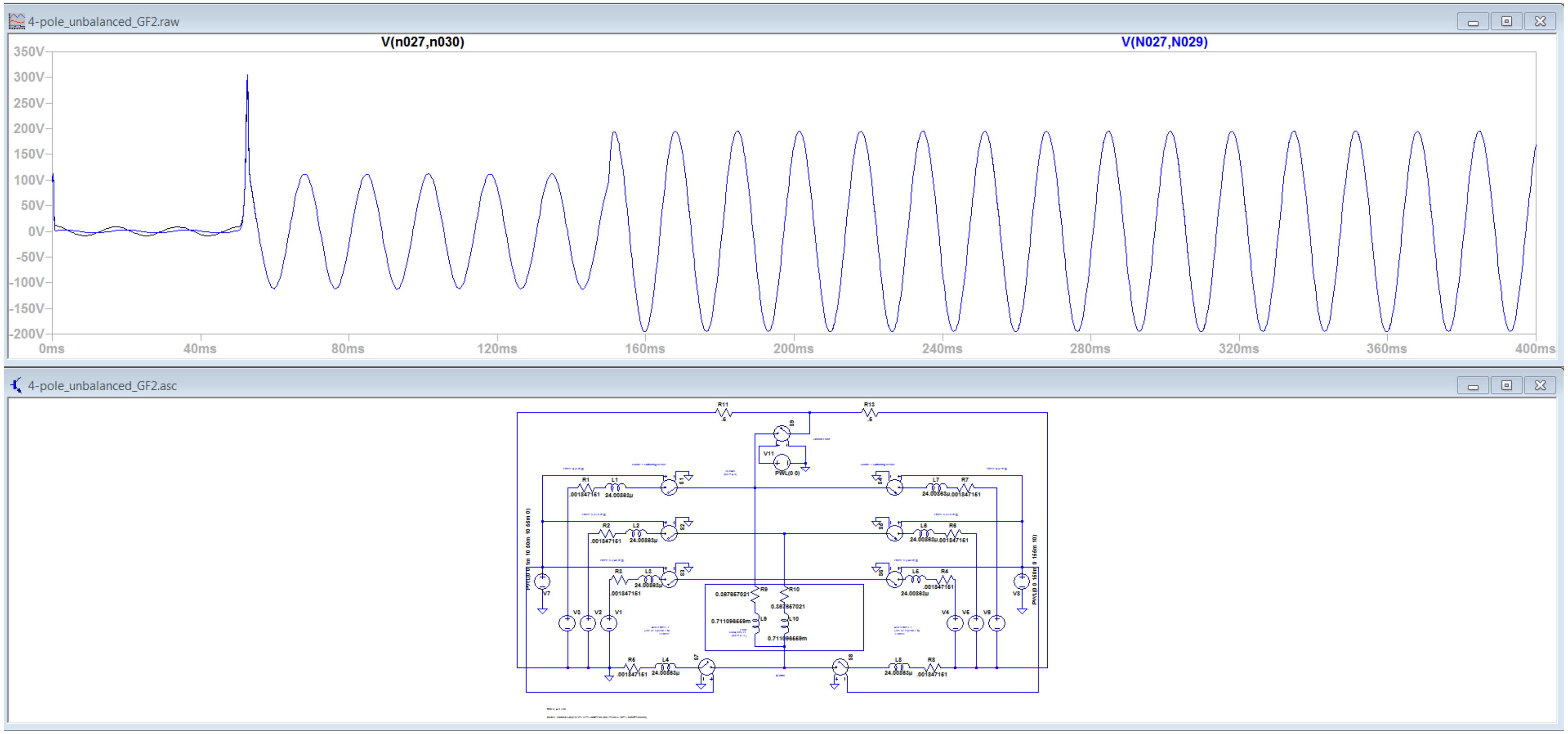
Source: *3-Pole and 4-Pole Transfer Switch Switching Characteristics, Eaton.com*

4-Pole Open Transition ATS



Source: *3-Pole and 4-Pole Transfer Switch Switching Characteristics, Eaton.com*

4-Pole Open Transition ATS

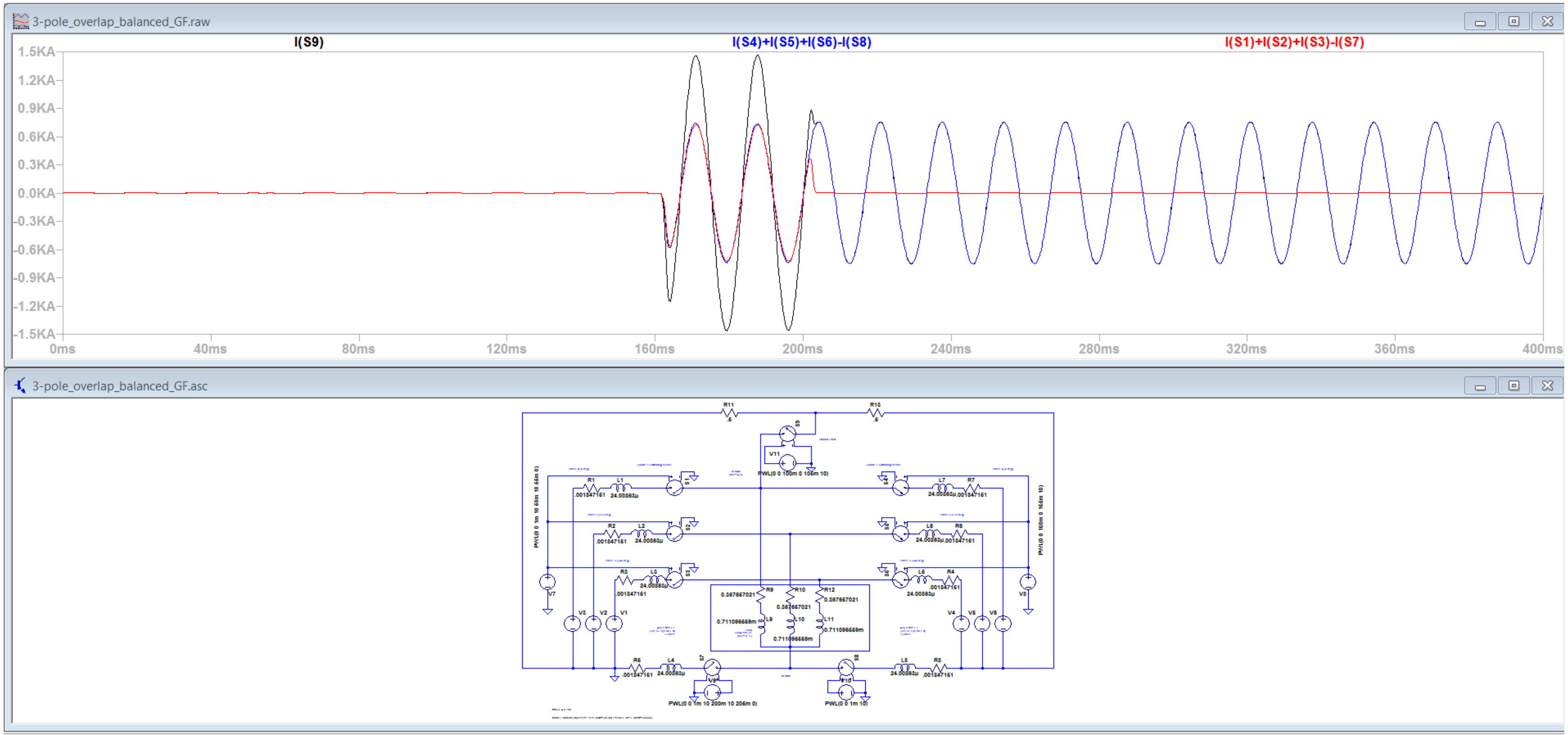


Source: *3-Pole and 4-Pole Transfer Switch Switching Characteristics, Eaton.com*

Overlapping Neutral 4-Pole ATS

- The Overlapping Neutral 4-Pole ATS allows ground fault current to flow back to the de-energized source – potentially resulting in a nuisance trip
- The Overlapping Neutral 4-Pole ATS maintains a solid neutral during the switching operation – similar to the 3-pole ATS
- The Overlapping Neutral 4-Pole ATS does not experience a rise in potential across its neutral contact during a switching operation

Overlapping Neutral 4-Pole ATS

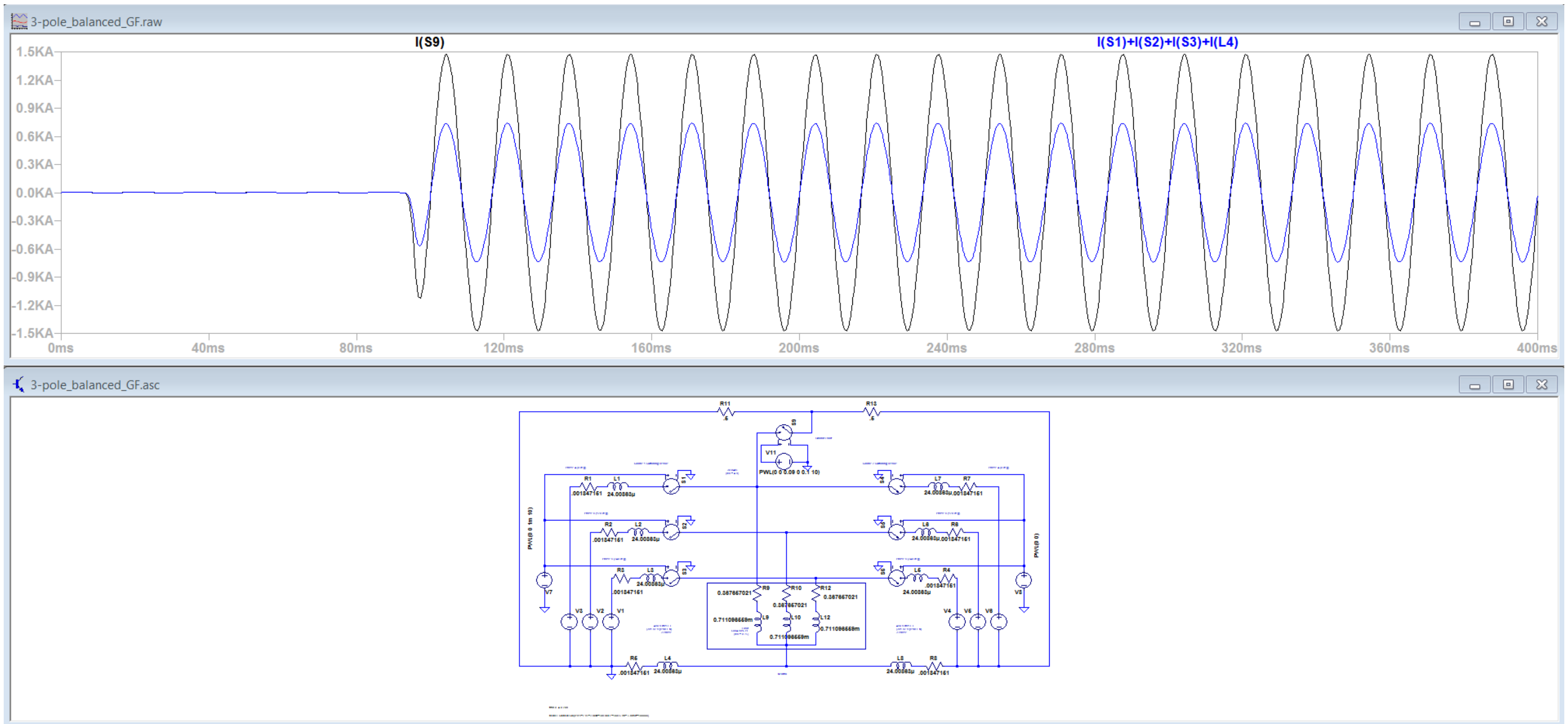


Source: *3-Pole and 4-Pole Transfer Switch Switching Characteristics, Eaton.com*

3-Pole ATS with Modified Ground Fault Protection

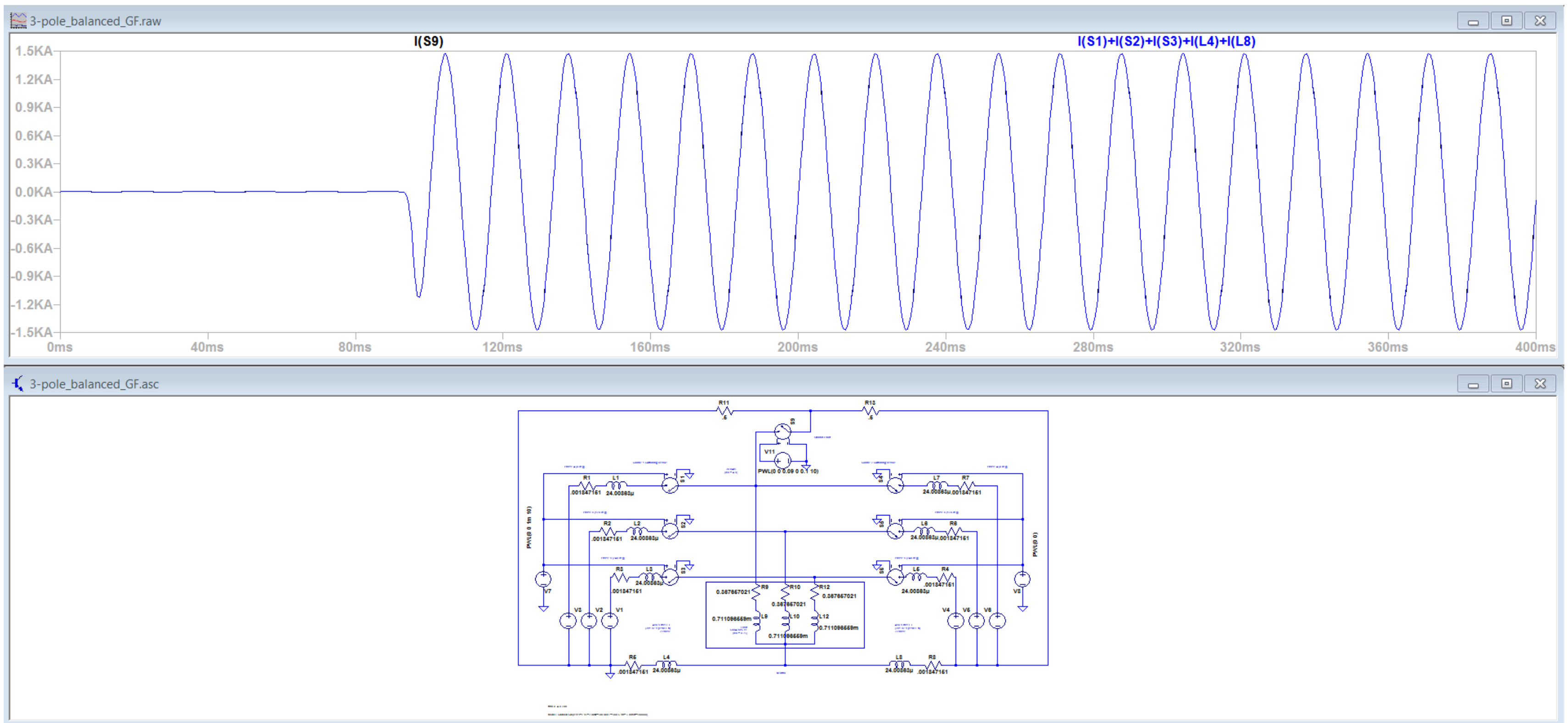
- The 3-Pole ATS allows ground fault current to flow back to the de-energized source. This can cause:
  - A decrease in the magnitude of ground fault current sensed by the energized source's zero sequence CT's
  - An increase in the opening time delay of the energized source protective device
- Adding Modified Differential Ground Fault Protection may prevent a nuisance trip of the de-energized source on a system with a 3-Pole ATS

3-Pole ATS with Modified Ground Fault Protection



Source: *3-Pole and 4-Pole Transfer Switch Switching Characteristics, Eaton.com*

3-Pole ATS with Modified Ground Fault Protection



Source: *3-Pole and 4-Pole Transfer Switch Switching Characteristics, Eaton.com*

Transient Voltage Mitigation

- Causes of Transient Voltage spikes can include:
  - Lightning Strikes
  - Re-striking voltage caused by disconnecting an inductive load
  - Resonance caused by circuit switching
  - Switch Mode power supplies
- Consider high-end VFDs or installation of dV/dT and sinusoidal filters to reduce transients
- Consider Snubber Circuits and Transient Voltage Surge Suppression to filter out transients

Re-striking Voltage

$V := 480 \cdot \sqrt{2} = 678.823$

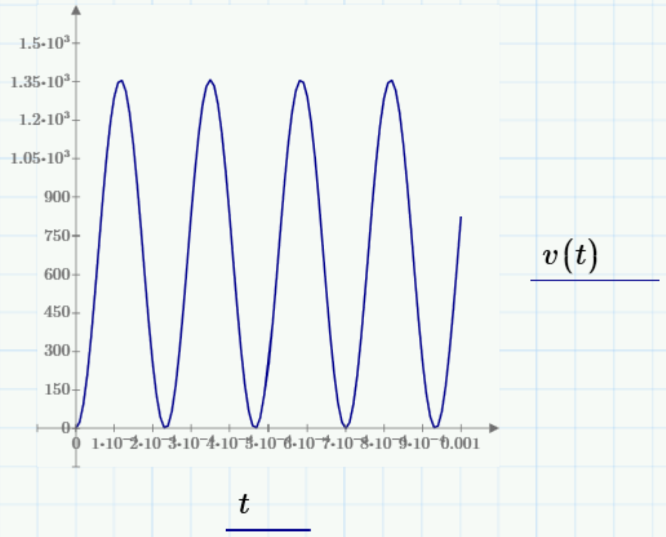
$XR := 1.77$

$C := .00001$

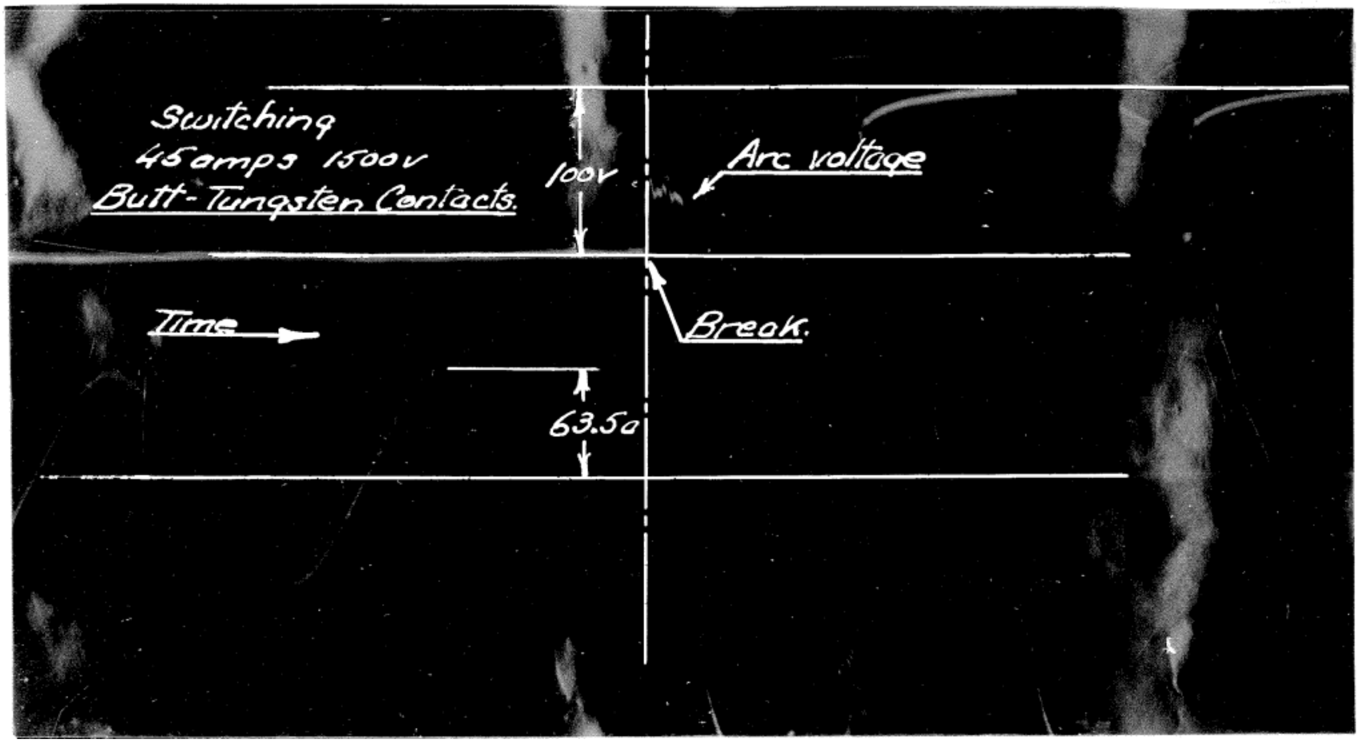
$L := .000138$

$$v(t) := V \cdot \left(1 - \cos\left(\frac{t}{\sqrt{L \cdot C}}\right)\right)$$

$t := 0, .00001 \ldots .001$

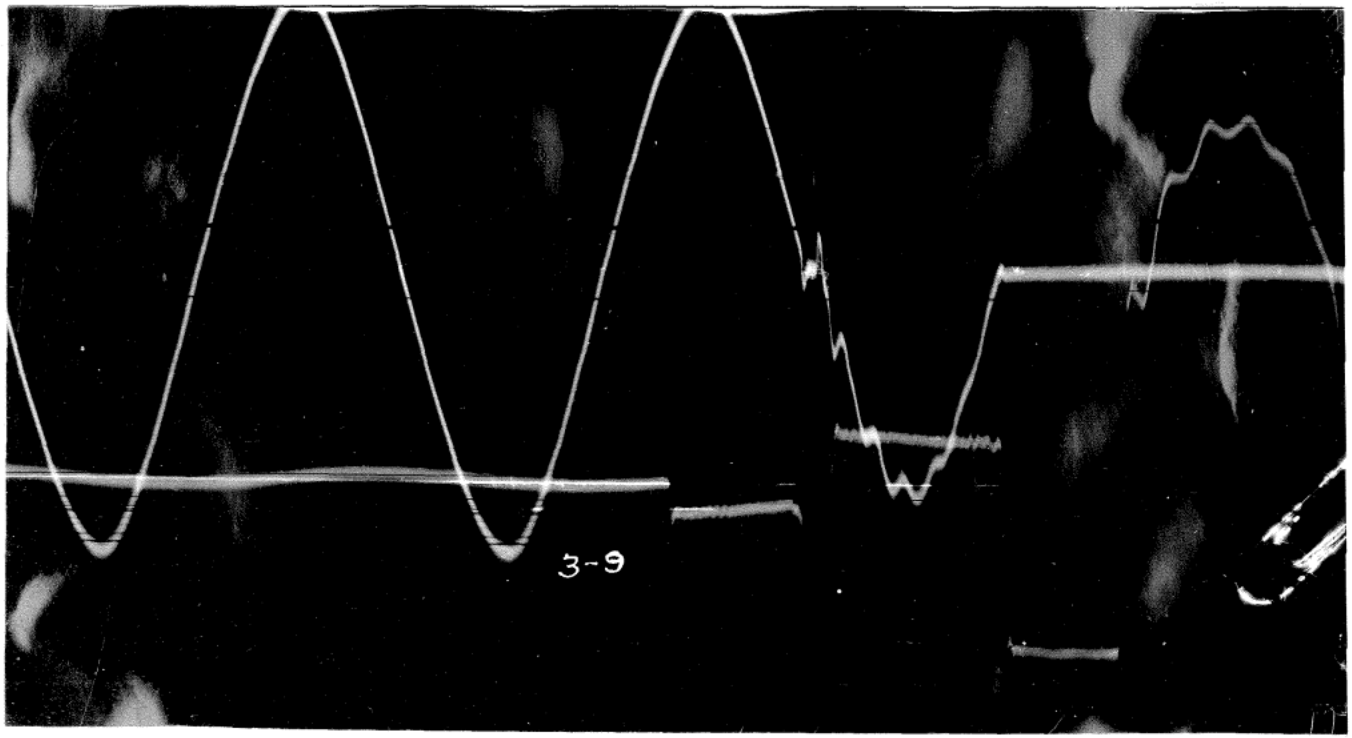


Re-striking Voltage



Source: Thesis paper by James Hugh Hamilton
California Institute of Technology 1928

Re-strike Voltage



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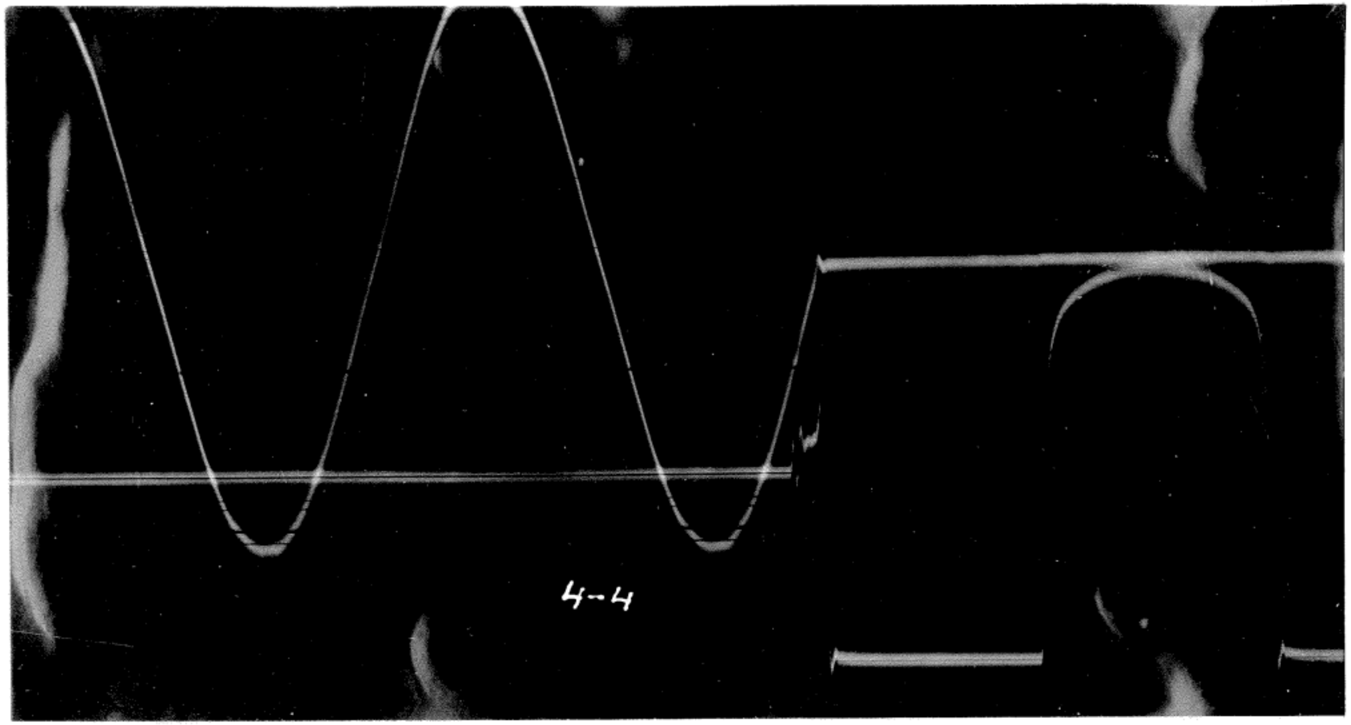
Re-strike Voltage



Source: Thesis paper by James Hugh Hamilton
California Institute of Technology 1928

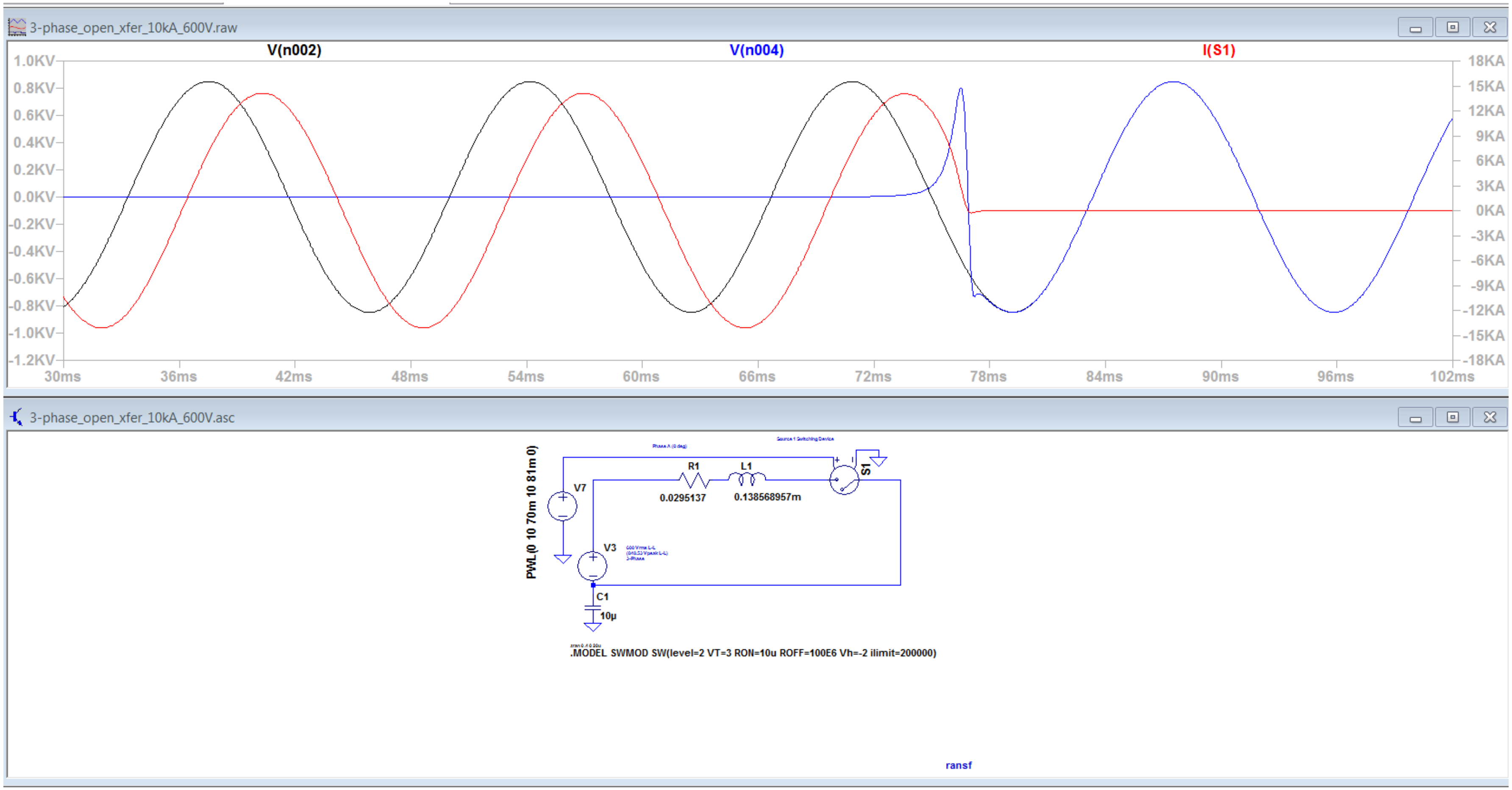
Re-strike Voltage

	Vacuum Switch	Oil Switch
I_{rms}	58.1 amp.	56 amp.
E_{line}	16.2 Kv.	16.2 Kv.
Time	0.008 sec.	0.05 sec.
Energy	7.2	552

$$\text{Ratio of energies} = \frac{552}{7.2} = 77 \text{ to } 1$$

Source: Thesis paper by James Hugh Hamilton
California Institute of Technology 1928

Re-strike Voltage

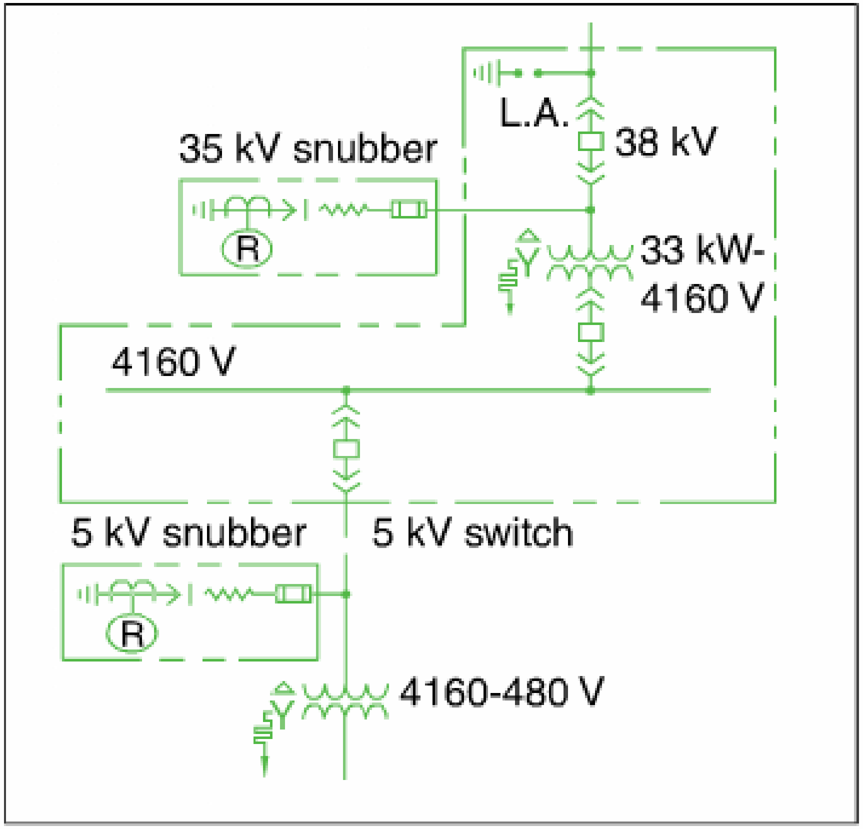


Source: *3-Pole and 4-Pole Transfer Switch Switching Characteristics, Eaton.com*

Snubber Circuit

- Snubber Circuits can absorb harmful waveforms
- Combined with a surge Arrester, snubber circuits can prevent transformers, Circuit Breakers, and PTs from exceeding their dV/dT and BIL limits

Snubber Circuit



Snubber Circuit

Source: http://www.electricenergyonline.com/

Snubber Circuit

$Vp := \frac{13800}{\sqrt{3}}\cdot\sqrt{2} = 1.127\times10^{4}$ $\quad \omega := 377 \quad Iload := 4000 \quad \theta := 4\cdot\frac{\pi}{12} \quad \theta = 1.047 \quad PFd := \theta\cdot\frac{180°}{\pi} = 1.047$

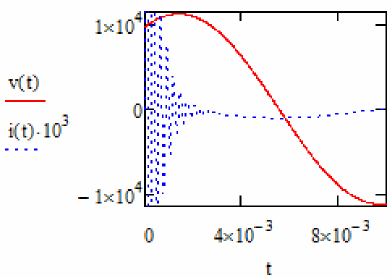
$Z := \frac{Vp\cdot\sqrt{3}}{\sqrt{2}\cdot Iload} = 3.45 \quad Rload := Z\cdot\cos(\theta) \quad Rload = 1.725 \quad PF := \cos(PFd) = 0.5 \quad X := Z\cdot\sin(\theta)$

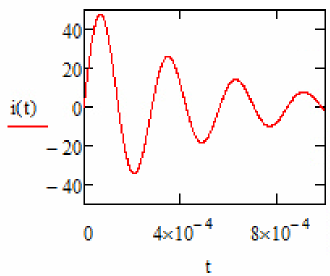
$C := .25\cdot10^{-6} \quad L := \frac{X}{\omega} \quad L = 7.925\times10^{-3} \quad v(t) := Vp\cdot\sin(\omega\cdot t+\theta) \quad Rs := 33 \quad R := Rload + Rs$

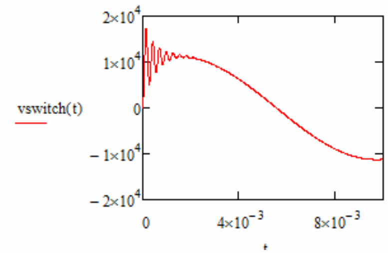
$V(s) := v(t) \text{ laplace}, t \rightarrow \frac{1.127\times10^{4}\cdot(0.866\cdot s + 188.5)}{s^{2} + 1.421\times10^{5}}$

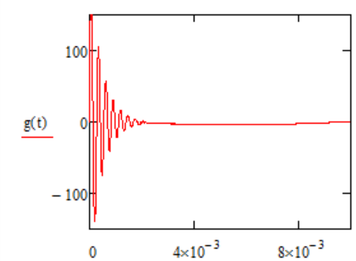
$I(s) := \frac{V(s)\cdot\frac{s}{L}}{s^{2} + \frac{R}{L}\cdot s + \frac{1}{L\cdot C}} \qquad \sqrt{\frac{1}{L\cdot C} - \left(\frac{R}{2\cdot L}\right)^{2}} = 2.236\times10^{4}$

$i(t) := I(s) \text{ invlaplace}, s \rightarrow 0.534\cdot\cos(377\cdot t) - 0.918\cdot\sin(377\cdot t) - 0.534\cdot\cos(2.236\times10^{4}\cdot t)\cdot e^{-2.191\times10^{3}\cdot t} + 55.032\cdot\sin(2.236\times10^{4}\cdot t)\cdot e^{-2.191\times10^{3}\cdot t}$







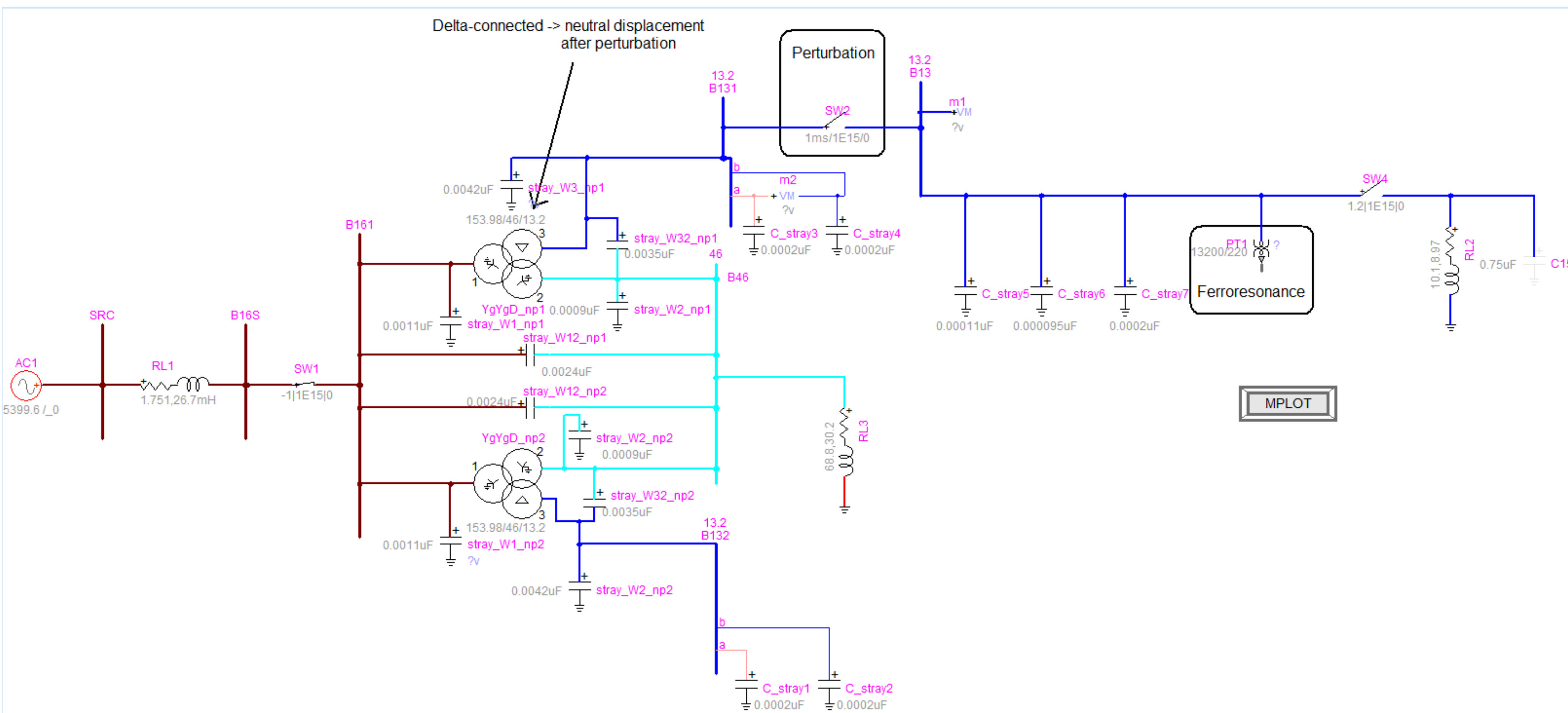


$Vswitch(s) := I(s)\cdot\left(Rs + \frac{1}{C\cdot s}\right)$

$vswitch(t) := Vswitch(s) \text{ invlaplace}, s \rightarrow 9.76\times10^{3}\cdot\cos(377\cdot t) + 5.637\times10^{3}\cdot\sin(377\cdot t) - 9.76\times10^{3}\cdot\cos(2.236\times10^{4}\cdot t)\cdot e^{-2.191\times10^{3}\cdot t} + 765.911\cdot\sin(2.236\times10^{4}\cdot t)\cdot e^{-2.191\times10^{3}\cdot t}$

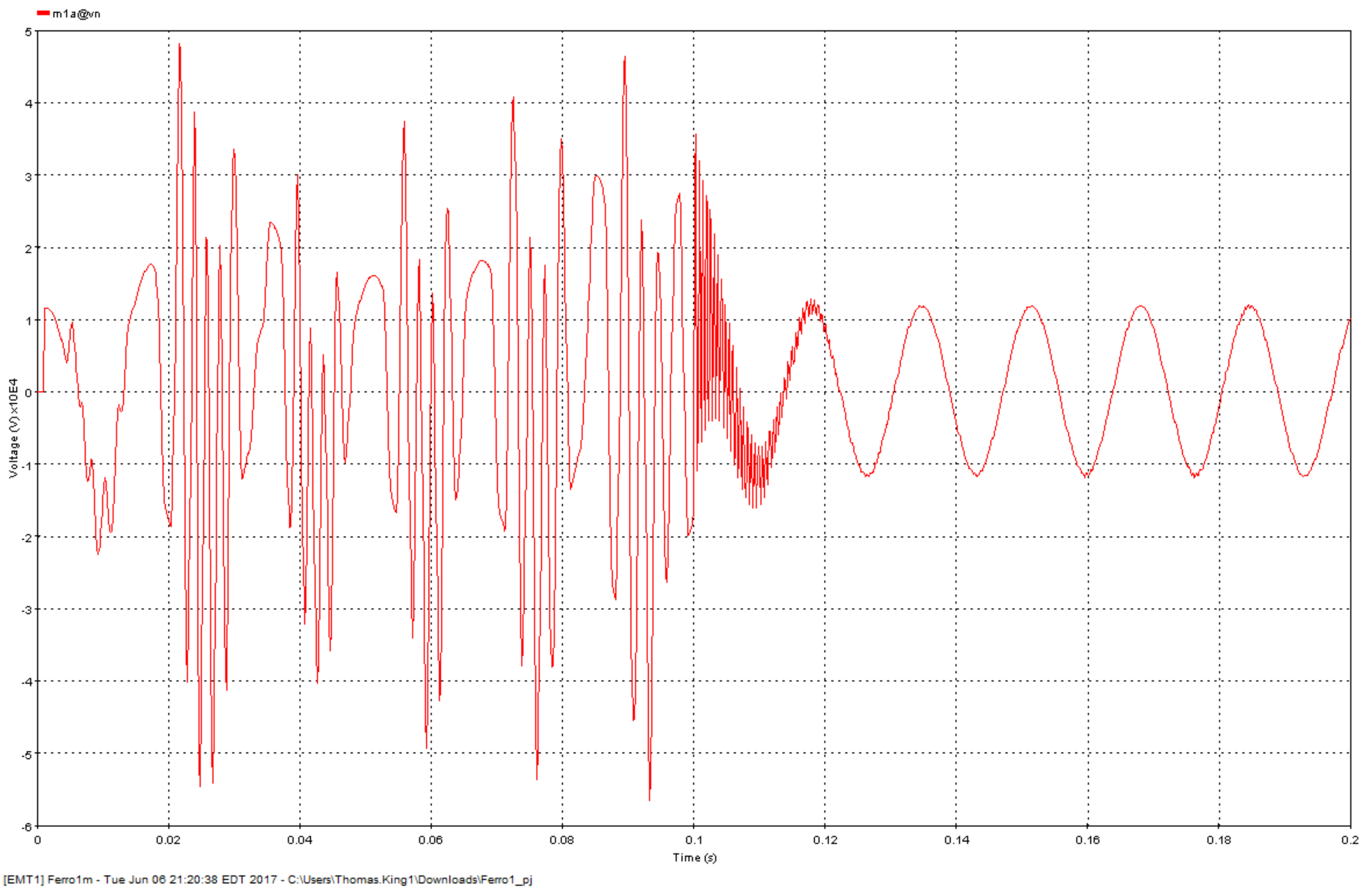
Source: www.clevenstineengineering.com

Snubber Circuit



Source: Henry GRAS, powersys-solutions.com

Snubber Circuit



Source: Henry GRAS, powersys-solutions.com

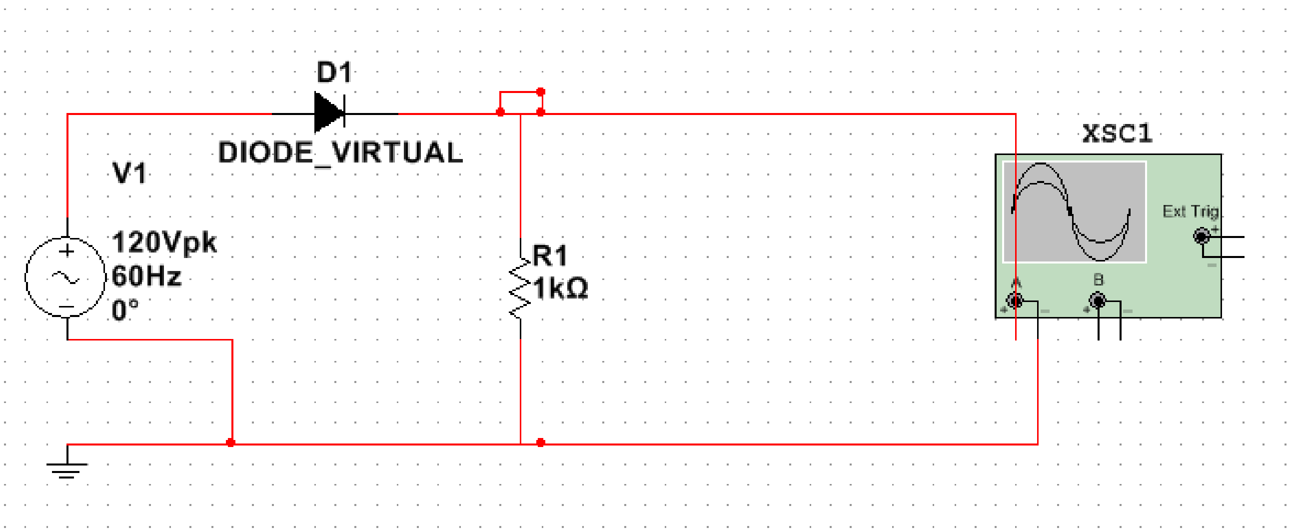
Switch-Mode Power Supplies

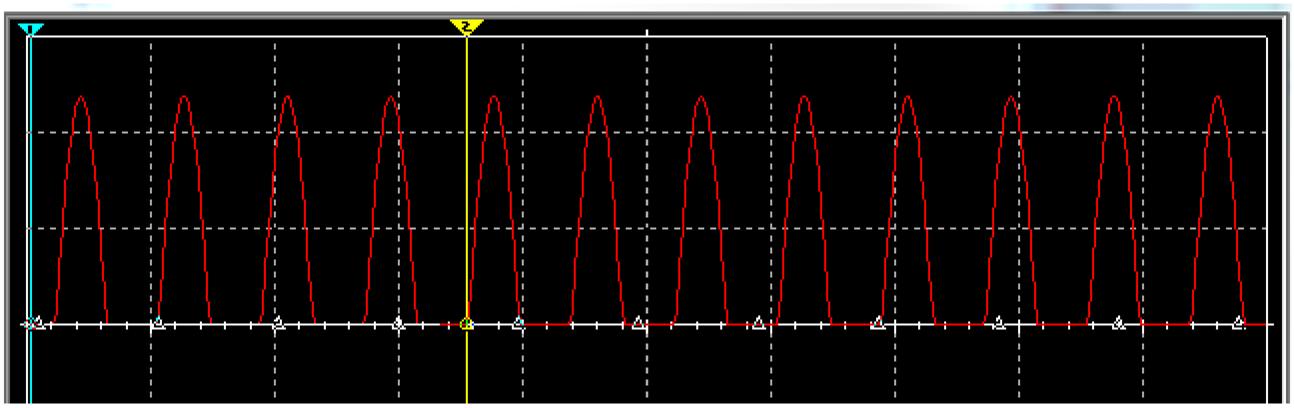
Source: Marco Bieri, Energy Management Specialist

Switch-Mode Power Supplies

- Switch-Mode Power Supplies include:
  - Half Wave Rectifiers
  - Full Wave Rectifiers (3, 6, and 12 pulse)
  - Variable Frequency Drives
  - Pulse-Width Modulation Inverters

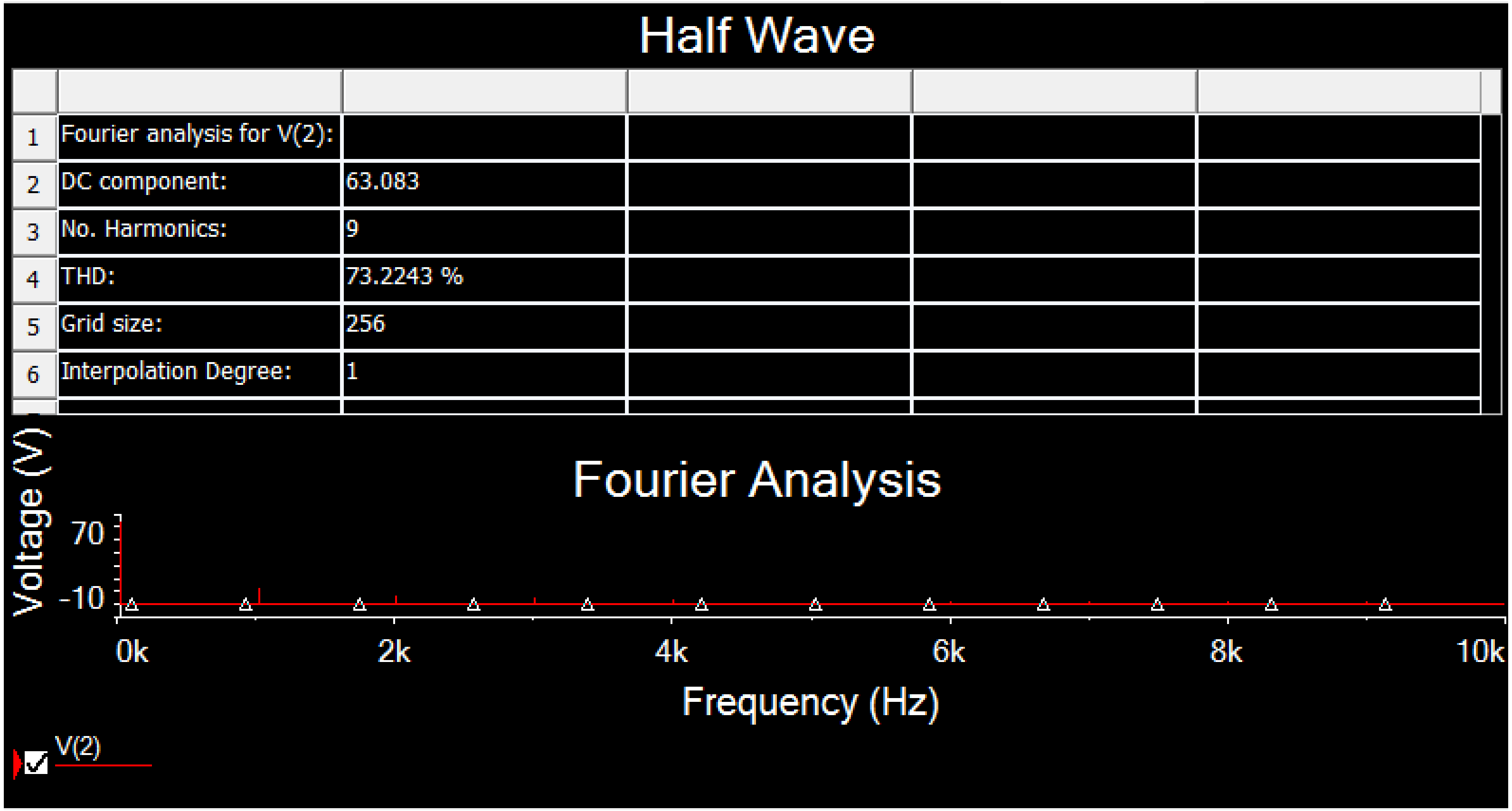
Half Wave Rectifier





Source: https://www.allaboutcircuits.com

Half Wave Rectifier

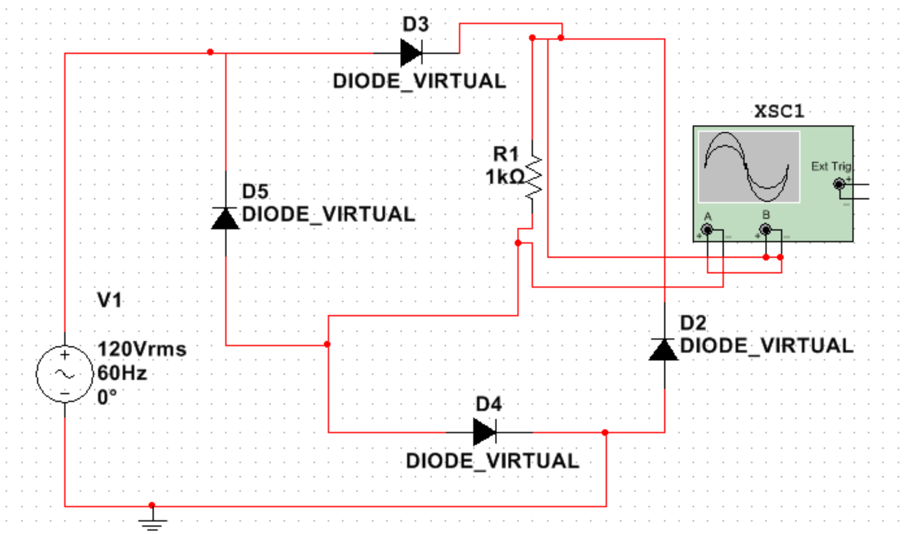


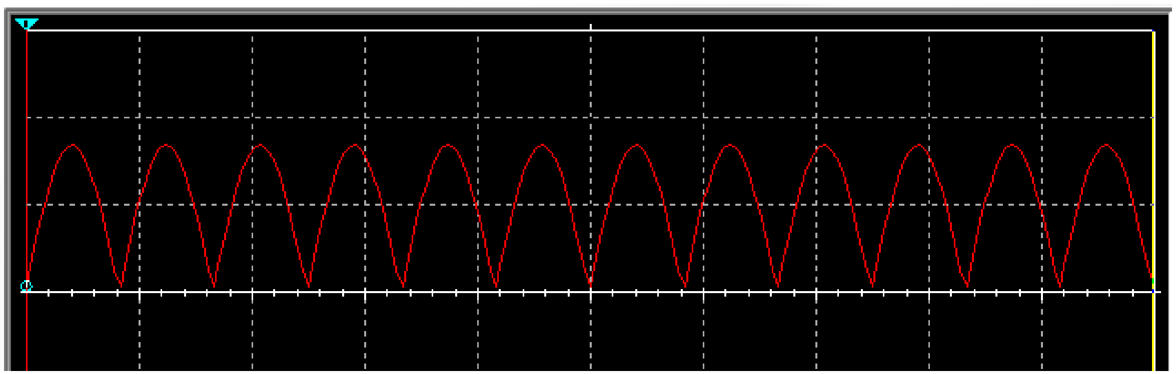
Half Wave

1	Fourier analysis for V(2):					
2	DC component:	63.083				
3	No. Harmonics:	9				
4	THD:	73.2243 %				
5	Grid size:	256				
6	Interpolation Degree:	1				

Source: https://www.allaboutcircuits.com

Full Wave Rectifier



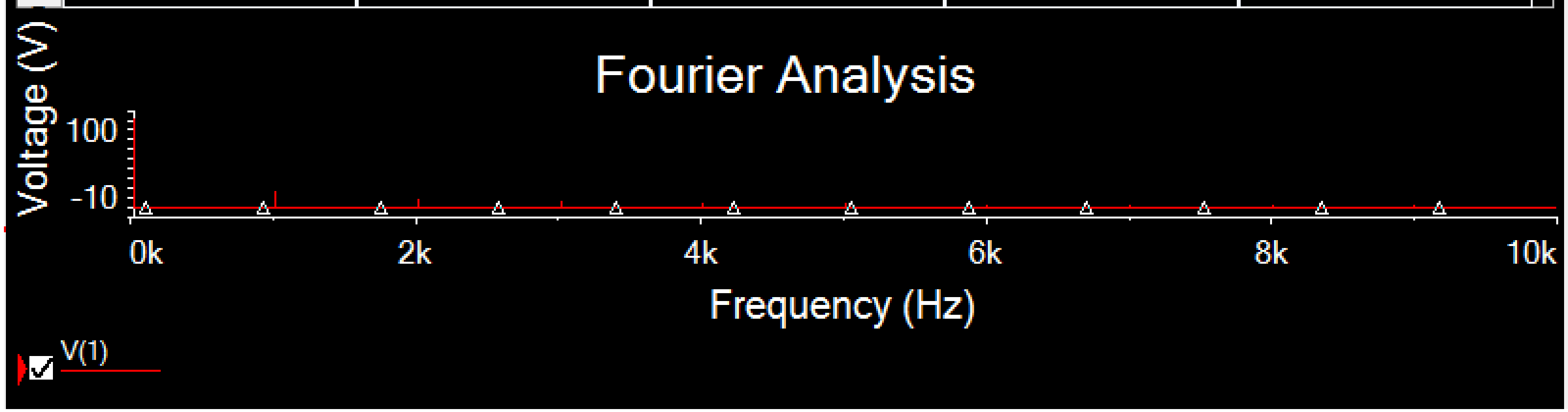


Source: https://www.allaboutcircuits.com

Full Wave Rectifier

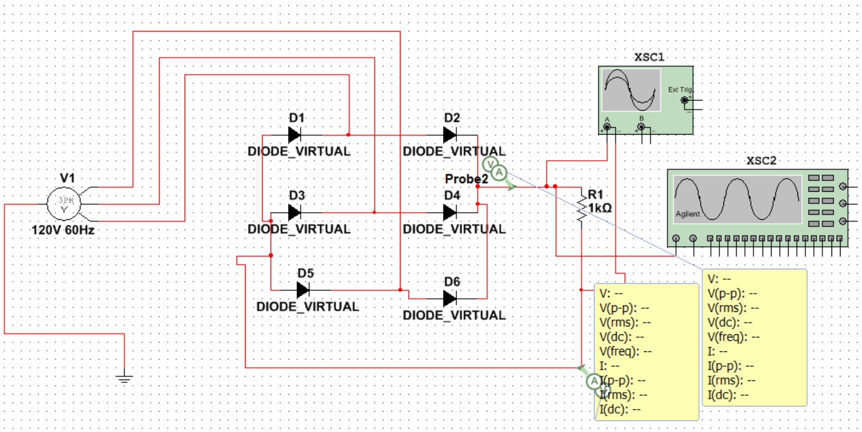
Full Wave

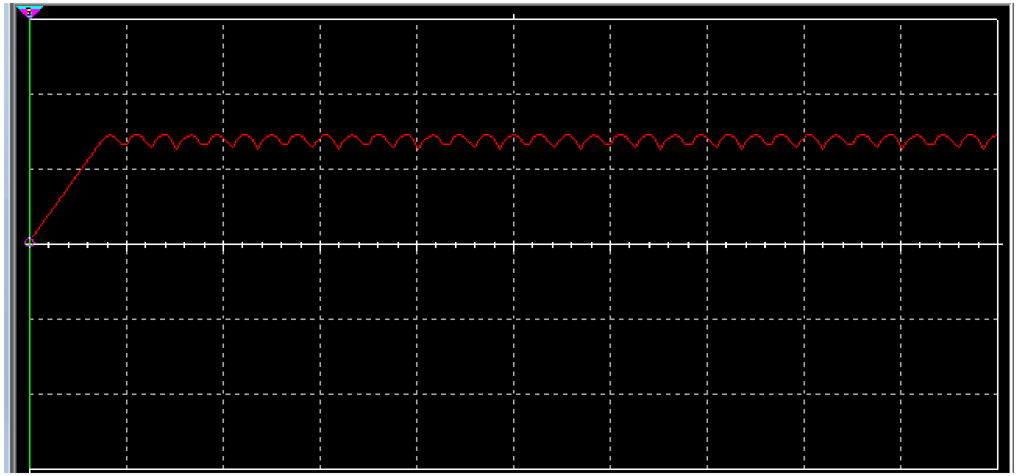
1	Fourier analysis for V(1):				
2	DC component:	90.2903			
3	No. Harmonics:	9			
4	THD:	73.225 %			
5	Grid size:	256			
6	Interpolation Degree:	1			



Source: https://www.allaboutcircuits.com

Full Wave 6-Pulse Rectifier



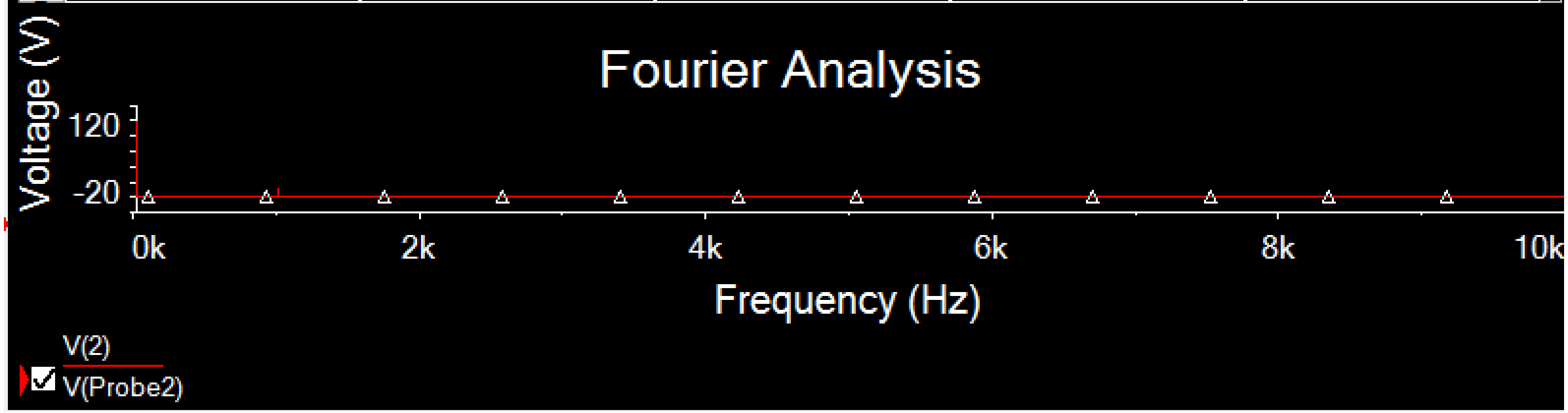


Source: https://www.allaboutcircuits.com

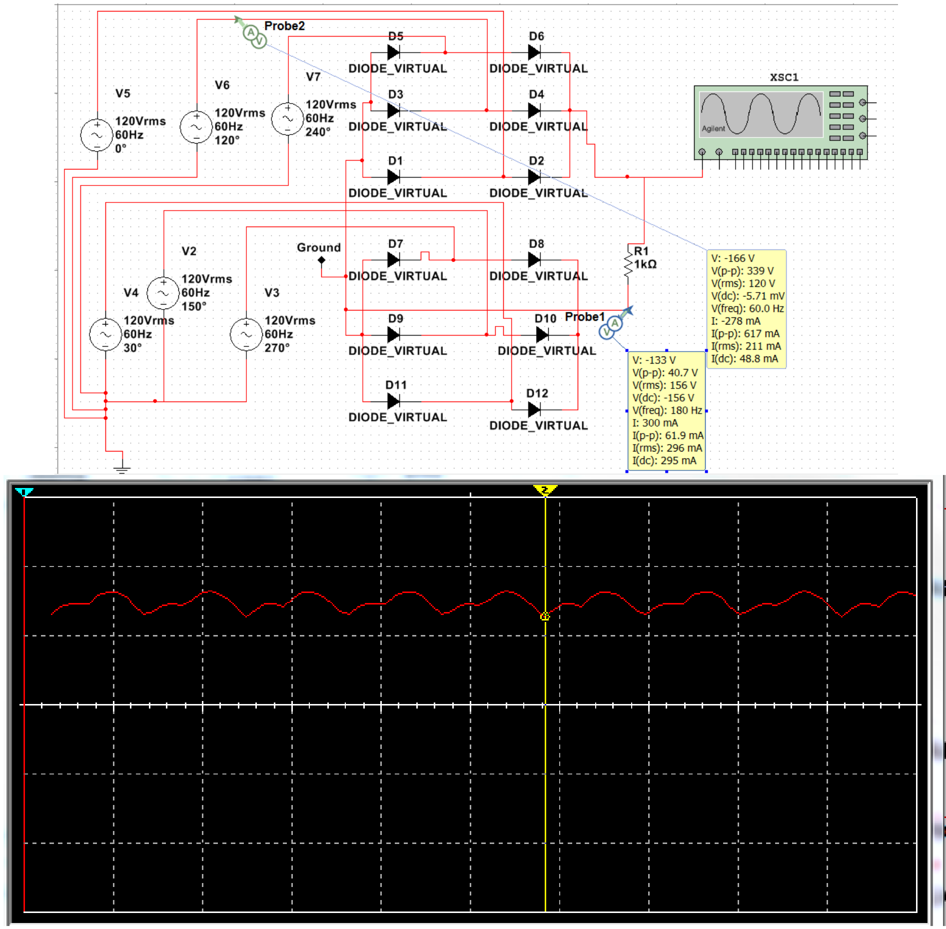
Full Wave 6 Pulse Rectifier

Full Wave 6 Pulse

1	Fourier analysis for V(Pro				
2	DC component:	97.9475			
3	No. Harmonics:	9			
4	THD:	21.4515 %			
5	Grid size:	256			
6	Interpolation Degree:	1			

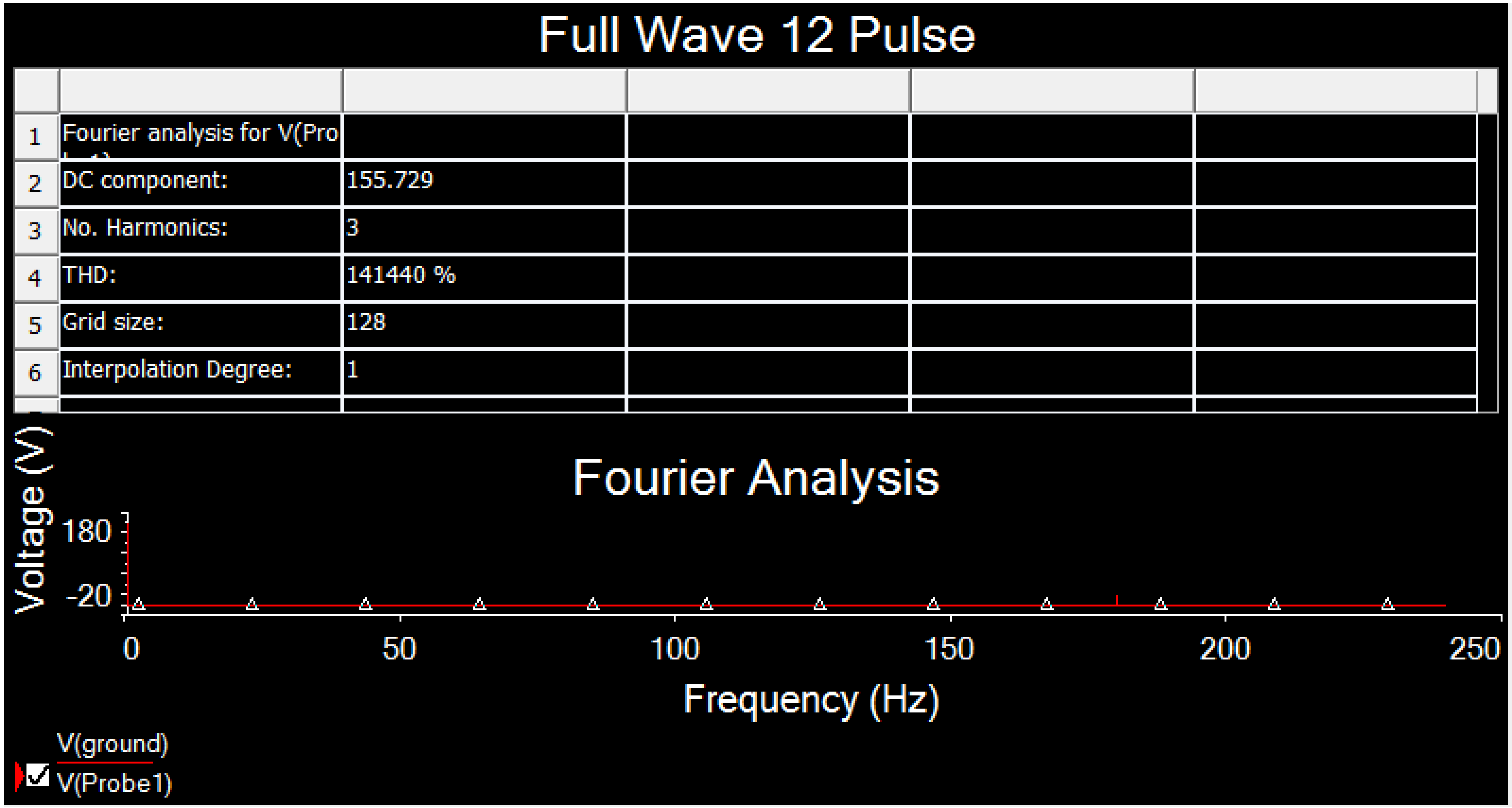


Full Wave 12 Pulse Rectifier



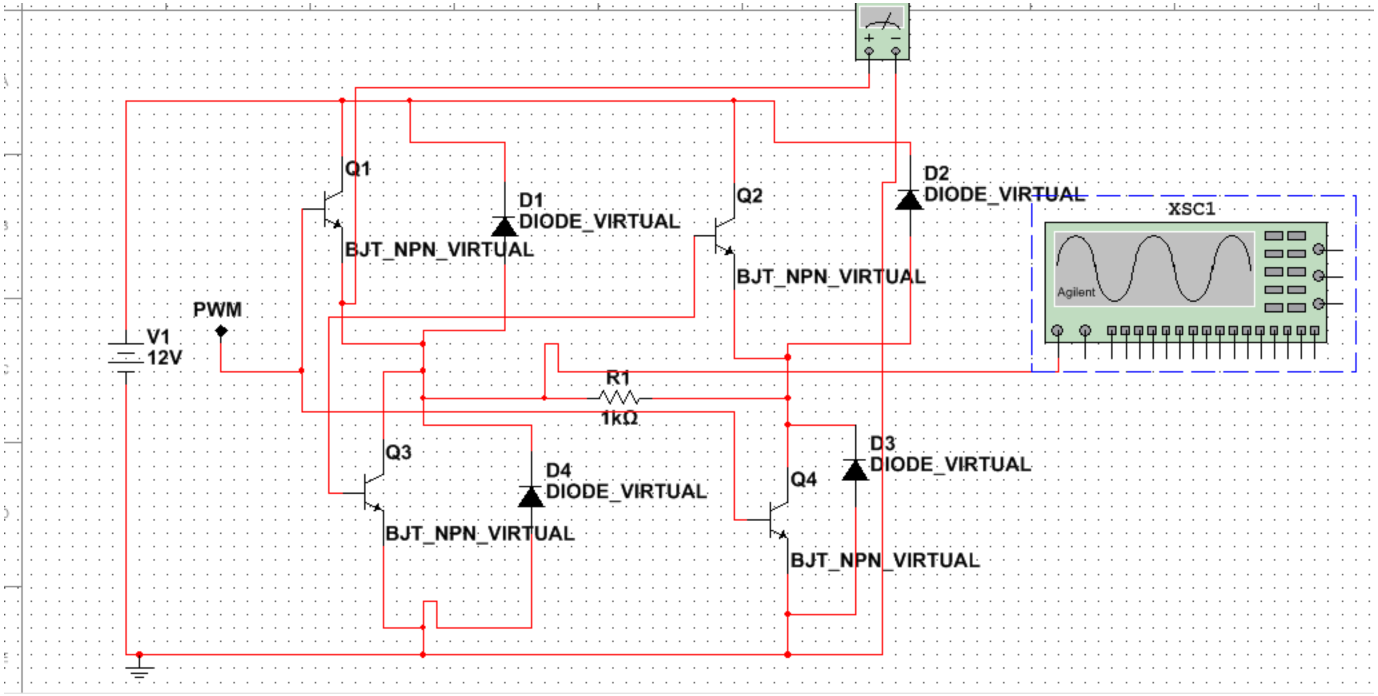
Source: https://www.allaboutcircuits.com

Full Wave 12 Pulse Rectifier



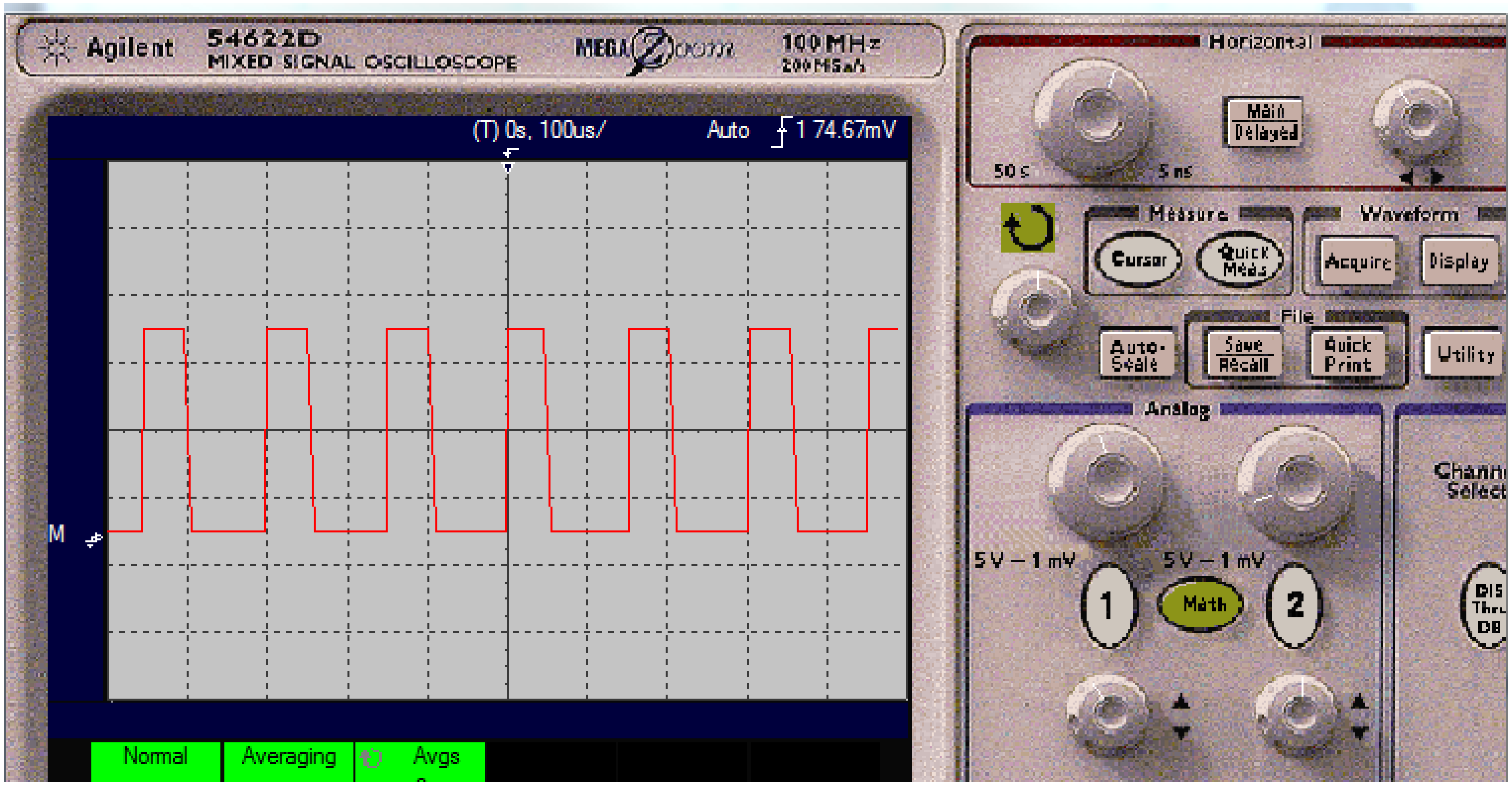
Source: https://www.allaboutcircuits.com

Pulse Width Modulation Inverter



Source: https://www.allaboutcircuits.com

Pulse Width Modulation Inverter

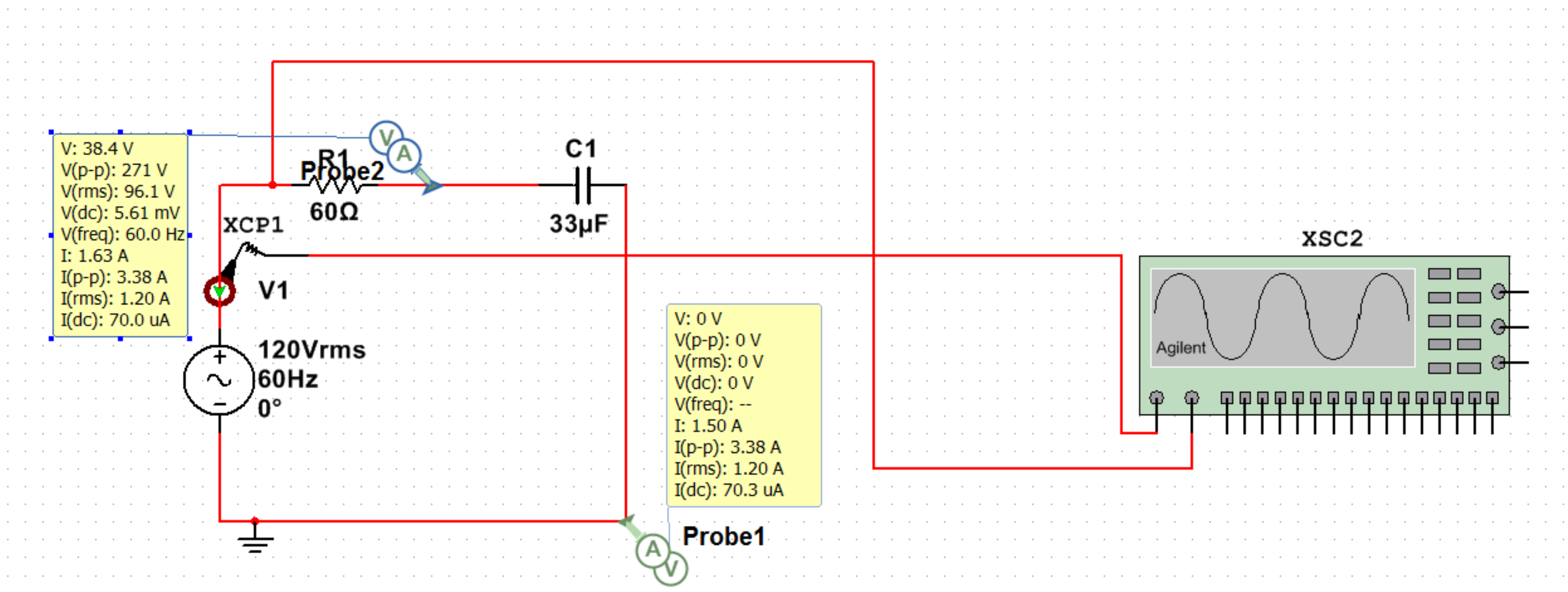


Source: https://www.allaboutcircuits.com

Power Factor

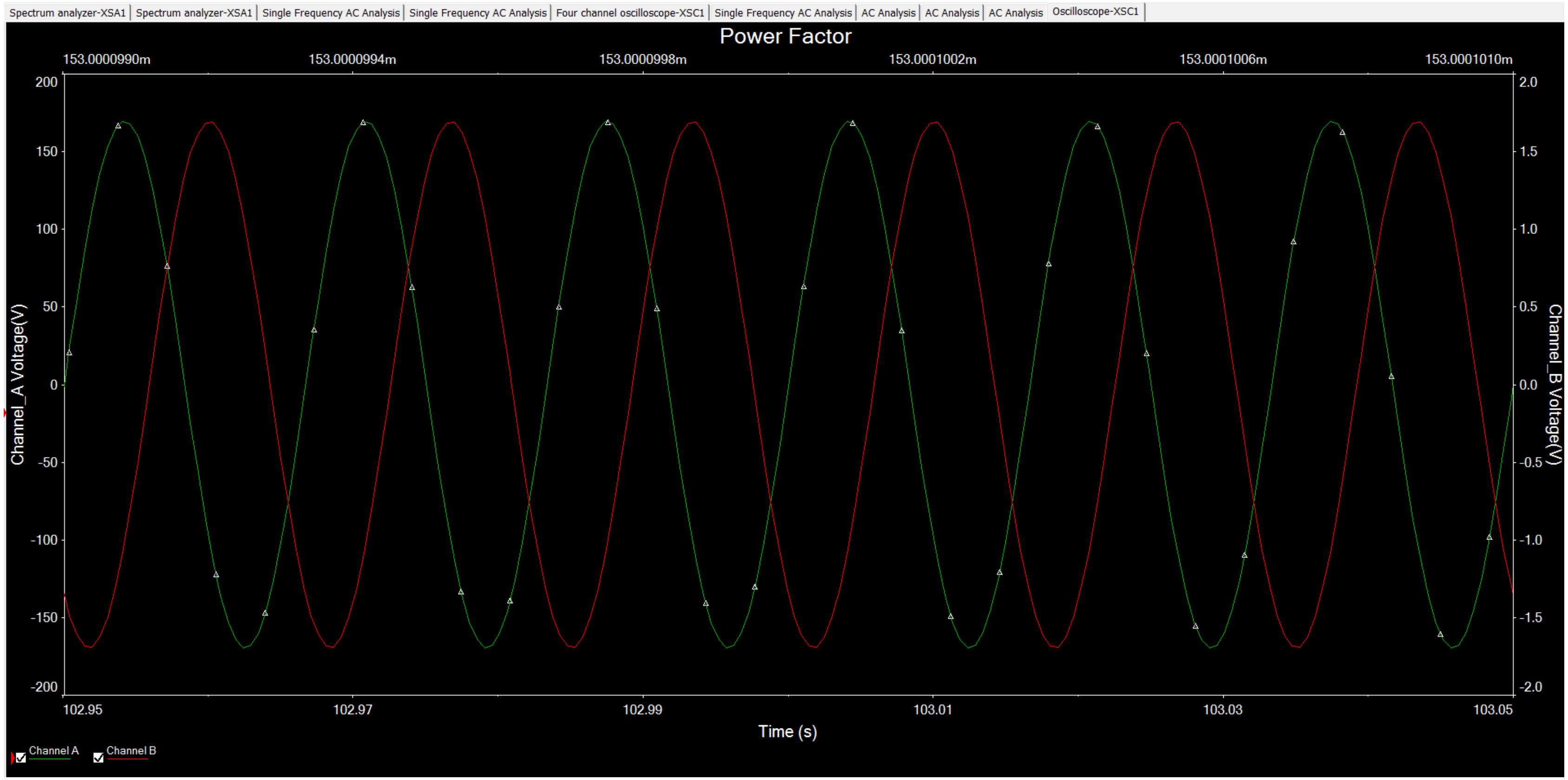
- Power factor is defined as the cosine of the phase angle between the current and voltage waveforms
- Many generators will reject a load with a leading power factor

Power Factor



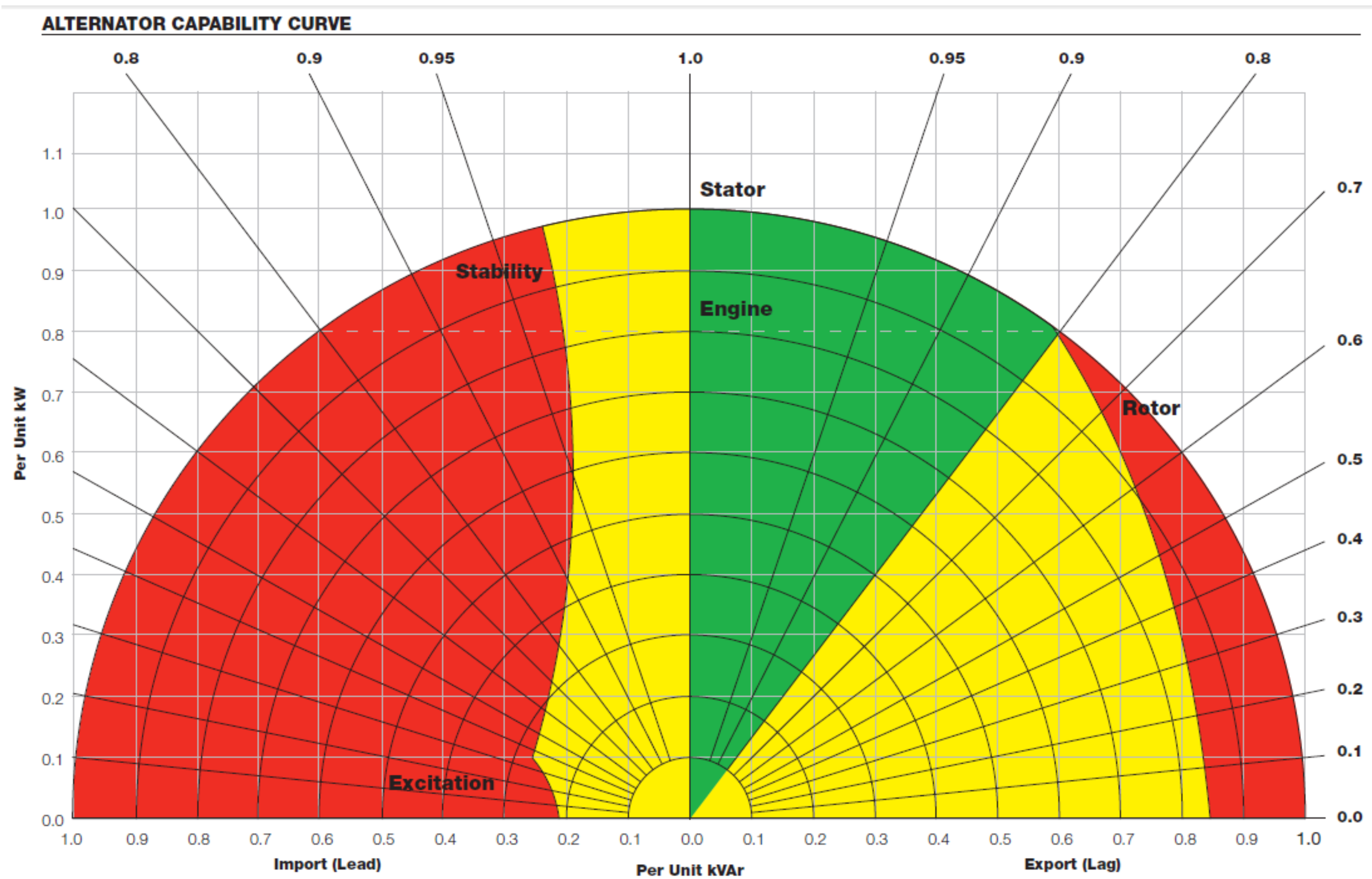
Source: https://www.allaboutcircuits.com

Power Factor



Source: https://www.allaboutcircuits.com

Power Factor

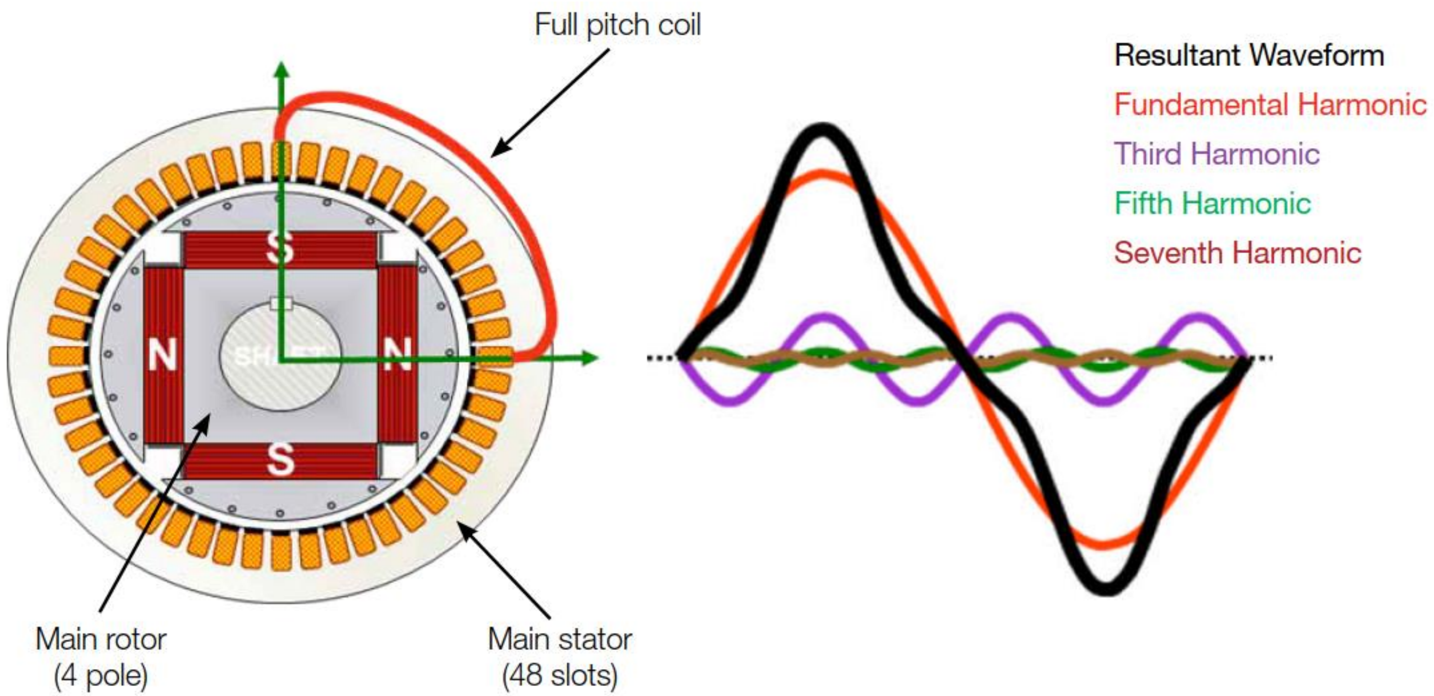


Source: https://www.allaboutcircuits.com

Pitch

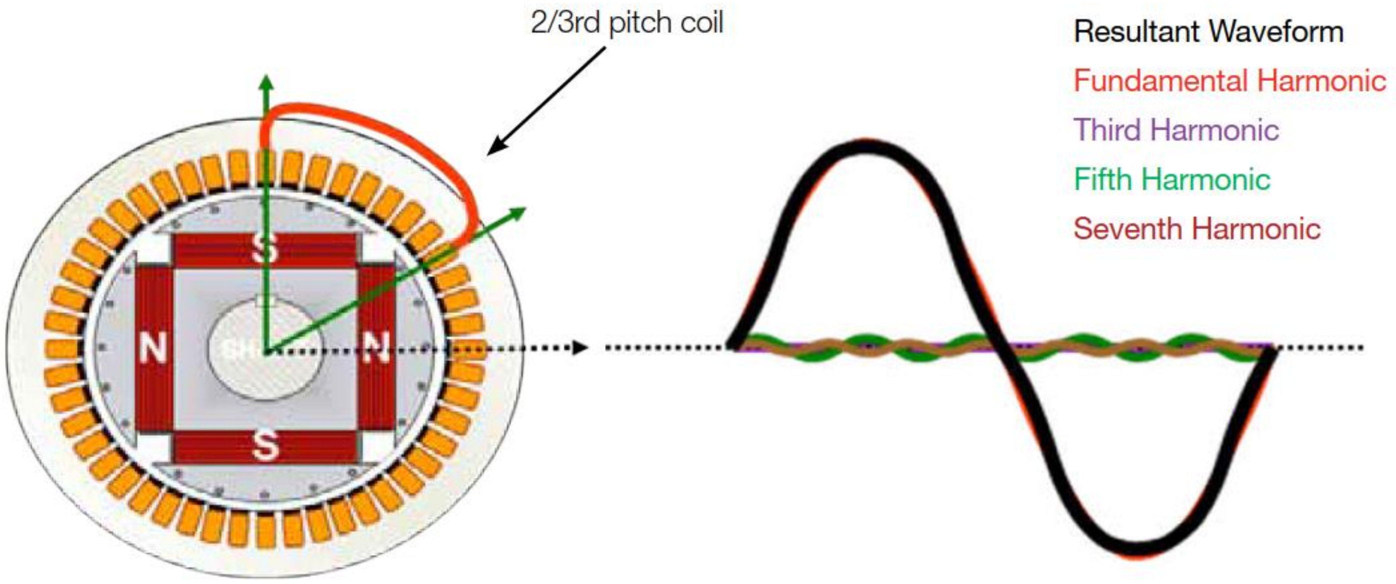
- Alternators do not generate perfect sine waves
- In order to eliminate or reduce specific harmonics, alternators are wound to a specific pitch
- If dissimilarly wound alternators are paralleled, there will be a flow of harmonic currents through the neutral conductor
- To eliminate a harmonic, divide 360 by the harmonic frequence that you want to eliminate, and then divide that by 180. The result is the desired pitch

Pitch



Source: Cummins Generator Technologies

Pitch



Source: Cummins Generator Technologies

Pitch

$$\frac{360}{3} = 120 \qquad \frac{120}{180} = \frac{2}{3}$$

$$\frac{360}{5} = 72 \qquad \frac{72 \cdot 2}{180} = \frac{4}{5}$$

$$\frac{360}{7} = 51 \qquad \frac{51 \cdot 2}{180} = \frac{4}{7}$$

Pitch

Pitch in electrical degrees

$\rho_0 := 180\text{deg} \quad \rho_1 := 120\text{deg} \quad \rho_2 := 144\text{deg}$

$$k_{p1} := \cos\left[N_1 \cdot 180\text{deg} \cdot \frac{\left(N_1 - \frac{2}{3}\right)}{2}\right] = 0.866$$

$$k_{p1} := \sin\left(\frac{N_1 \cdot \rho_1}{2}\right) = 0.866$$

$$k_{p3} := \sin\left(\frac{N_3 \cdot \rho_1}{2}\right) = 0$$

$$k_{p5} := \sin\left(\frac{N_5 \cdot \rho_1}{2}\right) = -0.866$$

$$k_{p9} := \sin\left(\frac{N_9 \cdot \rho_1}{2}\right) = 0$$

$$k_{p7} := \sin\left(\frac{N_7 \cdot \rho_1}{2}\right) = 0.866$$

Pitch

Pitch in electrical degrees

$\rho_0 := 180\text{deg}$ $\rho_1 := 120\text{deg}$ $\rho_2 := 144\text{deg}$

$$k_{p1} := \cos\left[N_1 \cdot 180\text{deg} \cdot \frac{\left(N_1 - \frac{2}{3}\right)}{2}\right] = 0.866$$

$$k_{p1} := \sin\left(\frac{N_1 \cdot \rho_2}{2}\right) = 0.951$$

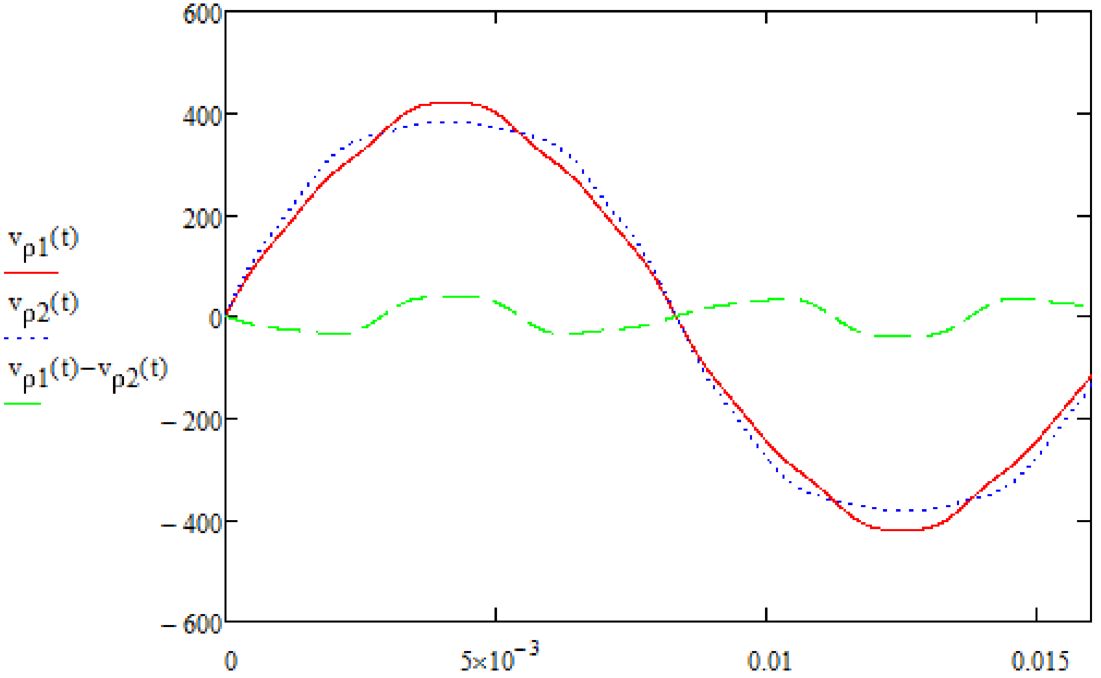
$$k_{p3} := \sin\left(\frac{N_3 \cdot \rho_2}{2}\right) = -0.588$$

$$k_{p5} := \sin\left(\frac{N_5 \cdot \rho_2}{2}\right) = 0$$

$$k_{p9} := \sin\left(\frac{N_9 \cdot \rho_2}{2}\right) = -0.951$$

$$k_{p7} := \sin\left(\frac{N_7 \cdot \rho_2}{2}\right) = 0.588$$

Pitch

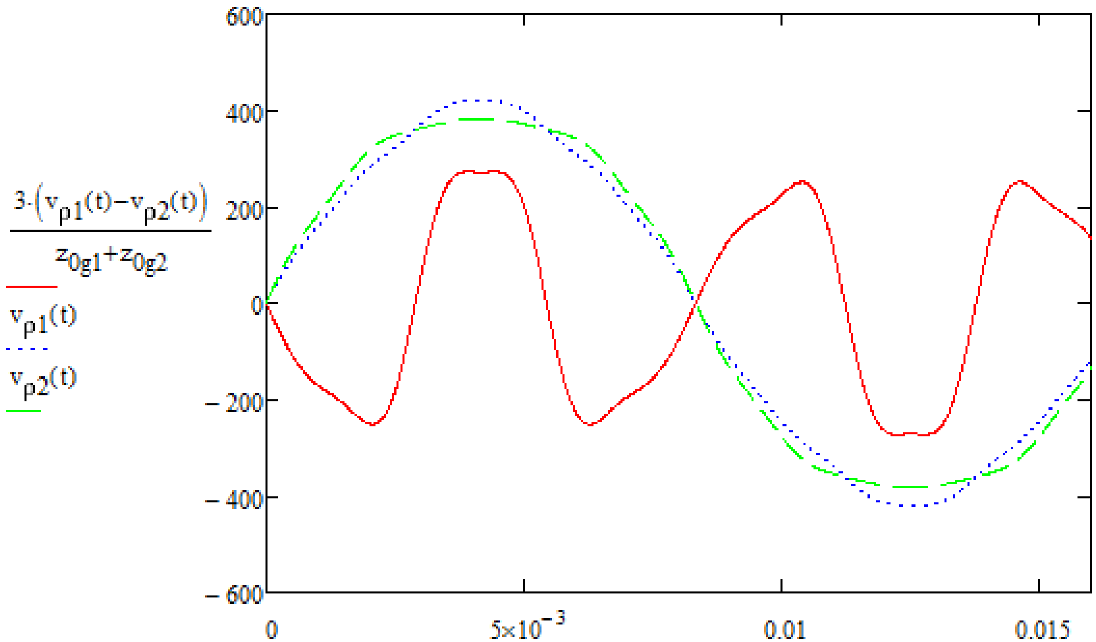


2/3 Pitch

$$v_{\rho 1}(t) := \left(k_{p1} \cdot Vp \cdot \sin\left(\omega \cdot N_1 \cdot t + \theta\right)\right) + \left(.0009 \cdot Vp \cdot \sin\left(\omega \cdot N_3 \cdot t + \theta\right)\right) \ldots$$
$$+ \left(.0211 \cdot Vp \cdot \sin\left(\omega \cdot N_5 \cdot t + \theta\right)\right) + \left(.0035 \cdot Vp \cdot \sin\left(\omega \cdot N_7 \cdot t + \theta\right)\right) \ldots$$
$$+ .0010 \cdot Vp \cdot \sin\left(\omega \cdot N_9 \cdot t + \theta\right) + \left(.0094 \cdot Vp \cdot \sin\left(\omega \cdot N_{11} \cdot t + \theta\right)\right)$$

Pitch

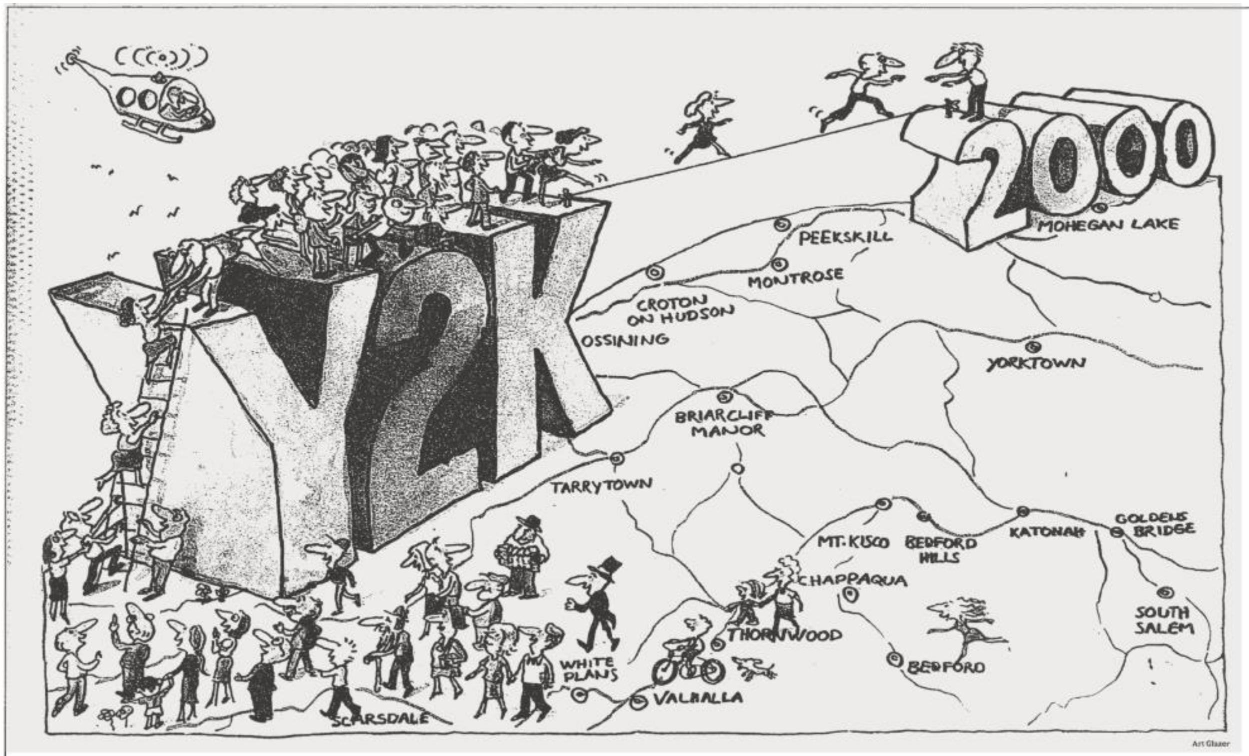
$z_{pu} := \frac{21.7}{100} = 0.217 \qquad z_{0g1} := .21 \qquad z_{0g2} := .21$



5/6 Pitch

$$v_{\rho 2}(t) := \left(k_{p1}\cdot Vp\cdot \sin(\omega\cdot N_1\cdot t+\theta)\right) + \left(.0766\cdot Vp\cdot \sin(\omega\cdot N_3\cdot t+\theta)\right) \ldots$$
$$+ \left(.0023\cdot Vp\cdot \sin(\omega\cdot N_5\cdot t+\theta)\right) + \left(.0018\cdot Vp\cdot \sin(\omega\cdot N_7\cdot t+\theta)\right) \ldots$$
$$+ .0115\cdot Vp\cdot \sin(\omega\cdot N_9\cdot t+\theta) + \left(.0063\cdot Vp\cdot \sin(\omega\cdot N_{11}\cdot t+\theta)\right)$$

Avoid the Fads



Ready to Battle the Unseen

Thousands of Workers Will Be at Their Stations or on Call if Computers Fail