University of Idaho
College of Engineering

ECE 528 – Understanding Power Quality

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

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Lecture 5

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Today…

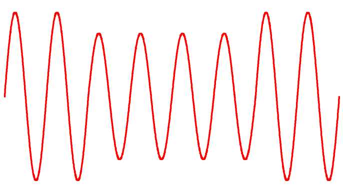
- Voltage sags, short interruptions, and swells
  - Definitions
  - Causes
  - Fault clearing
    - Fuse/trip-saving
    - Time-current curves
  - Motor starting

Voltage Sags, Interruptions, and Swells

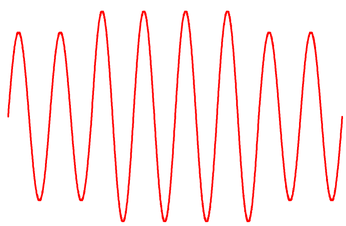
- Definitions: (see table 2.2 in either text)
  - Magnitude (of nominal voltage)
    - Sag: 0.1 pu - 0.9 pu
    - Interruption: < 0.1 pu
    - Swell: >1.1 pu – 1.8 pu
  - Duration
    - Instantaneous: 0.5 cycles - 30 cycles
    - Momentary: 30 cycles - 3 seconds
    - Temporary: 3 seconds - 1 minute

Note – events >1 minute are "long duration" undervoltage, overvoltage, or interruptions

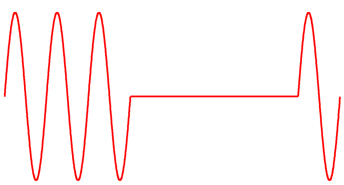
Voltage Sags, short interruptions, and swells



Voltage Sag



Voltage Swell



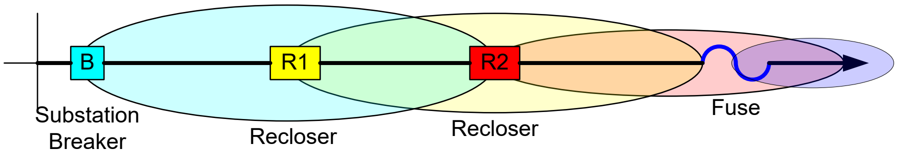
Interruption

Sources of voltage sags:

- From first principles:
  - Current through impedance results in a voltage across the impedance.
  - Excessive current results in excessive voltage drop.
  - Sources of sudden, brief, excessive currents:
    - Faults
    - Motor starting

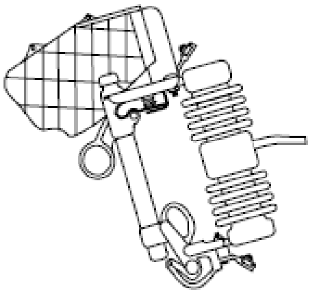
System protection overview

- Typical Objectives
  - Distinguish fault current from load current
  - Minimize number of customers off
  - Minimize interruption duration
- Issues:
  - Fault current varies – system impedance, fault impedance
  - Coordinating multiple devices can be difficult



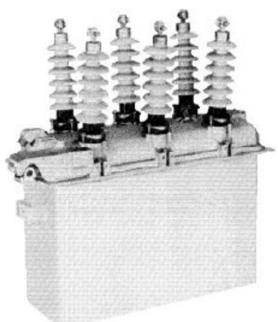
Clearing faults

- Fuses
  - Inexpensive
  - Require manual replacement
  - Help locate faults
  - In general, fuses are used to disconnect, or "sectionalize" portions of the system with permanent faults from the rest of the system.
  - "Current Limiting" fuses can have a PQ benefit.



Clearing faults

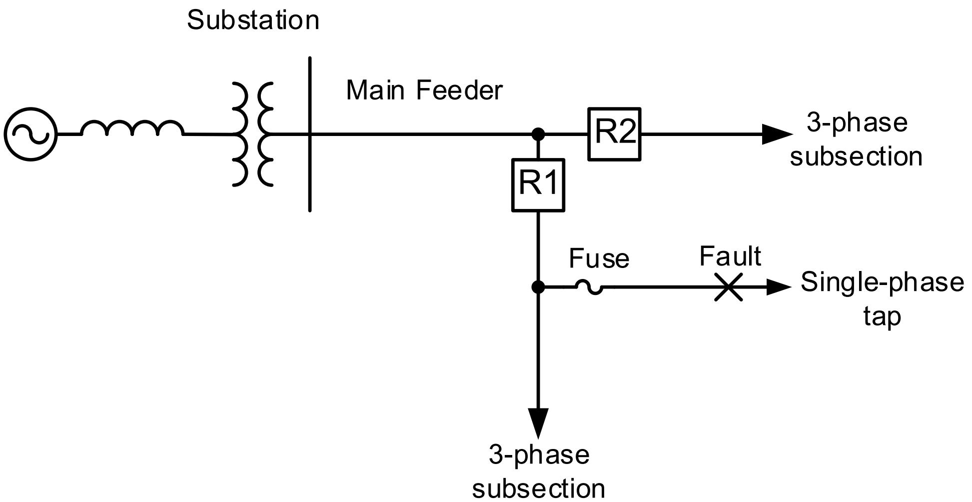
- Reclosers
  - Automatic circuit breakers
  - Used where faults may be temporary
  - Can be programmed to respond differently to different faults.
  - Can "test" the downstream system to see if a fault is cleared.
  - Generally used to protect larger parts of the system.
  - May protect past downstream fuses.



Clearing faults

- Reclosers and fuses can work together
  - Fuse saving
    - Recloser trips very quickly to clear a temporary fault before a fuse has time to operate.
    - If the fault is still present when the recloser closes, the recloser trips more slowly to allow a downstream fuse to operate.
  - Example…

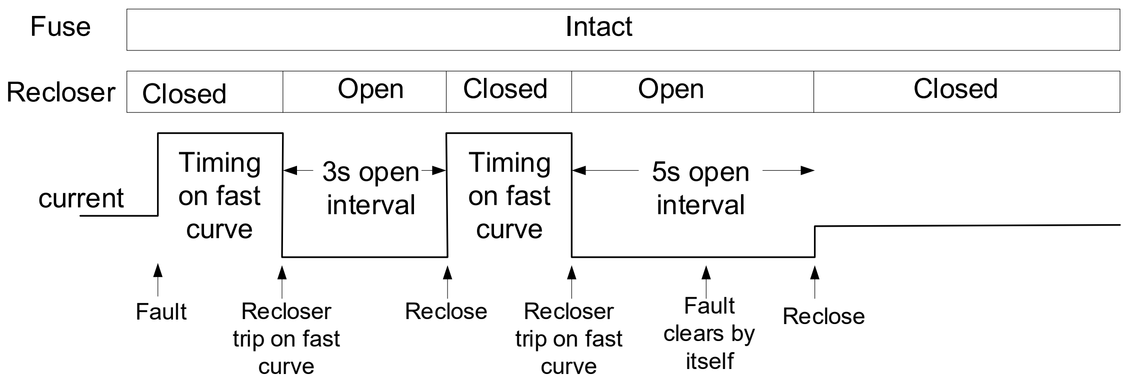
Clearing faults with and without fuse saving



Distribution voltage sag and interruption

- Fault occurs
  - Voltage sags. Fuses, circuit breakers, and reclosers, start to heat up or time-out.
  - Response time is predictable based on Time-Current-Characteristic (TCC) curves.
- Fault is cleared
  - Fuse, circuit breaker, or recloser opens. Voltage returns to normal (usually) for upstream loads.
  - Voltage swells or overvoltages are possible with significant load shedding while system adjusts
    - Regulators and transformers may change taps or steps. Capacitors may switch off.
  - Voltage drops to zero for downstream loads.
- Circuit breakers/reclosers may reclose

Recloser with fuse saving – Temporary fault



Recloser with fuse saving – Permanent fault

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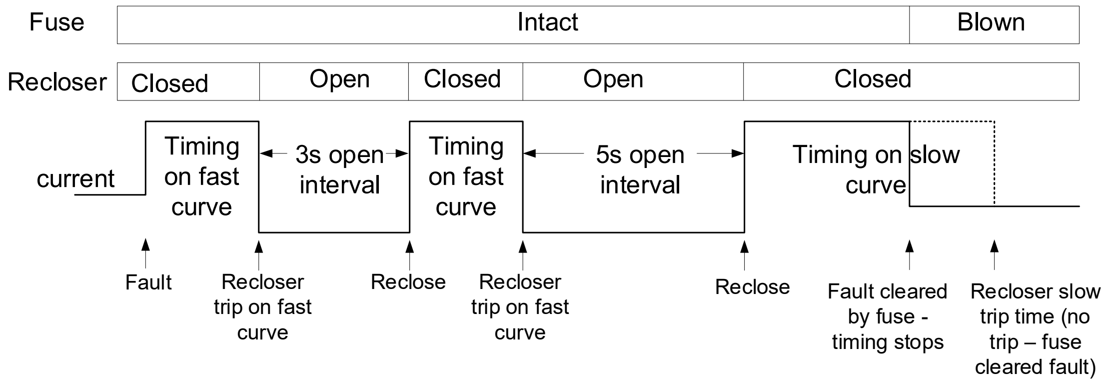

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Recloser operation

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Log of recloser operations during a temporary fault.

Can you tell where the recloser tested to see if the fault was cleared? Was it? What did customers see during the test?

Call Type	*Date*	*Time*	*Duration*
ON	8/24/2006	13:34:34.961	CONTINUING
OFF	8/24/2006	13:34:25.039	09.935
ON	8/24/2006	13:34:24.707	00.316
OFF	8/24/2006	13:34:19.457	05.266

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Fuse saving tradeoffs

- What are the advantages of using fuse saving?
- What are the disadvantages?

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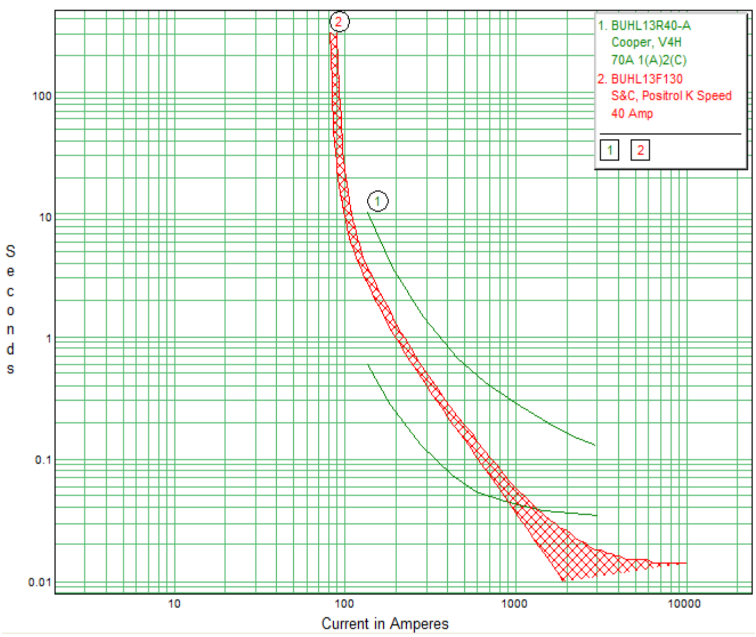

Time- current curves

Find the current at the bottom, then go up to find the response time for various devices.

Note log-log scales.

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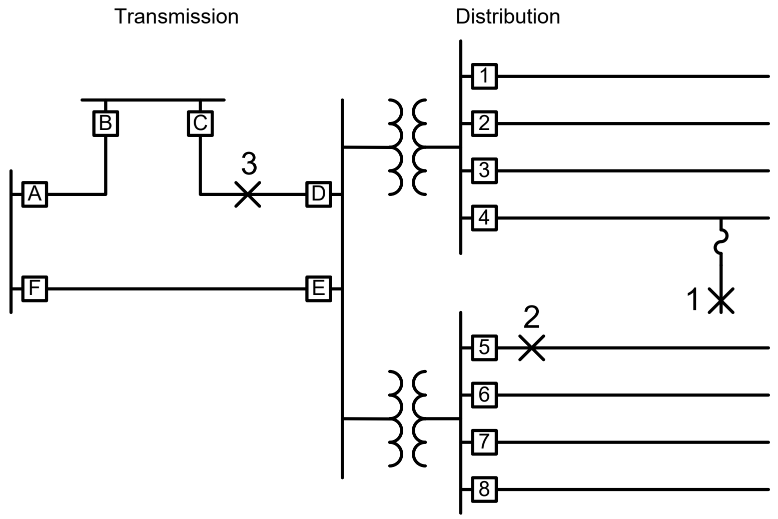
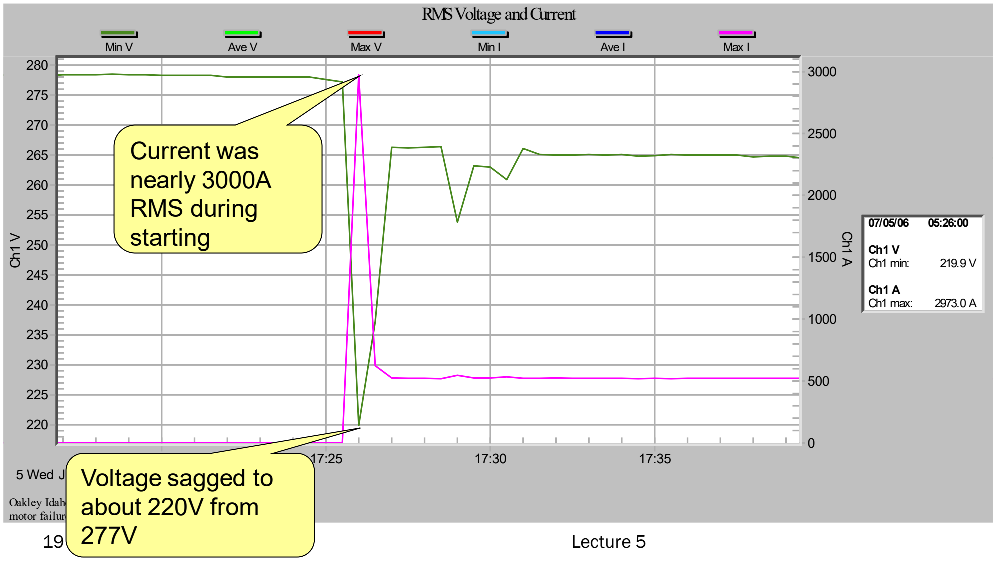
Voltage Sag Impacts – location matters



Motor starting

- Motors may start and stop frequently or only occasionally.
- Common cause of voltage sags in industrial facilities – the facility's own large motors may cause voltage sags.
- Power systems are typically designed for the peak steady-state load or "demand", not the motor-starting demand.

Motors – starting 500Hp



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Motor Starting

- "Across the line" or full voltage starting
  - Typically 6 to 8 times normal running current
  - Inexpensive
  - Fast acceleration
  - Results in largest voltage sag or flicker compared to using a "soft starting" system.

See FPQ, pp 113-131 for motor starting examples.

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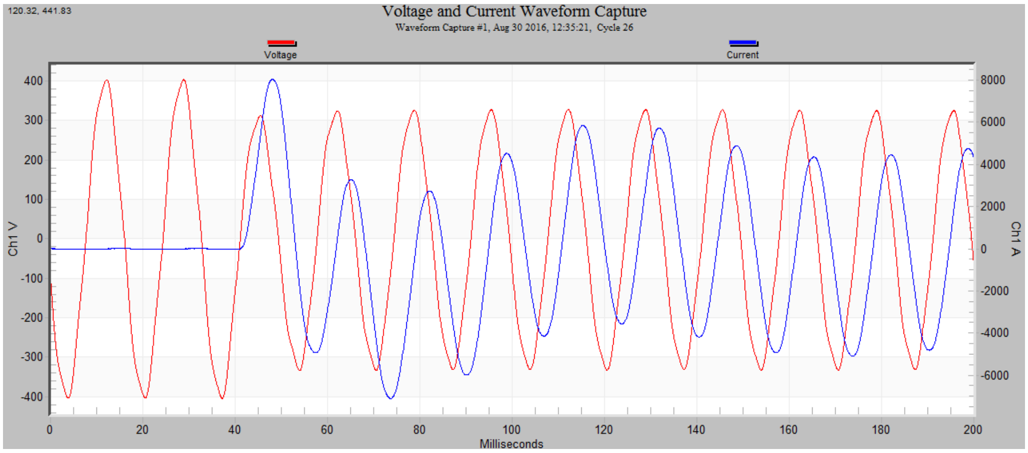
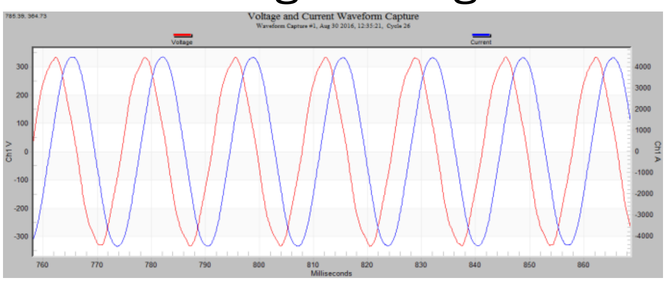
Motor starting – 3 stages

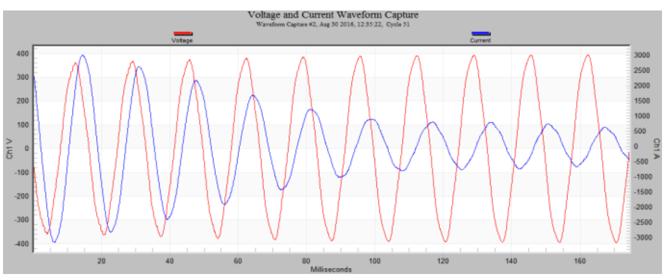


Stage 1 – Transient inrush current – note initial offset and low frequency oscillation

Motor starting – 3 stages



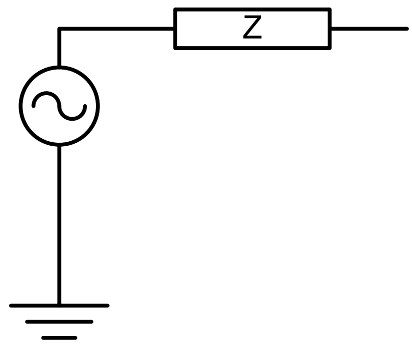
Stage 2 – steady current during acceleration – This is what is usually considered the “starting current”



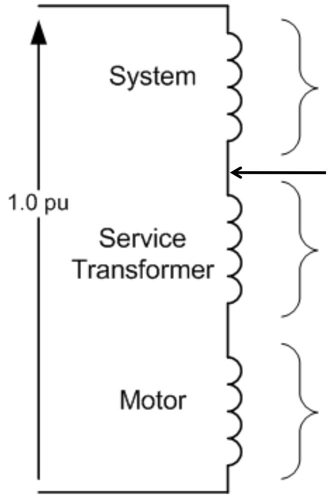
Stage 3 – Current drops and voltage recovers as motor reaches operating speed

Thevenin equivalents

- We can reduce the upstream system to a voltage source in series with an impedance, or maybe a few impedances so we can determine the voltages at different locations.



Motor starting analysis: voltage division



Xs: determines short-circuit MVA at primary side of service transformer

Other customers are connected here

Xt: with Xs, determines short-circuit MVA at the motor terminals

Xm: with Xs and Xt, determines magnitude of voltage sag when motor starts

Reactances and kVA or MVA

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- Can solve problem using reactance or the KVAsc or MVAsc values
- Working in per-unit we can convert back and forth between reactances and short-circuit kVA or MVA.

$$\frac{V_{base}^{2}}{Z_{base}} = MVA_{base} \qquad \frac{(1pu\ voltage)^{2}}{1pu\cdot impedance} = 1pu\cdot Power$$

- The system fault capacity in MVA is based on 1pu voltage and 1pu impedance. So the fault capacity is the base MVA of the primary system.

Basic calculation example:

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Using reactance:

$$Xs := 0.05\cdot pu \qquad Xt := 0.06\cdot pu \qquad Xm := 0.5\cdot pu$$

$$Vmin := \frac{Xm}{Xs + Xt + Xm} = 0.82pu \qquad Vmin = 81.967\%$$

Basic voltage division…

Same example using MVA values

- Motor draws 3MVA starting at rated voltage. (See table 4.2 in FPQ)
- System can deliver 30 MVA to a 3-phase fault at transformer primary.
- Transformer is 1.5MVA, 6% impedance.

$MVA := MW \qquad kVA := kW \qquad pu := 1$

$kVAs_{sc} := 30MVA \qquad kVA_{LR} := 3MVA \qquad kVAt_{sc} := \frac{1.5MVA}{0.06} = 25\,MVA$

$$kVAst_{sc} := \frac{1}{\frac{1}{kVAs_{sc}} + \frac{1}{kVAt_{sc}}} = 13.636\,MVA$$

Fault duty at transformer secondary side.

See page 117 in FPQ.

$$Vmin := \frac{kVAst_{sc}}{kVAst_{sc} + kVA_{LR}} = 0.82 \qquad Vmin = 81.967\,\%$$

Same result…

Converting reactances and fault capacities

- First, pick a base MVA – One of the existing ones makes things easier – I'll use the transformer rating:

$pu := 1 \qquad kVAt := 1.5MVA \qquad kVA_{base} := kVAt$

- System short circuit MVA, and motor starting MVA both imply 1pu impedance on their own bases. We'll convert both to the transformer base:

$$kVAs_{sc} := 30MVA \qquad kVA_{LR} := 500hp \cdot 6\frac{kVA}{hp} = 3\,MVA$$

$$Xs := \frac{kVA_{base}}{kVAs_{sc}} = 0.05pu \qquad Xt := 0.06 \cdot pu \qquad Xm := \frac{kVA_{base}}{kVA_{LR}} = 0.5pu$$

Obtaining motor and transformer data

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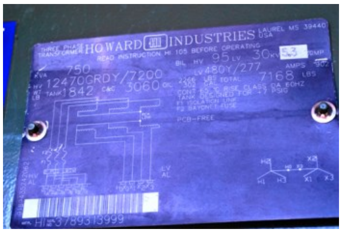

Transformer:
12.47kV:480V (L-L) Wye-wye
750kVA
X = 5.3%

Motor:
460V (L-L) 3-phase
100HP
NEMA Code letter G
Full-load Amps: 117

Primary system data

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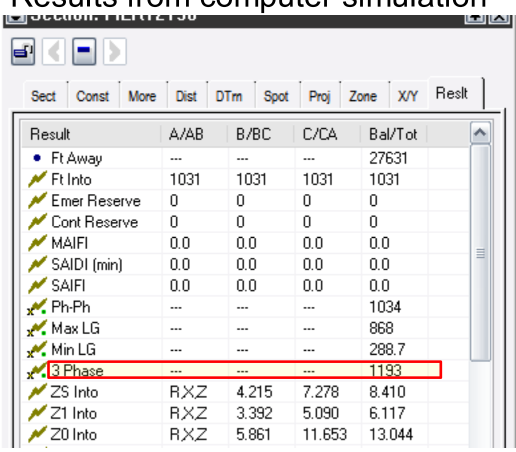
Results from computer simulation



Result	A/AB	B/BC	C/CA	Bal/Tot
Ft Away	---	---	---	27631
Ft Into	1031	1031	1031	1031
Emer Reserve	0	0	0	0
Cont Reserve	0	0	0	0
MAIFI	0.0	0.0	0.0	0.0
SAIDI (min)	0.0	0.0	0.0	0.0
SAIFI	0.0	0.0	0.0	0.0
Ph-Ph	---	---	---	1034
Max LG	---	---	---	868
Min LG	---	---	---	288.7
3 Phase	---	---	---	1193
ZS Into	RXZ	4.215	7.278	8.410
Z1 Into	RXZ	3.392	5.090	6.117
Z0 Into	RXZ	5.861	11.653	13.044

Primary System:
12.47 kV (L-L) 3-phase
3-phase Fault duty: 1193A

Note that this software also reports sequence impedances

$$12.47\text{kV}\cdot\sqrt{3}\cdot 1193\text{A} = 25.767\,\text{MVA}$$

Next time, and things to do:

- Next time: More on voltage sags
  - Motor starting mitigation
  - Equipment impacts – rectifier-based loads
- Things to do:
  - Homework 2 – You have enough information to complete problems 2, 3, and 5.
  - Download the paper: *Troubleshooting induction motors,* by W.R.Finley, IEEE, 2000. Read section V; "Motor Instantaneously Taken Off Line" for information on the impact of the initial DC offset in motor starting current.