Creation and maintaining a Web based Protection Database and Desktop based Protection setting calculation tool for Eastern Regional Grid

" An Overview of Protection System Analysis" for ER Utilities

Agenda

- Introduction
- Project Delivery Milestones
- Scope of work under Operational Studies
- Activities undertaken for Operational Studies
- Load flow study
- Short circuit study
- Validation of simulated results with ERLDC SCADA records
- Conclusion
- Queries
- Path forward in system studies

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Creation and maintaining a Web based Protection Database and Desktop based Protection setting calculation tool for Eastern Regional Grid

Training Programme on

" An Overview of Protection System Analysis"

for ER Utilities

Topics

1. Understanding Power System Protection through Simulations
2. Power Flow Solution Practical considerations
3. Short Circuit Studies
4. Transient Stability Studies
5. Introduction to Power System Protection
6. Protection Case Studies
7. Principles of Unit Protection
8. Generator Protection
9. Frequency Relays
10. Electromagnetic Transient analysis & Overvoltage Studies
11. COMTRADE
12. Tripping Analysis - Methodoloy

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“ An Overview of Protection System Analysis” for ER Utilities

Understanding Power System Protection through

Organization of the Lecture

- Introduction
- Role of protection Engineer
- Recent Trends
- Simulation Tools
- Simulation Cases

❑Introduction

- ❑**Reliability of a power system operation**

- ❑**<u>Reliable</u>: Equipment used in the system are in operation and perform the function for which they are designed for**

- ❑**<u>Reliability Index</u>: Performance index measured in terms of customer load affected in a year or particular duration**

Methods to enhance system reliability

Duplicate everything

Minimize the outage During the fault

Economics ?

How to achieve minimum outage ?

1. A good and integrated performance of power system relays.
2. Successful operation of relay for all short circuits in its zone.
3. Adequate backup protection for the faults in the adjoining section.

Operations involved in protection engineering:

1. Periodic fault studies
2. Relay setting calculation
3. Checking and co-ordination studies

Difficulties:

- Wide variety of relays in operation.
    - Functionality
    - Manufacturer
    - Technology
- System operational changes.
- System growth

It is just impossible to overcome the above difficulties by a human (Operator).

Solution???

Apply judiciously the computer and simulation tools.

Damage Minimization

- To minimize damage to equipment and interruption to the services
- To incorporate features of design aimed at preventing failures
- To include provisions for mitigating the effects of failures when it occurs

Preventing Electrical Failure

- Provision for adequate insulation, instantaneous setting, overload and unbalance factors
- Co-ordination of insulation strength with capabilities of lightning arrestors
- Use of overhead ground wires and low tower footing resistance
- Design for mechanical strength to reduce exposure, and to minimize the likelihood of failure causable by animals, birds, dirt sleet etc.

Damages Caused

1. Loss of equipment (permanent or partial damage)
2. Loss of production
3. Revenue loss
4. Fire hazard, loss of life
5. Loss of confidence level in using electricity as a commodity

Mitigate The Effects of Failure

1. Features that mitigate the immediate effects of failure
   - Design to limit the magnitude of short circuit current
   - Design to withstand mechanical stresses and heating
   - Time delay under voltage relays on circuit breakers to prevent dropping loads during momentary voltage dips
   - Ground fault neutralizers (Petersen coils)

2. Features for promptly disconnecting the faulty elements
   - Protective relaying
   - Circuit breakers with sufficient interrupting capacity
   - Fuses

Mitigate The Effects of Failure

3. Features that mitigate the loss of faulty element
   - Alternate circuits
   - Reserve generator
   - Automatic re-closing
4. Features that operate throughout the period from the inception of the fault until after its removal, to maintain voltage and stability of protective relaying
   - Automatic voltage regulators
   - Stability characteristics of generator

Mitigate The Effects of Failure

5. Means for observing the effectiveness of the foregoing features
   - Automatic oscillographs
   - Efficient human observations
   - Record keeping

6. Frequent surveys as system changes or additions are made, to be sure that the fore going features are still adequate

Relaying Quantity Behavior

- Fault occurs – Voltage dips, current increases, reactive power feed increases, speed increases, rotor angle increases, impedance decreases.
- SLG fault occurs in un-grounded system – Healthy phase voltage increases, capacitive current will flow at fault location.
- Generator trips – Frequency falls, Voltage dips
- Load trips – Frequency increases, voltage may increase

Relaying Quantity Behavior

- Line Trips – Voltage dips, overloading of other lines
- Motor Starting – Voltage dips, current increases, reactive power increases
- Transformer Energization – Inrush current, 2^{nd} harmonic predominant.
- Loss of Field – Machine draws reactive power from grid, Active power output reduces.
- Capacitor Energization – Over voltage, inrush current.

Types of Protection

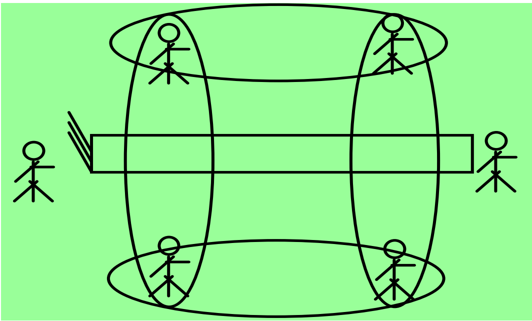
- **Over voltage protection –** **Lightning/Surge arrestors, insulation co-ordination**

- **Fault protection -** **Application of relays**

- **Protection for human (safety) –** **Earthing and Earth mat design, clearances, insulation**

- **Environmental protection?? –** **Integration of more and more renewable energy to grid**

Protection - Cricket Field Analogy

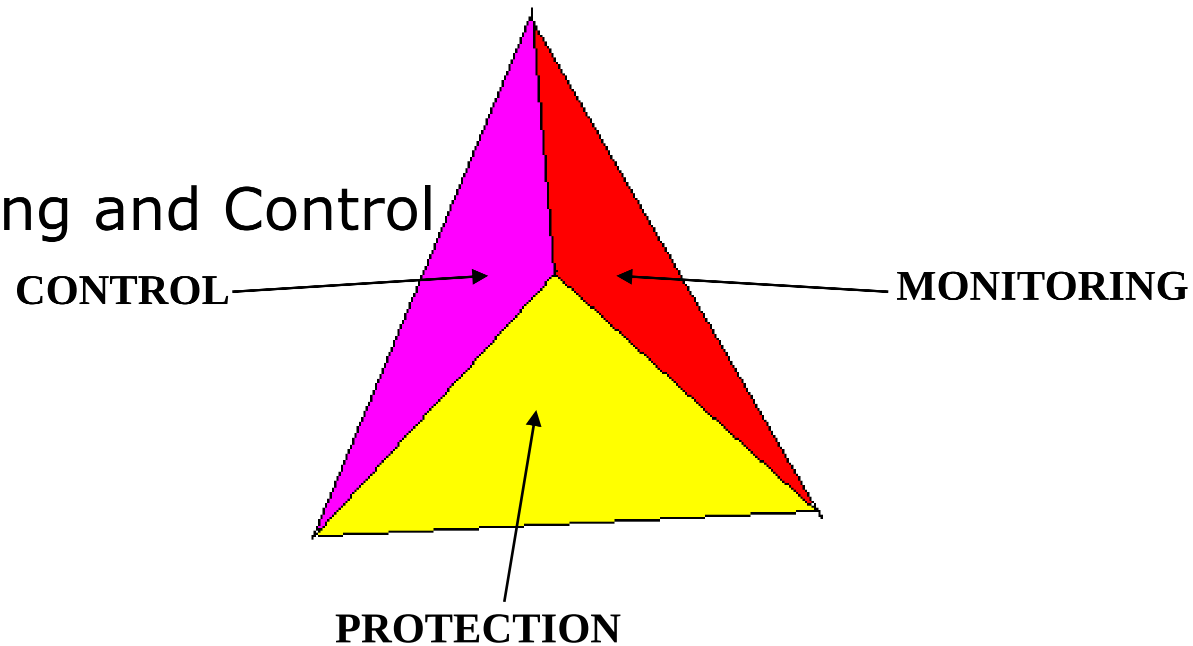


Sl. No.	Cricket Field (Fielding side Bowler)	Protection field (Protection Engineer)
1.	Positions the fielders	Designs the system and sets the relays
2.	Bowls the ball	Charges the system
3.	Batsman hits the ball	Fault occurs
4.	Mid-off stops/fails	Primary relay operates/ fails
5.	Long-off stops/ fails	Backup relay operates / fails
6.	If boundary, gets dropped	If fails, Has to face enquiry commission

Intelligent Electronic Device (IED)

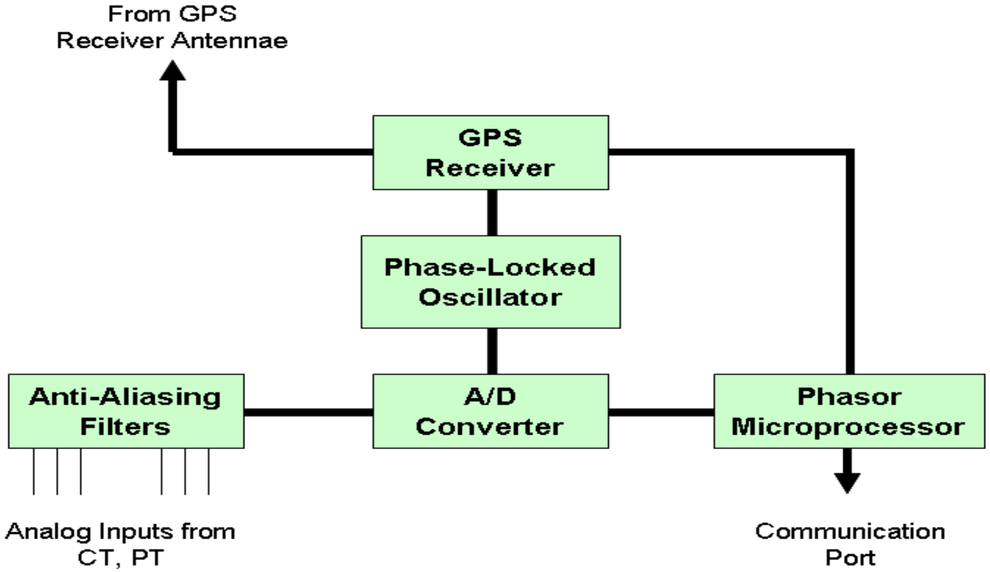
Relay has changed its functionality
from
protection to

Protection Monitoring and Control



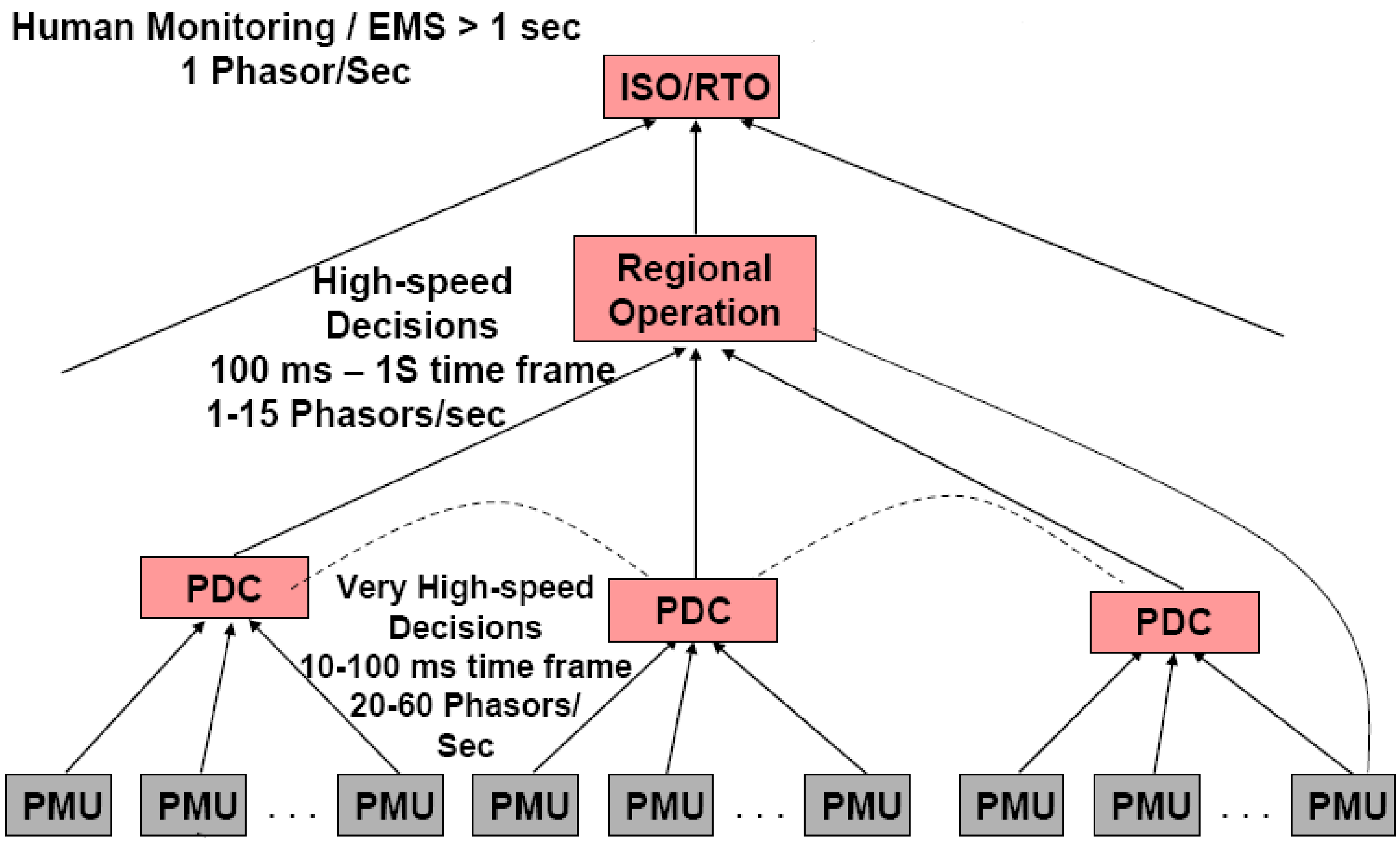
Recent Trends – Application of Phasor measurement unit

A device that samples analog voltage and current data in synchronism with a GPS-clock.



Phasor Measurement Unit Block Diagram

Architectural Hierarchy



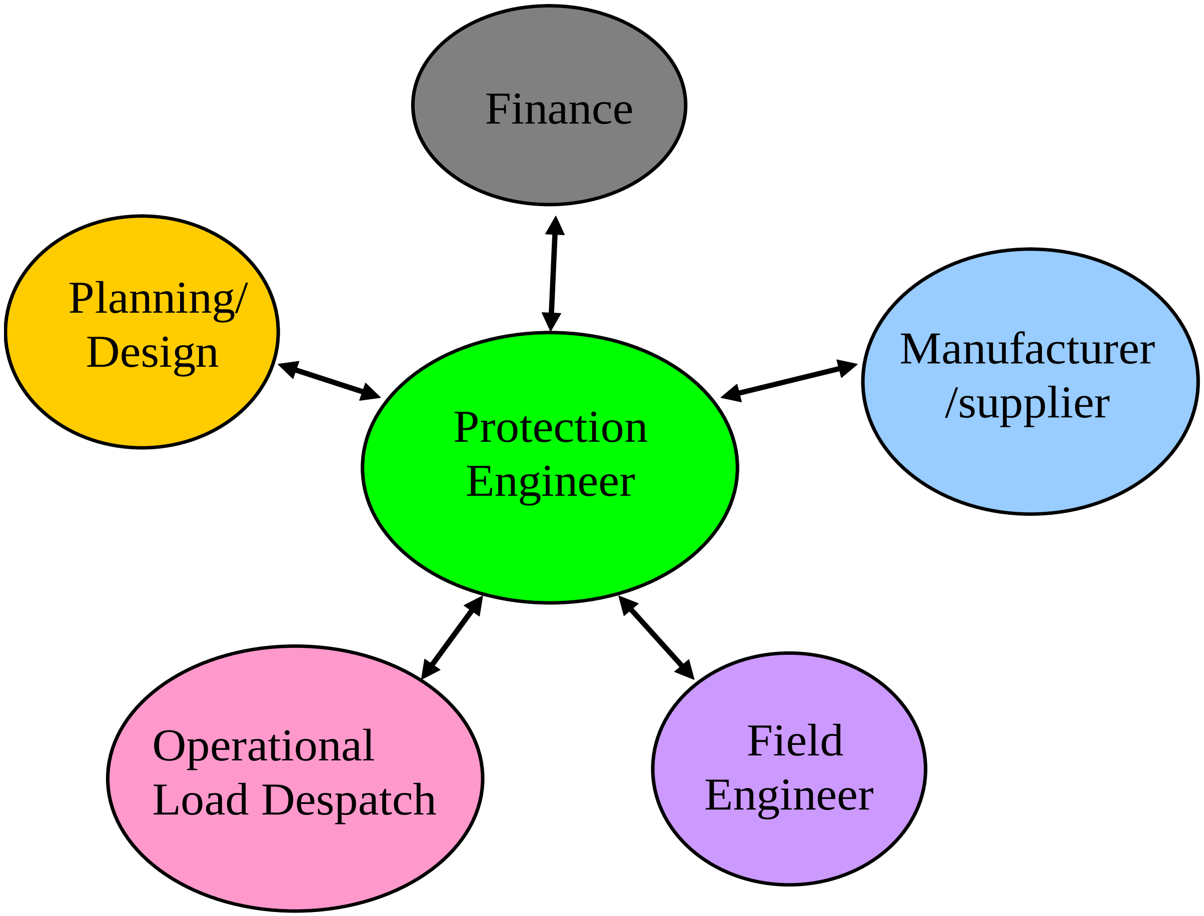
Applications of PMU

- Real time visualization of power system
- Design of advanced warning system
- Analysis for causes of total or partial blackouts
- Enhancement in state estimation
- Real time angular and voltage stability analysis
- Improved damping of inter area oscillations
- Design of adaptive protection scheme
- Fine tuning of system models

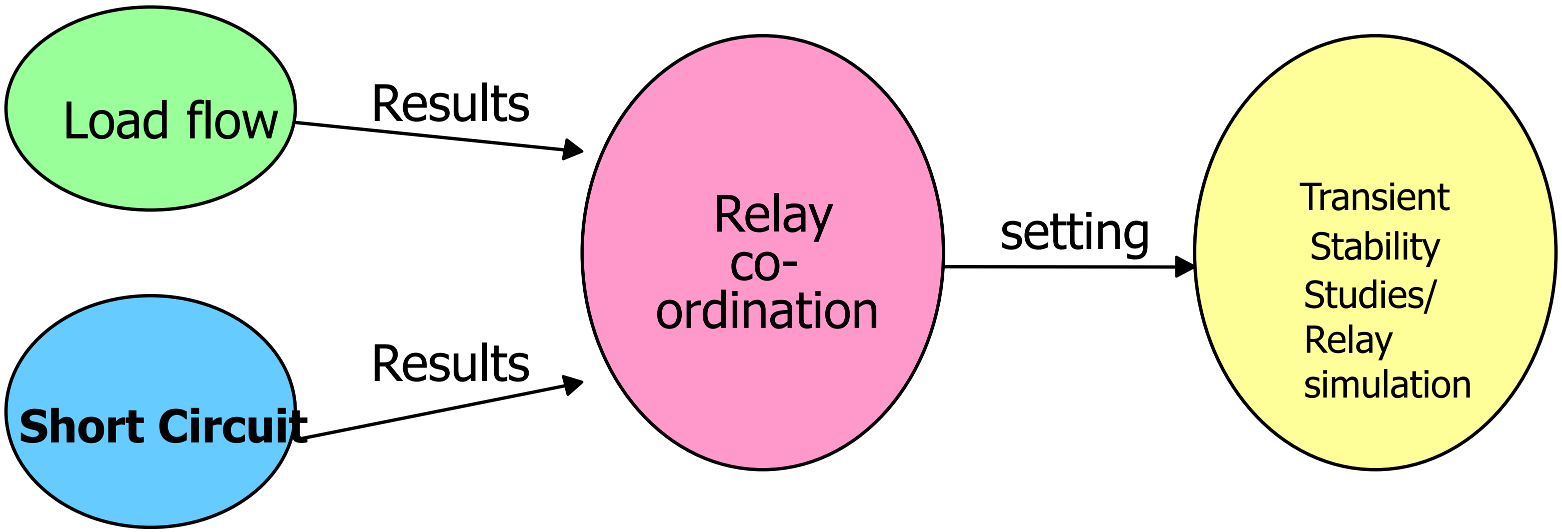
Adaptive Relaying

- Online activity
- Modifies preferred protective response to a change in system conditions or requirements.
- Special application in case of -
  - * Multi terminal lines.
  - * Out of step protection.
  - * Back up protection of distance relays.

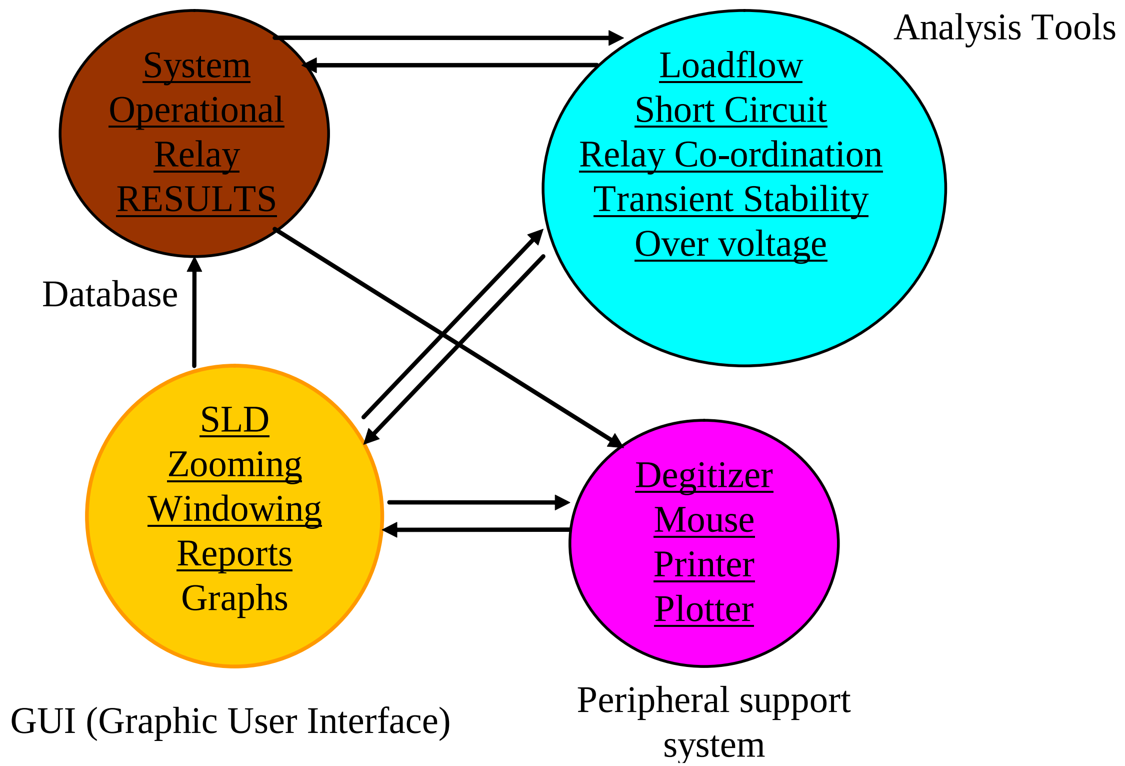
Co-ordination With Different Departments



Data Flow in Simulation



Computer Aided Protection Co-ordination



Duration Spectra of Main Effects

Electrical Switching Transients Over Voltages Fault Transients	Electrical machine & System Dynamics	System Governing & load Controls	Prime mover energy supply system dynamics	Energy resource dynamics
μs/ms	Few seconds	Seconds to minutes	Several minutes	Days to weeks

Transient Phenomena

μs → Initial transient, Recovery Voltage

❖ Scale ⇨ ms → Switching surges, Fault transients

Several cycles → Ferro - resonance

- ❑ Surge period
- ❑ Dynamic period
- ❑ Steady State period

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Simulation Cases

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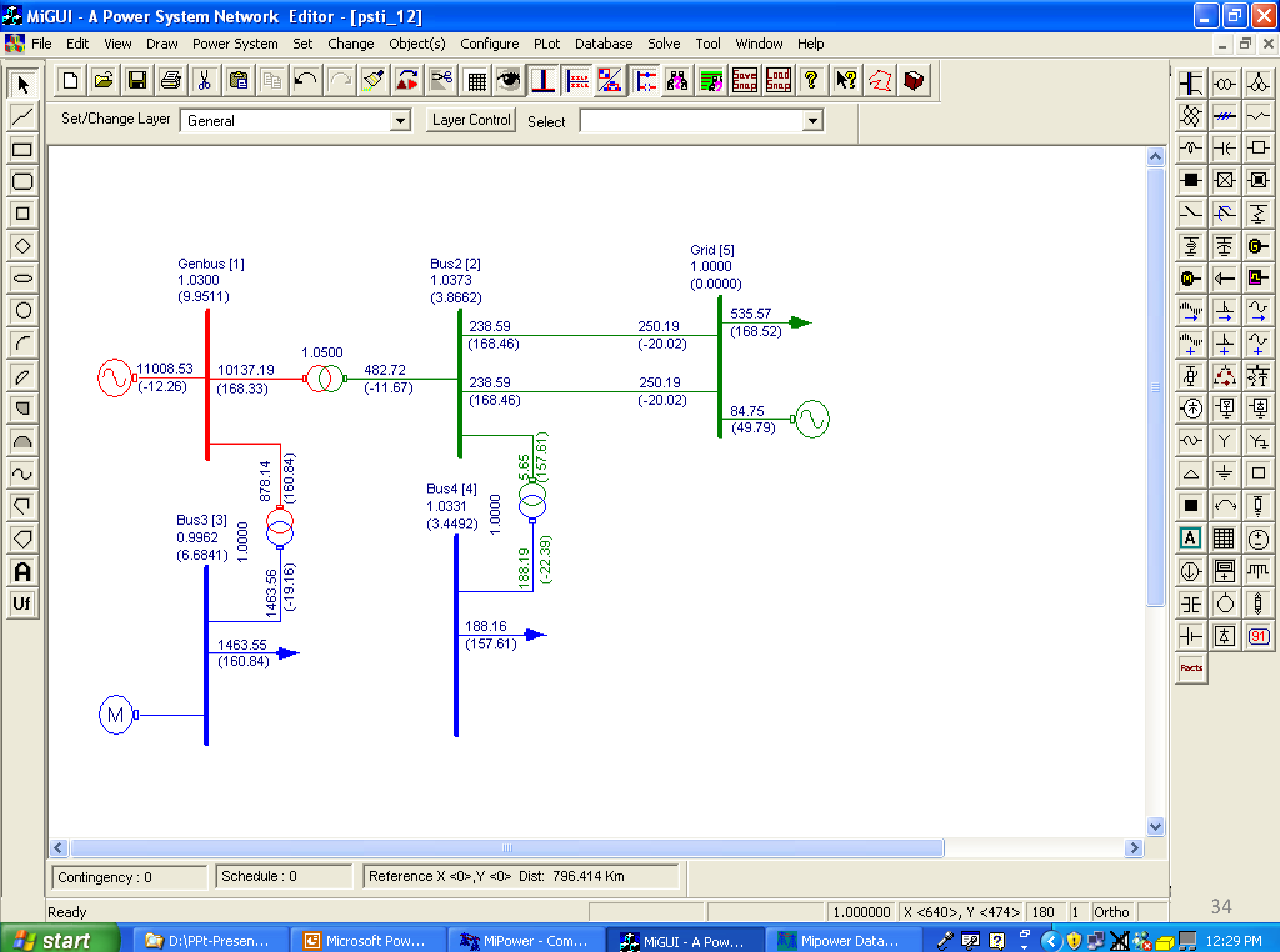
Why Load flow study for protection Engineer?


MiGUI - A Power System Network Editor - [psti_12]
File Edit View Draw Power System Set Change Object(s) Configure PLot Database Solve Tool Window Help
Set/Change Layer
General
Layer Control
Select
Genbus [1]
1.0300
(9.9511)
Bus2 [2]
1.0373
(3.8662)
Grid [5]
1.0000
(0.0000)
11008.53
(-12.26)
10137.19
(168.33)
1.0500
482.72
(-11.67)
238.59
(168.46)
250.19
(-20.02)
238.59
(168.46)
250.19
(-20.02)
535.57
(168.52)
84.75
(49.79)
878.14
(160.84)
5.65
(157.61)
Bus4 [4]
1.0331
(3.4492)
1.0000
Bus3 [3]
0.9962
(6.6841)
1.0000
1463.56
(-19.16)
188.19
(-22.39)
188.16
(157.61)
1463.55
(160.84)
M
Contingency : 0
Schedule : 0
Reference X <0>,Y <0> Dist: 796.414 Km
Ready
1.000000
X <640>, Y <474>
180
1
Ortho
start
D:\PPt-Presen...
Microsoft Pow...
MiPower - Com...
MiGUI - A Pow...
Mipower Data...
12:29 PM

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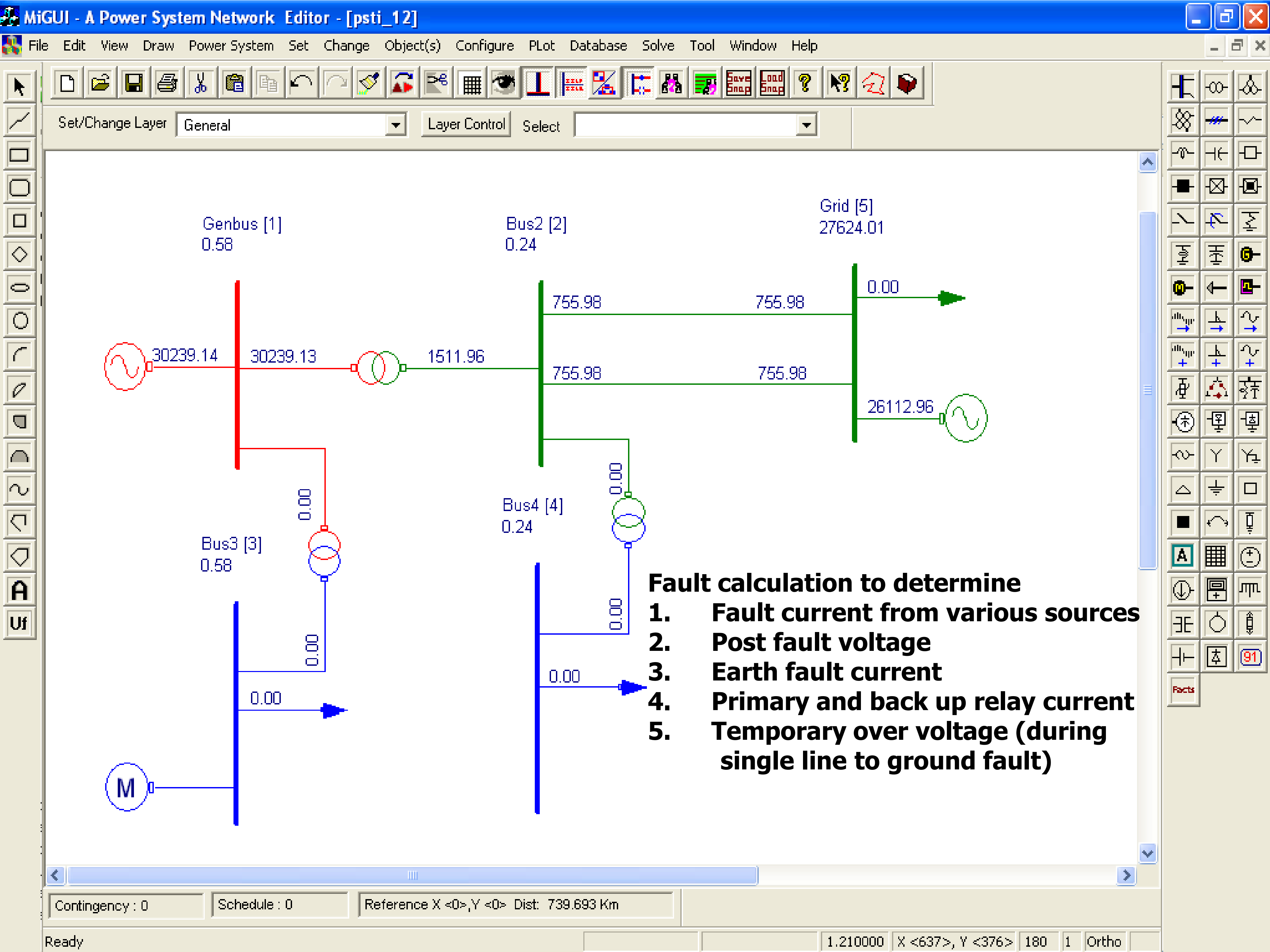
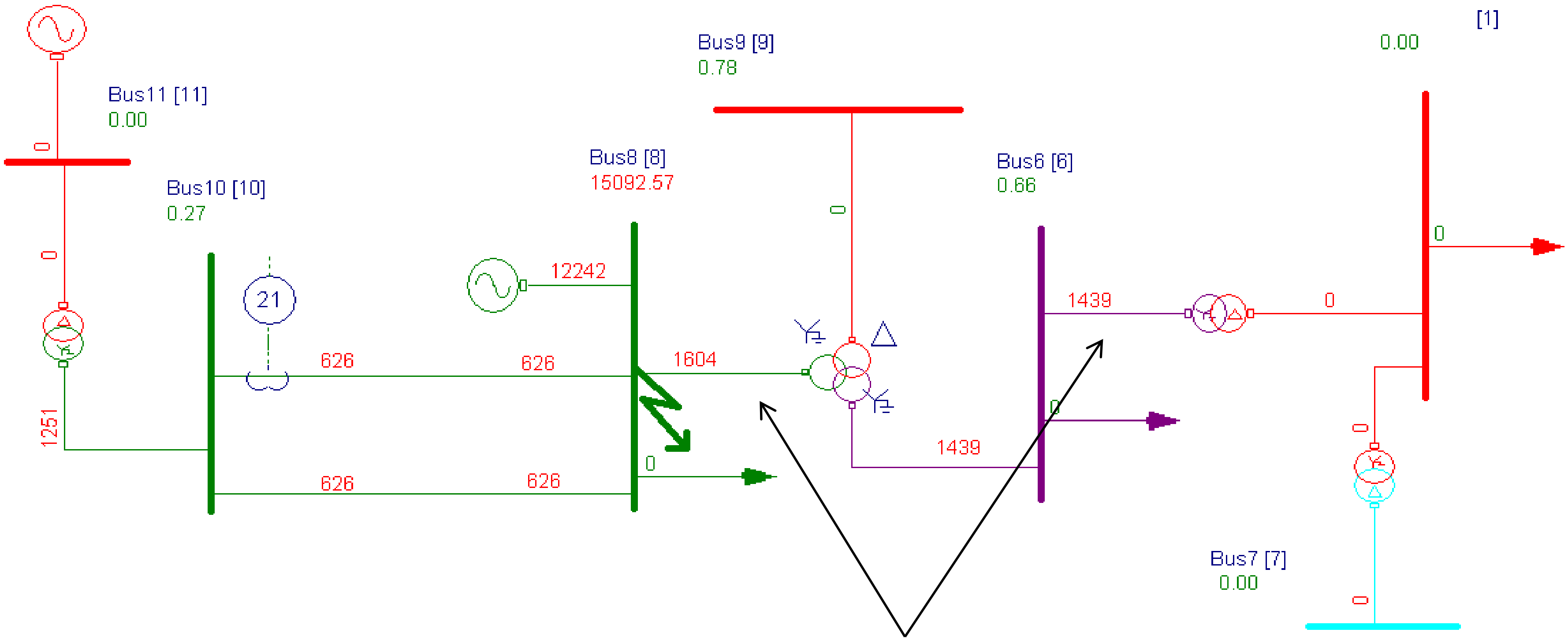
Fault Simulation to Aid Protection Engineer

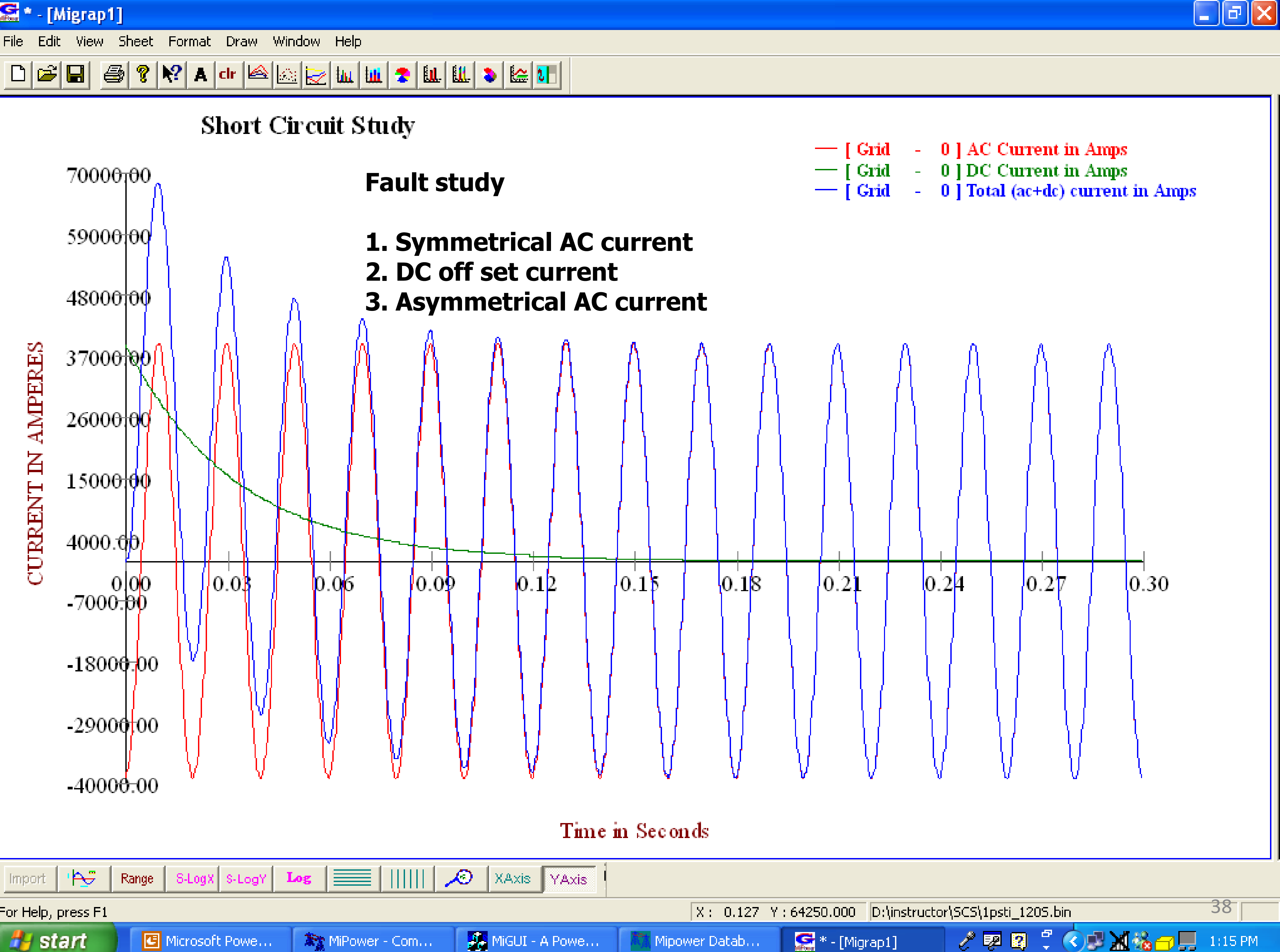

MiGUI - A Power System Network Editor - [psti_12]
File Edit View Draw Power System Set Change Object(s) Configure PLot Database Solve Tool Window Help
Set/Change Layer
General
Layer Control
Select
Genbus [1]
0.58
Bus2 [2]
0.24
Grid [5]
27624.01
30239.14
30239.13
1511.96
755.98
755.98
755.98
755.98
0.00
26112.96
0.00
0.00
0.00
0.00
Bus3 [3]
0.58
Bus4 [4]
0.24
0.00
0.00
M
Fault calculation to determine
1. Fault current from various sources
2. Post fault voltage
3. Earth fault current
4. Primary and back up relay current
5. Temporary over voltage (during single line to ground fault)
Contingency : 0
Schedule : 0
Reference X <0>,Y <0> Dist: 739.693 Km
Ready
1.210000
X <637>, Y <376>
180
1
Ortho

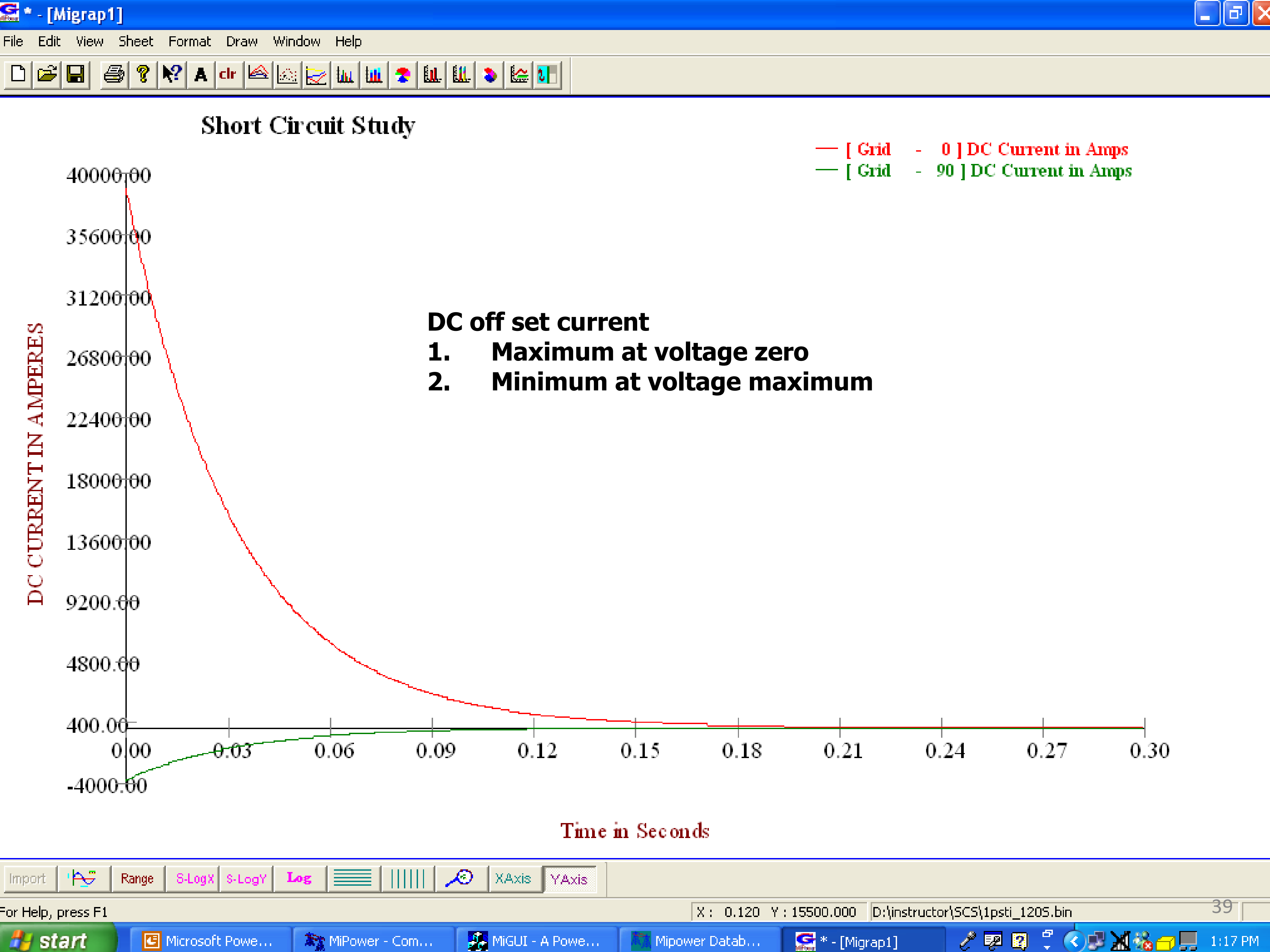
Earth fault relay operation - Explained



No source in this part of the network

Earth fault relay picks up, because of transformer Vector group


* - [Migrap1]
File Edit View Sheet Format Draw Window Help
Short Circuit Study
[Grid - 0] AC Current in Amps
[Grid - 0] DC Current in Amps
[Grid - 0] Total (ac+dc) current in Amps
Fault study
1. Symmetrical AC current
2. DC off set current
3. Asymmetrical AC current
CURRENT IN AMPERES
70000.00
59000.00
48000.00
37000.00
26000.00
15000.00
4000.00
-7000.00
-18000.00
-29000.00
-40000.00
0.00
0.03
0.06
0.09
0.12
0.15
0.18
0.21
0.24
0.27
0.30
Time in Seconds
Import
Range
S-LogX
S-LogY
Log
XAxis
YAxis
For Help, press F1
X : 0.127 Y : 64250.000
D:\instructor\SCS\1psti_120S.bin
start
Microsoft Powe...
MiPower - Com...
MiGUI - A Powe...
Mipower Datab...
* - [Migrap1]
1:15 PM


* - [Migrap1]
File Edit View Sheet Format Draw Window Help
Short Circuit Study
[Grid - 0] DC Current in Amps
[Grid - 90] DC Current in Amps
DC off set current
1. Maximum at voltage zero
2. Minimum at voltage maximum
DC CURRENT IN AMPERES
40000.00
35600.00
31200.00
26800.00
22400.00
18000.00
13600.00
9200.00
4800.00
400.00
-4000.00
0.00
0.03
0.06
0.09
0.12
0.15
0.18
0.21
0.24
0.27
0.30
Time in Seconds
Import
Range
S-LogX
S-LogY
Log
XAxis
YAxis
For Help, press F1
X : 0.120 Y : 15500.000
D:\instructor\SCS\1psti_120S.bin
start
Microsoft Powe...
MiPower - Com...
MiGUI - A Powe...
Mipower Datab...
* - [Migrap1]
1:17 PM

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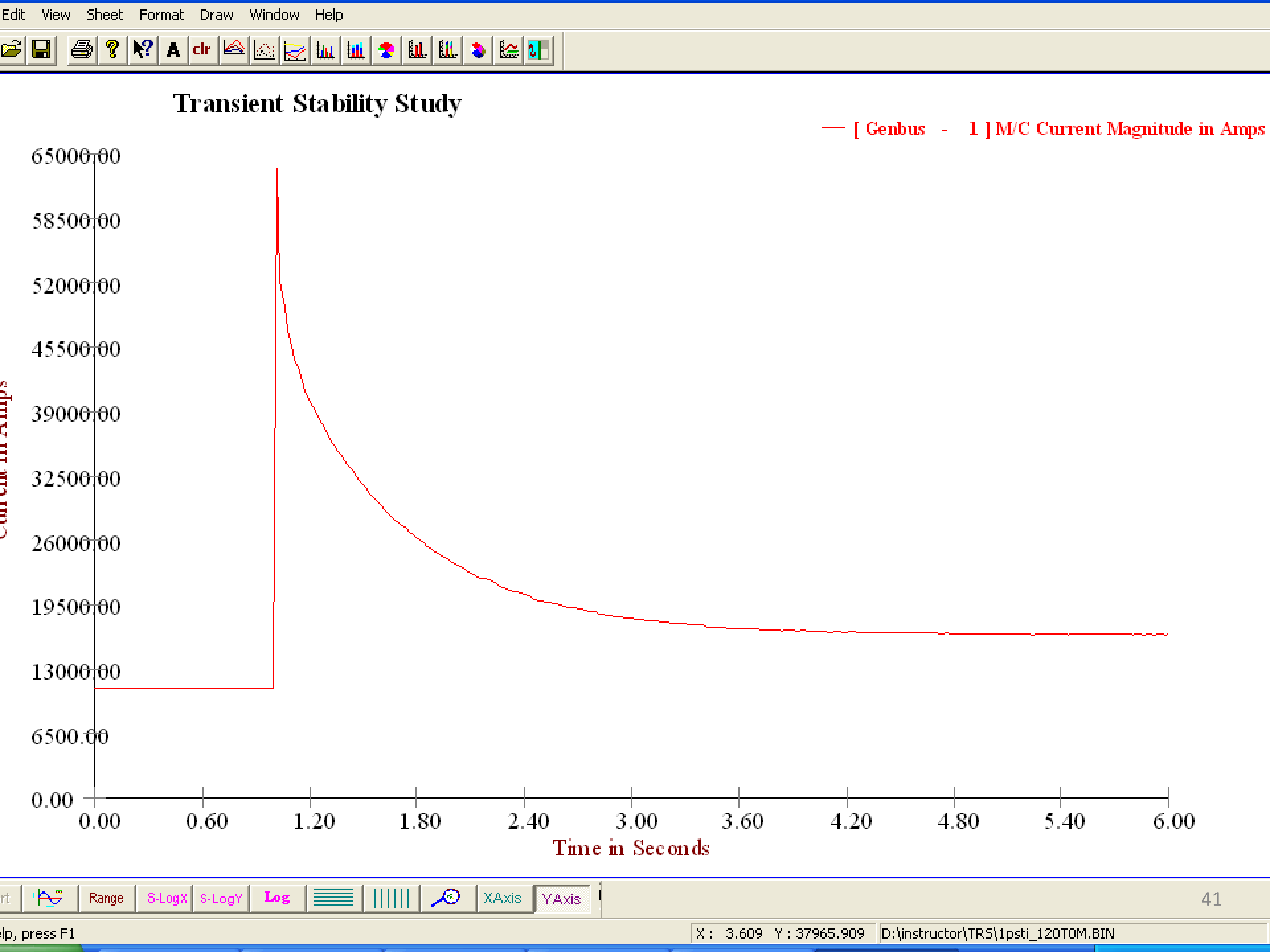
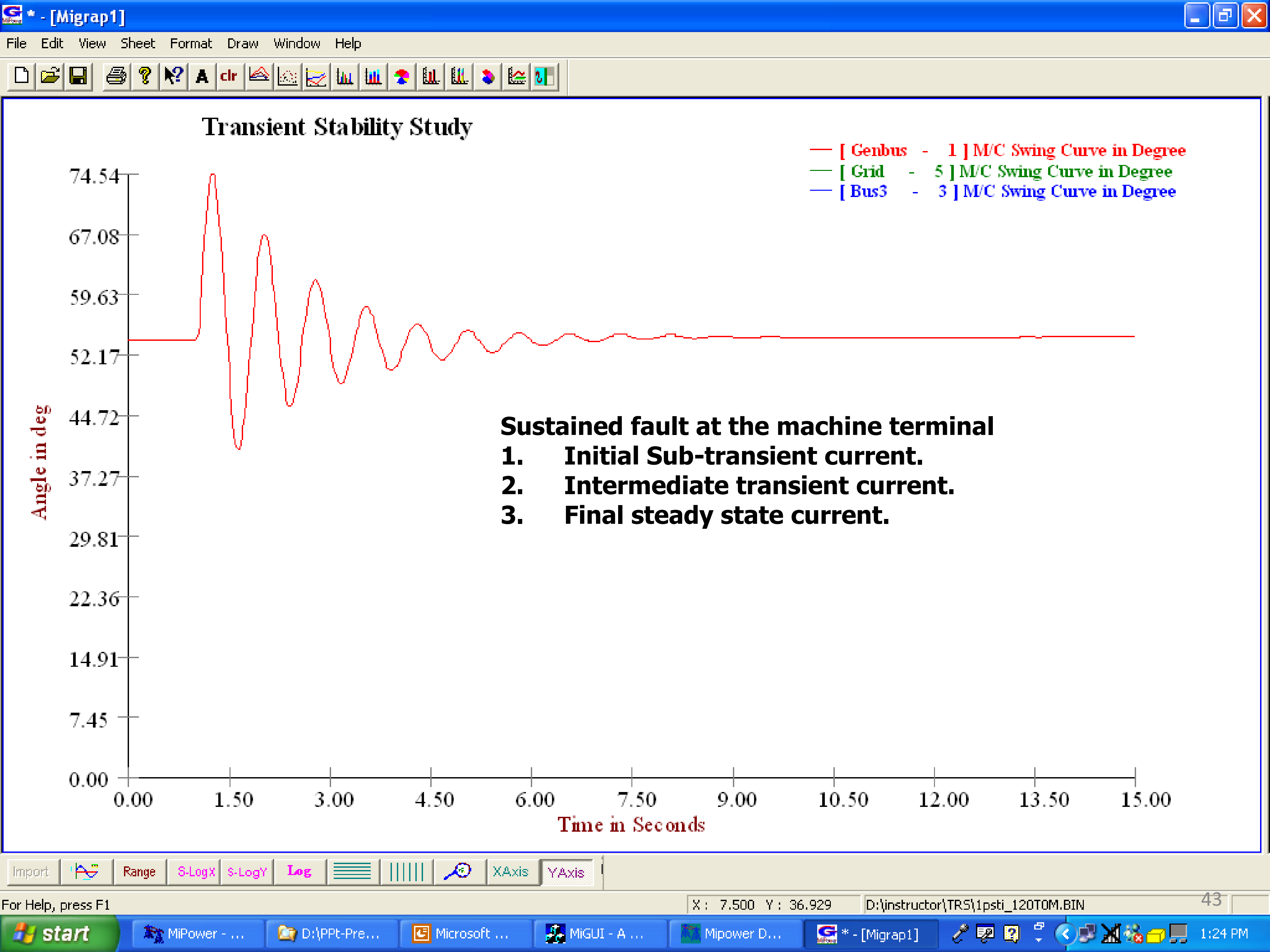
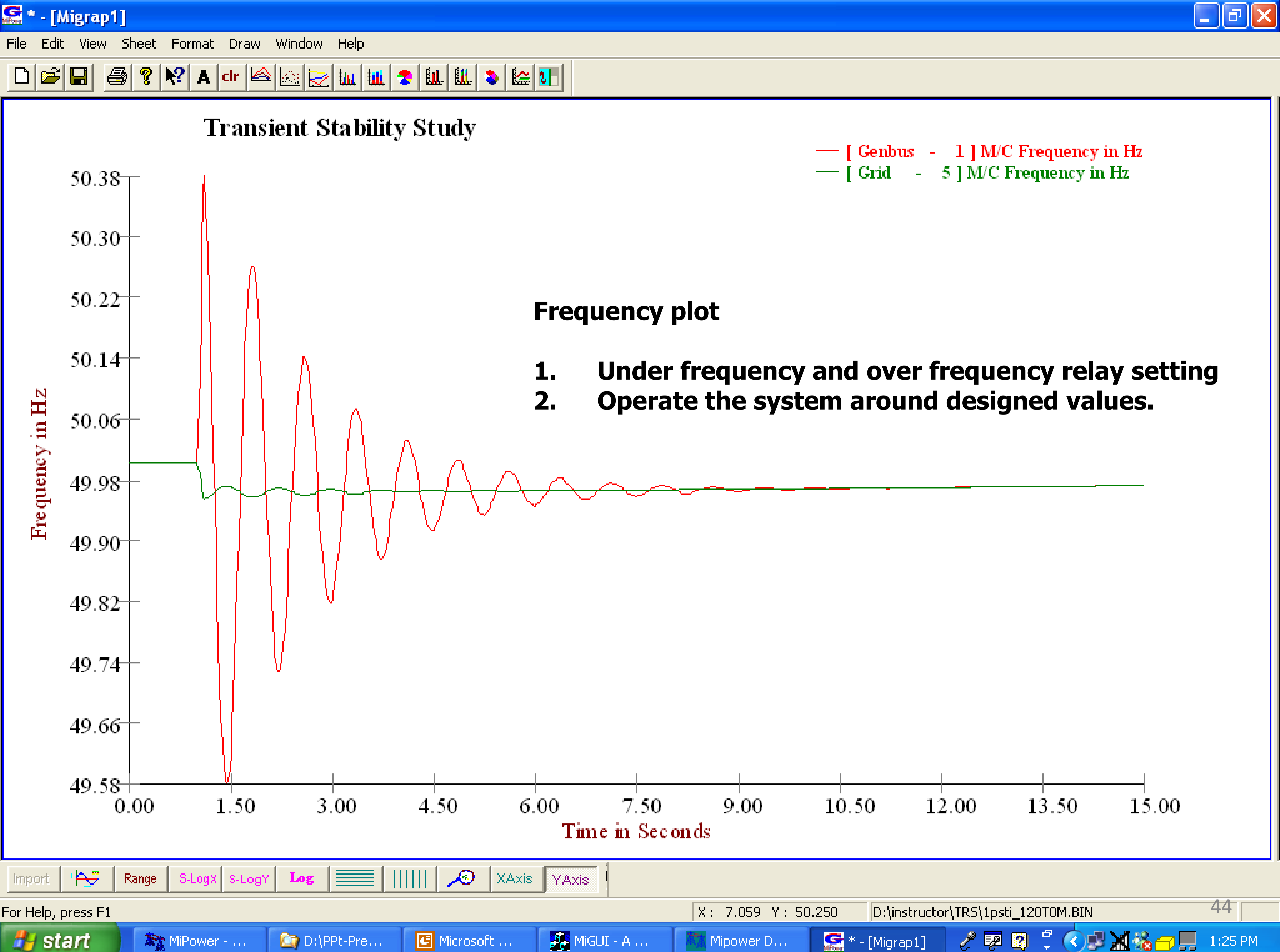
What machine impedance to consider for fault study and relay-coordination?


Edit View Sheet Format Draw Window Help
Transient Stability Study
[Genbus - 1] M/C Current Magnitude in Amps
65000.00
58500.00
52000.00
45500.00
39000.00
32500.00
26000.00
19500.00
13000.00
6500.00
0.00
0.00
0.60
1.20
1.80
2.40
3.00
3.60
4.20
4.80
5.40
6.00
Time in Seconds
Range
S-LogX
S-LogY
Log
XAxis
YAxis
X : 3.609 Y : 37965.909
D:\instructor\TRS\1psti_120T0M.BIN

Protection Analytic tool

Stability study simulation and its importance


* - [Migrap1]
File Edit View Sheet Format Draw Window Help
Transient Stability Study
[Genbus - 1] M/C Swing Curve in Degree
[Grid - 5] M/C Swing Curve in Degree
[Bus3 - 3] M/C Swing Curve in Degree
74.54
67.08
59.63
52.17
44.72
37.27
29.81
22.36
14.91
7.45
0.00
Angle in deg
0.00 1.50 3.00 4.50 6.00 7.50 9.00 10.50 12.00 13.50 15.00
Time in Seconds
Sustained fault at the machine terminal
1. Initial Sub-transient current.
2. Intermediate transient current.
3. Final steady state current.
Import Range S-LogX S-LogY Log XAxis YAxis
For Help, press F1
X : 7.500 Y : 36.929
D:\instructor\TRS\1psti_120TOM.BIN
start MiPower - ... D:\PPt-Pre... Microsoft ... MiGUI - A ... Mipower D... * - [Migrap1]
1:24 PM

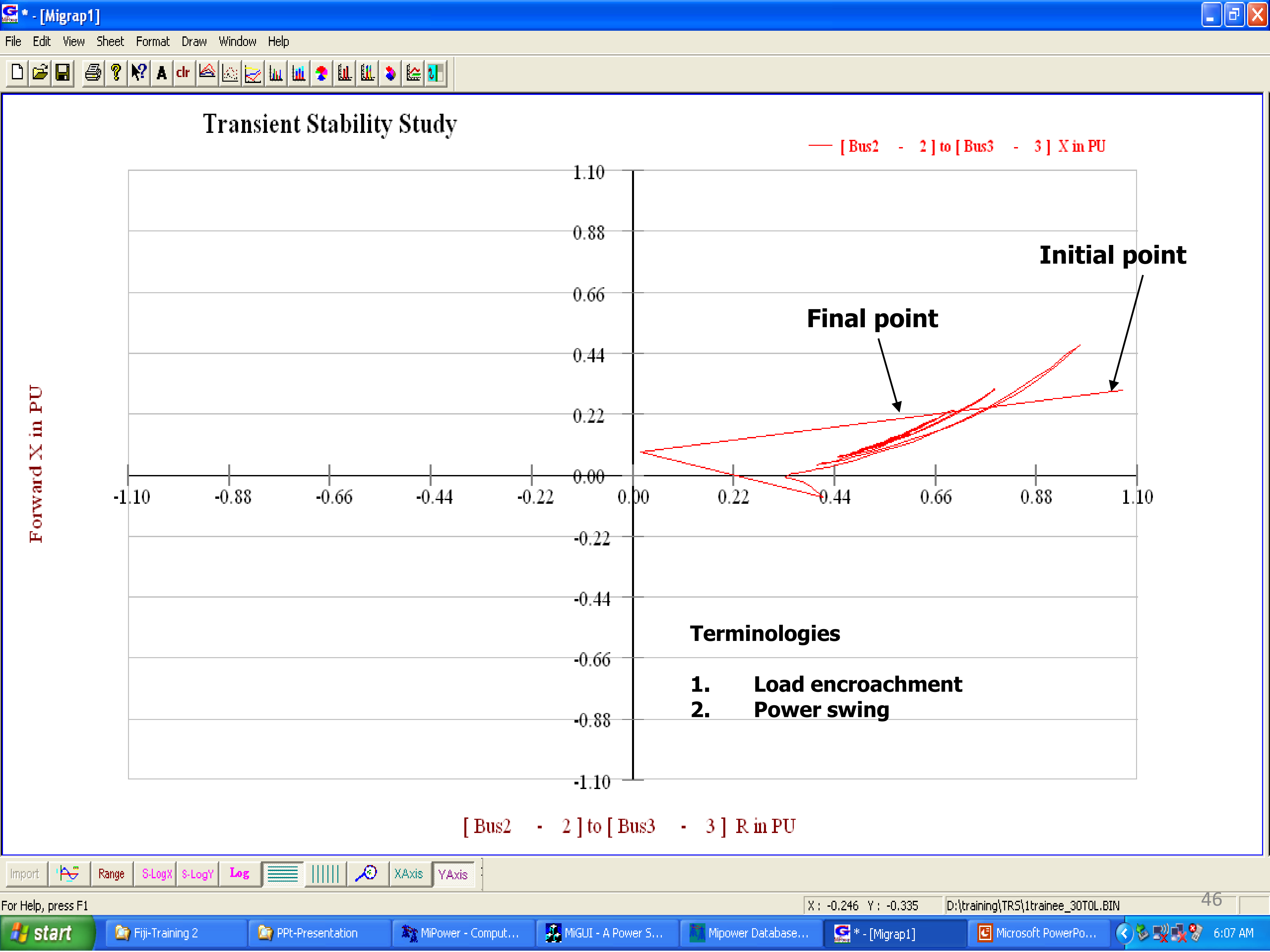


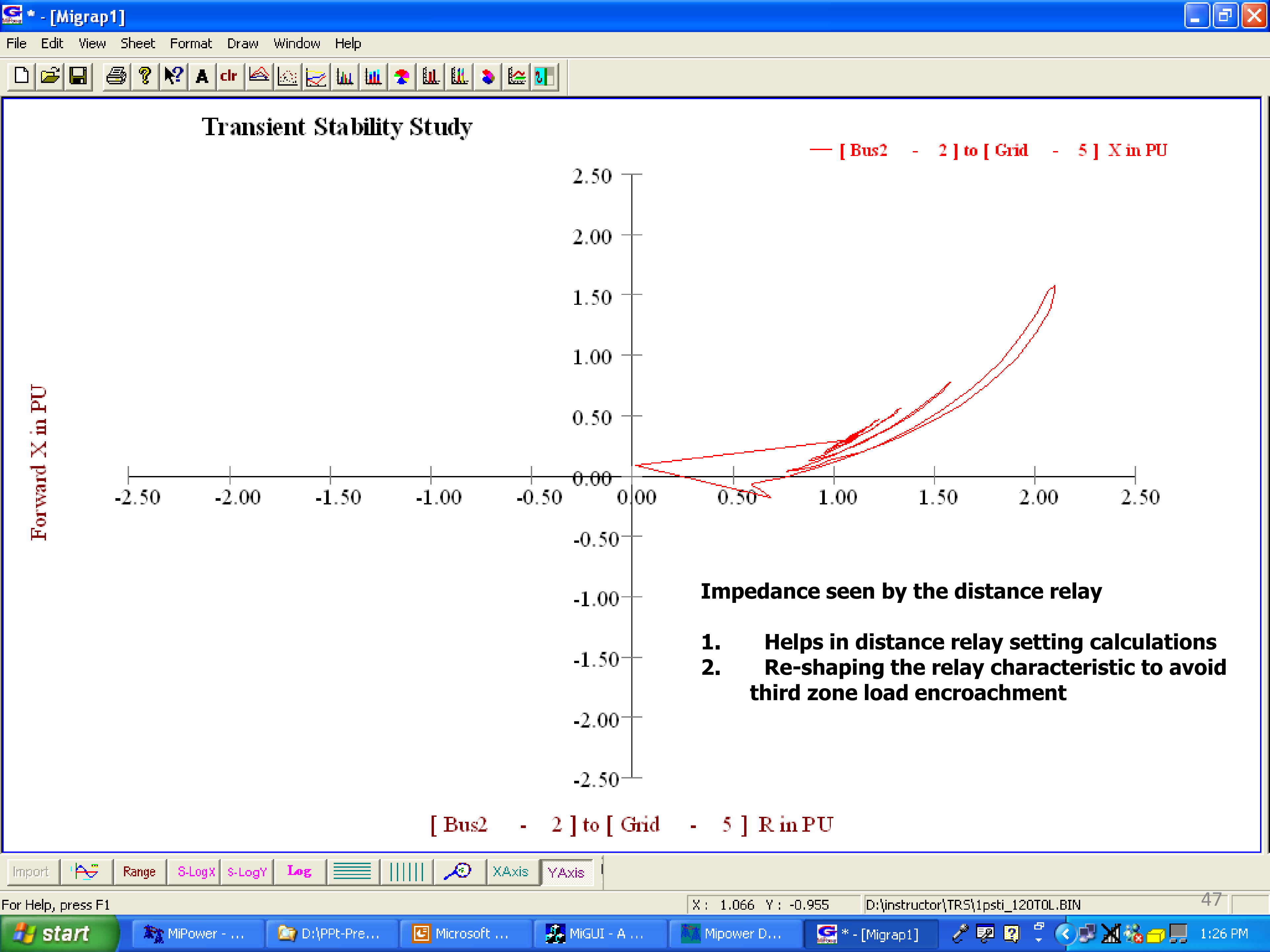
Frequency plot

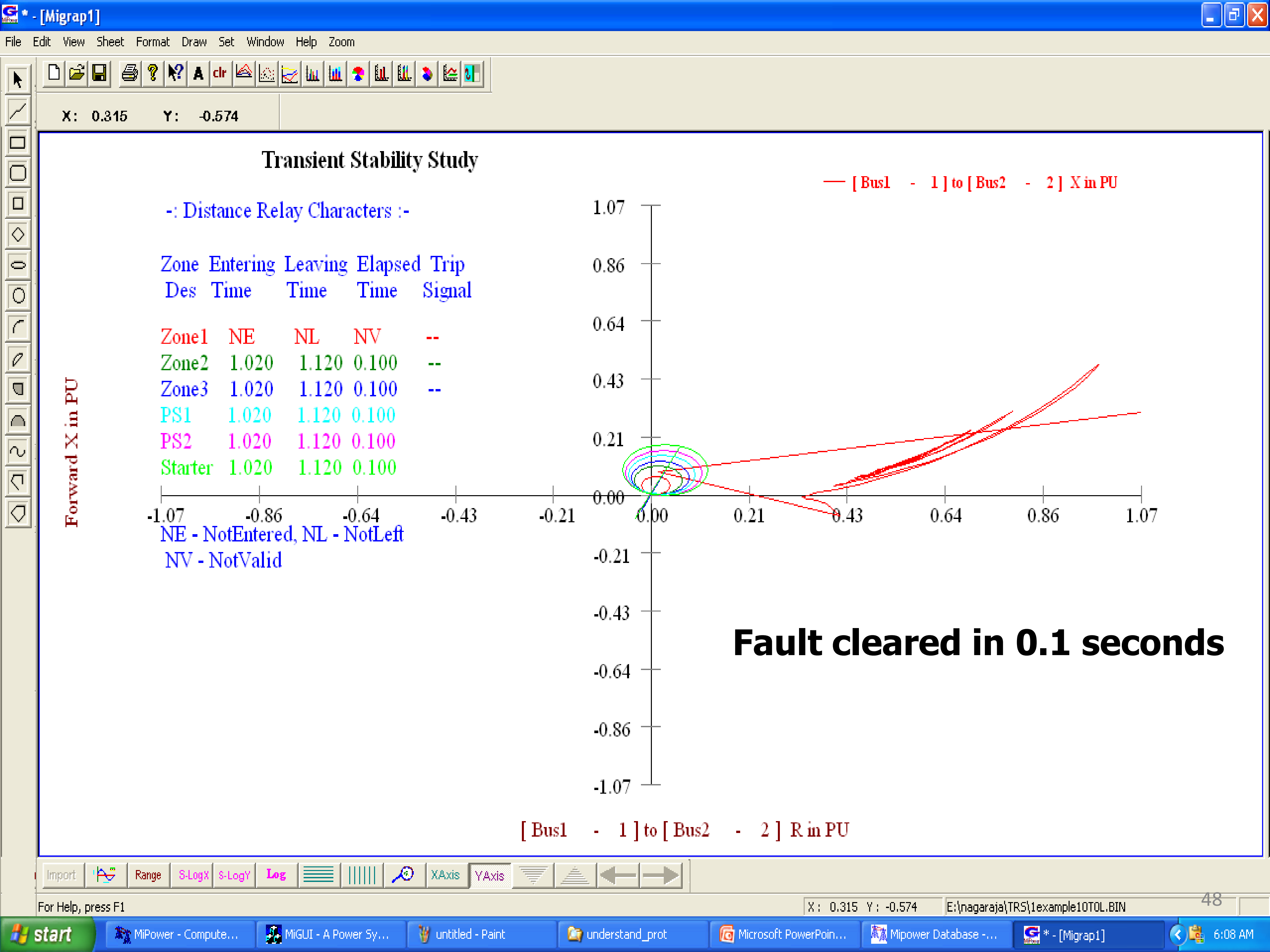
1. **Under frequency and over frequency relay setting**
2. **Operate the system around designed values.**

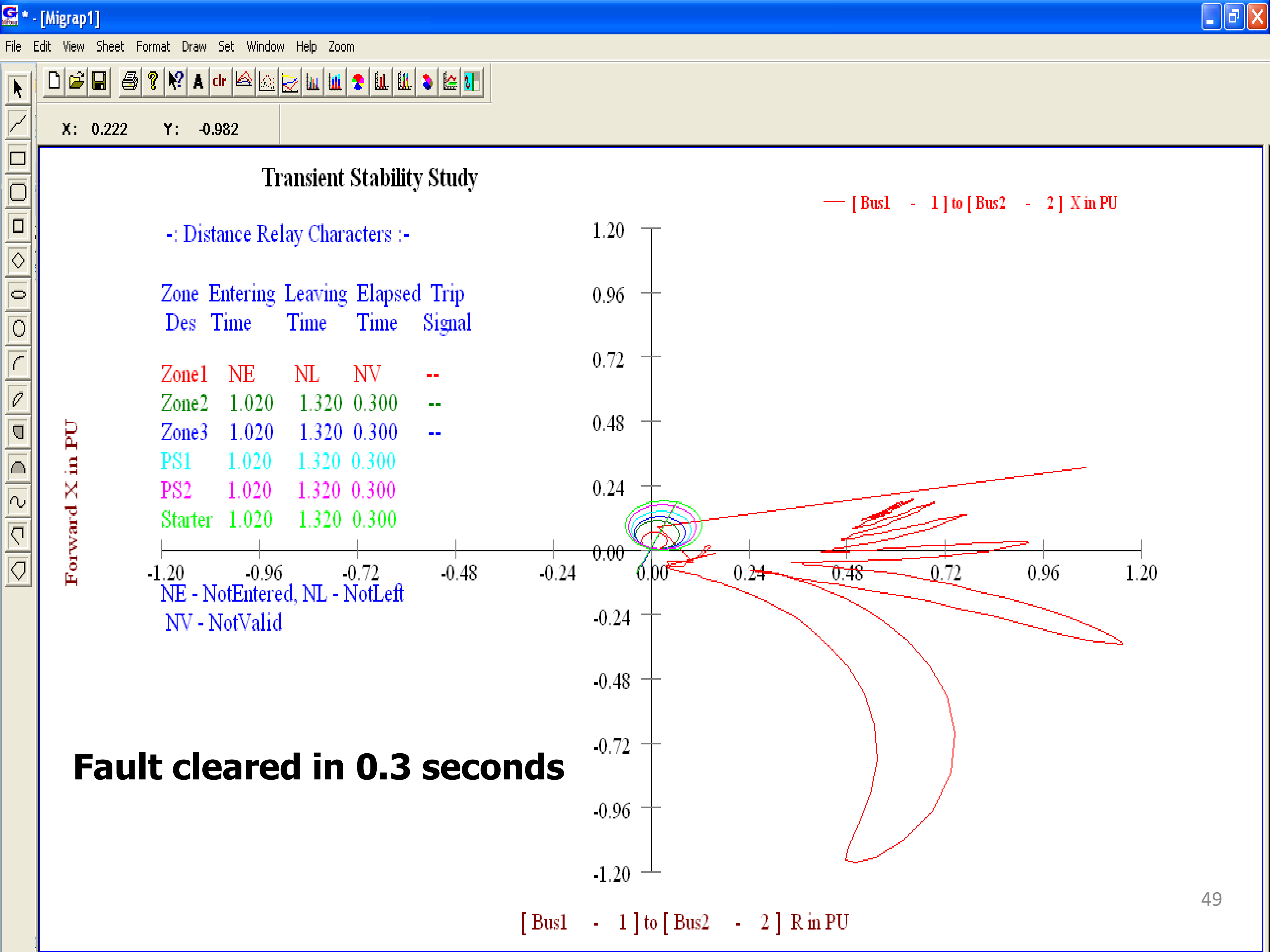
Parallel line, one line trips

1. Directional over current relay should not operate for the healthy line.
2. There should not be load encroachment

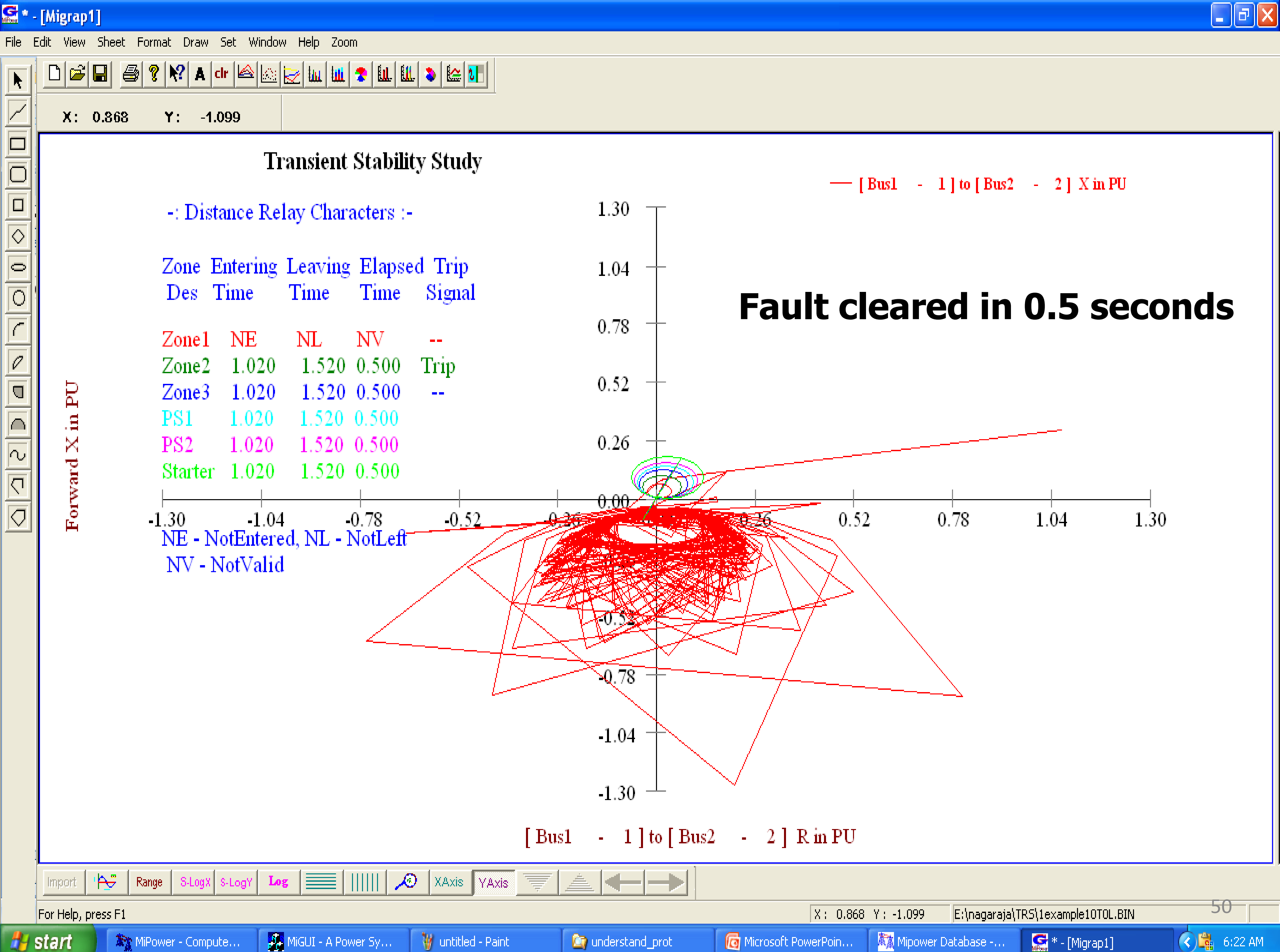

* - [Migrap1]
File Edit View Sheet Format Draw Window Help
Transient Stability Study
[Bus2 - 2] to [Bus3 - 3] X in PU
Initial point
Final point
Forward X in PU
1.10
0.88
0.66
0.44
0.22
0.00
-0.22
-0.44
-0.66
-0.88
-1.10
-1.10 -0.88 -0.66 -0.44 -0.22 0.00 0.22 0.44 0.66 0.88 1.10
Terminologies
1. Load encroachment
2. Power swing
[Bus2 - 2] to [Bus3 - 3] R in PU
Import
Range
S-LogX
S-LogY
Log
XAxis
YAxis
For Help, press F1
X : -0.246 Y : -0.335
D:\training\TRS\1trainee_30T0L.BIN
start
Fiji-Training 2
PPt-Presentation
MiPower - Comput...
MiGUI - A Power S...
Mipower Database...
* - [Migrap1]
Microsoft PowerPo...
6:07 AM

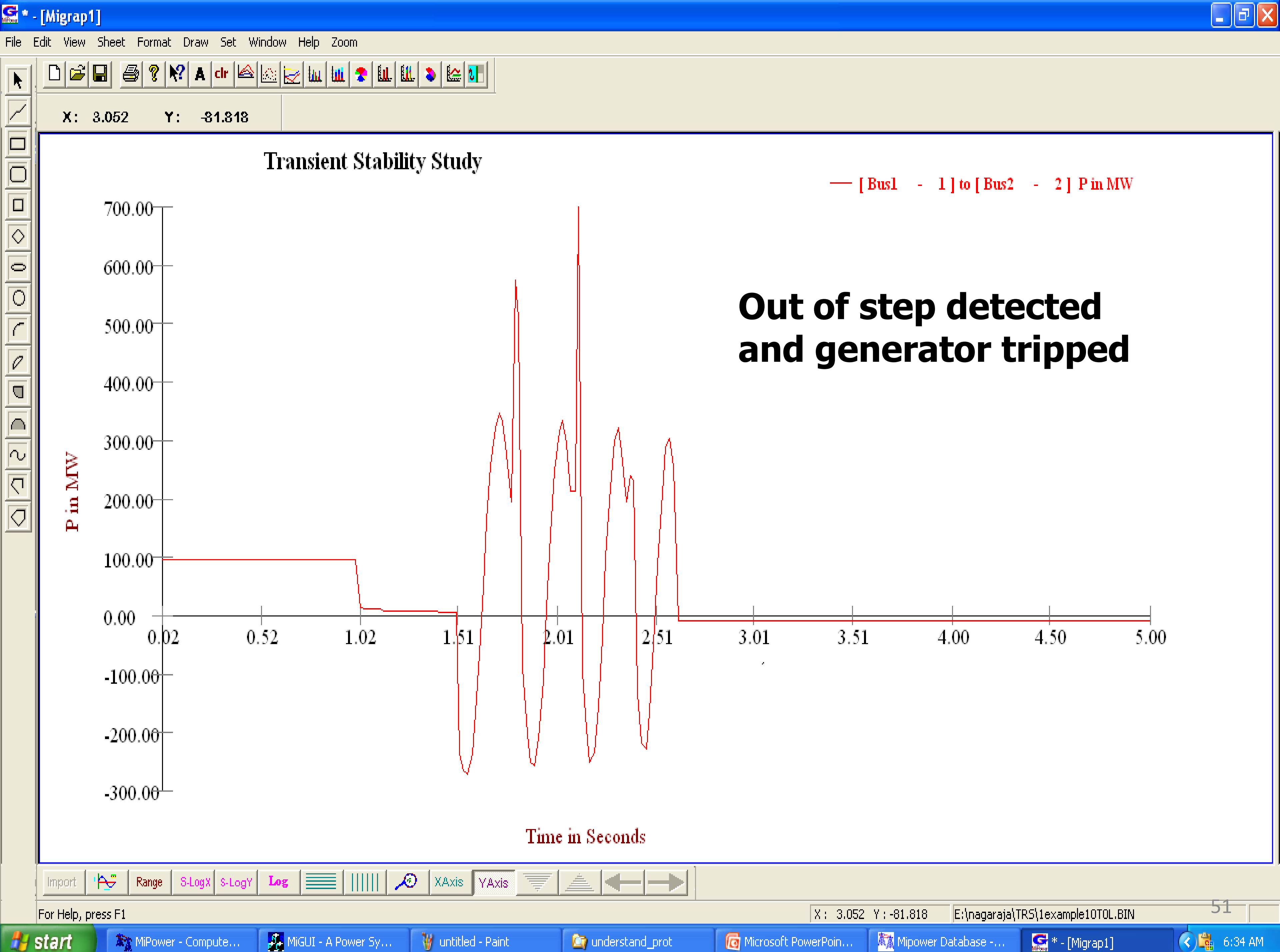

* - [Migrap1]
File Edit View Sheet Format Draw Window Help
Transient Stability Study
— [Bus2 - 2] to [Grid - 5] X in PU
Forward X in PU
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-2.50 -2.00 -1.50 -1.00 -0.50 0.00 0.50 1.00 1.50 2.00 2.50
Impedance seen by the distance relay
1. Helps in distance relay setting calculations
2. Re-shaping the relay characteristic to avoid third zone load encroachment
[Bus2 - 2] to [Grid - 5] R in PU
Import Range S-LogX S-LogY Log XAxis YAxis
For Help, press F1
X : 1.066 Y : -0.955
D:\instructor\TRS\1psti_120TOL.BIN
start MiPower - ... D:\PPt-Pre... Microsoft ... MiGUI - A ... Mipower D... * - [Migrap1]
1:26 PM


* - [Migrap1]
X: 0.315 Y: -0.574
Transient Stability Study
-: Distance Relay Characters :-
Zone Des Entering Time Leaving Time Elapsed Time Trip Signal
Zone1 NE NL NV --
Zone2 1.020 1.120 0.100 --
Zone3 1.020 1.120 0.100 --
PS1 1.020 1.120 0.100
PS2 1.020 1.120 0.100
Starter 1.020 1.120 0.100
NE - NotEntered, NL - NotLeft
NV - NotValid
[Bus1 - 1] to [Bus2 - 2] X in PU
Forward X in PU
[Bus1 - 1] to [Bus2 - 2] R in PU
Fault cleared in 0.1 seconds
For Help, press F1
E:\nagaraja\TRS\1example10TOL.BIN

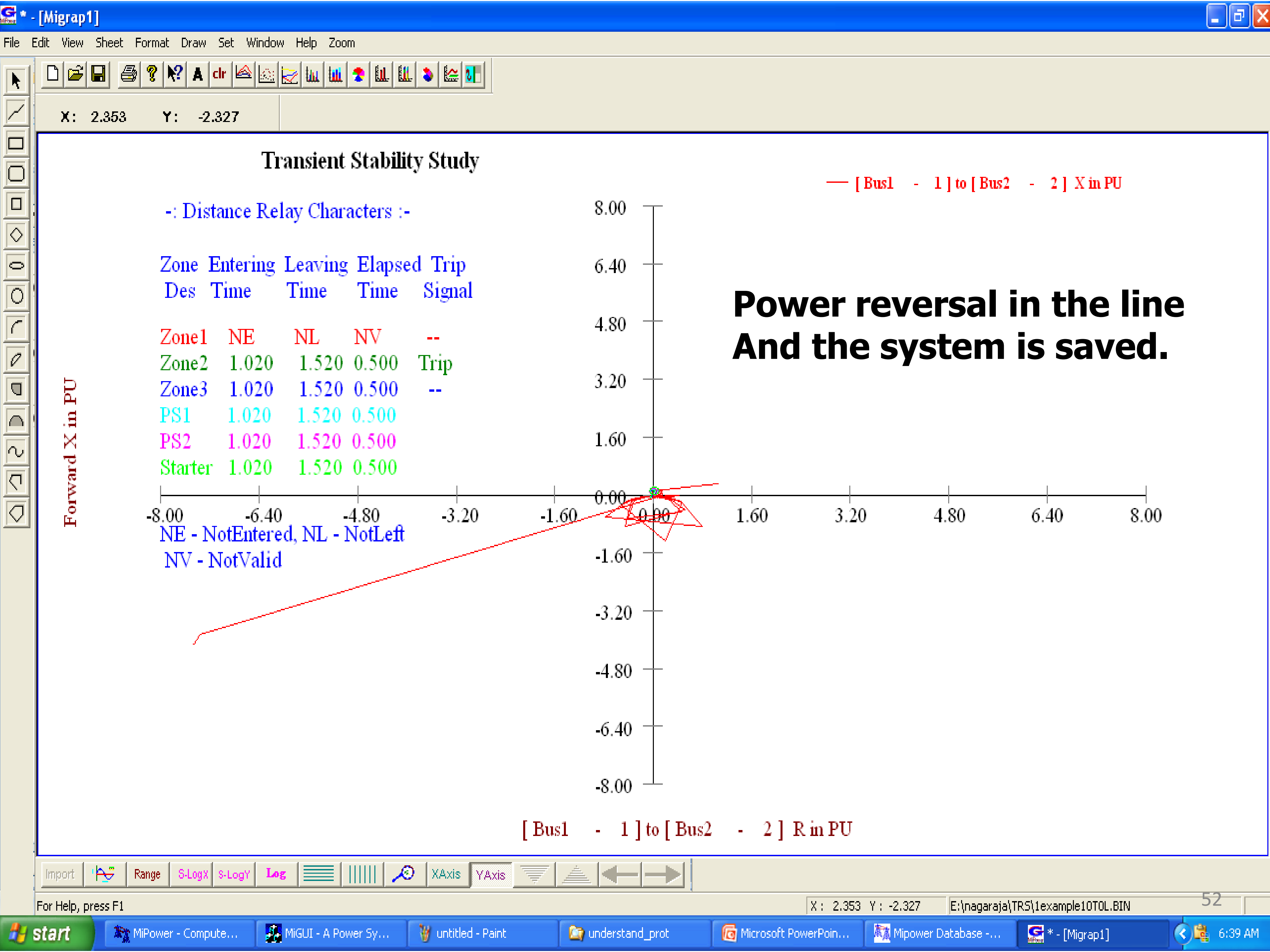


Fault cleared in 0.3 seconds


* - [Migrap1]
File Edit View Sheet Format Draw Set Window Help Zoom
X: 0.868 Y: -1.099
Transient Stability Study
-: Distance Relay Characters :-
Zone Des
Entering Time
Leaving Time
Elapsed Time
Trip Signal
Zone1 NE NL NV --
Zone2 1.020 1.520 0.500 Trip
Zone3 1.020 1.520 0.500 --
PS1 1.020 1.520 0.500
PS2 1.020 1.520 0.500
Starter 1.020 1.520 0.500
NE - NotEntered, NL - NotLeft
NV - NotValid
[Bus1 - 1] to [Bus2 - 2] X in PU
Fault cleared in 0.5 seconds
Forward X in PU
[Bus1 - 1] to [Bus2 - 2] R in PU
Import
Range
S-LogX
S-LogY
Log
XAxis
YAxis
For Help, press F1
X: 0.868 Y: -1.099
E:\nagaraja\TRS\1example10TOL.BIN
start
MiPower - Compute...
MiGUI - A Power Sy...
untitled - Paint
understand_prot
Microsoft PowerPoin...
Mipower Database -...
* - [Migrap1]
6:22 AM

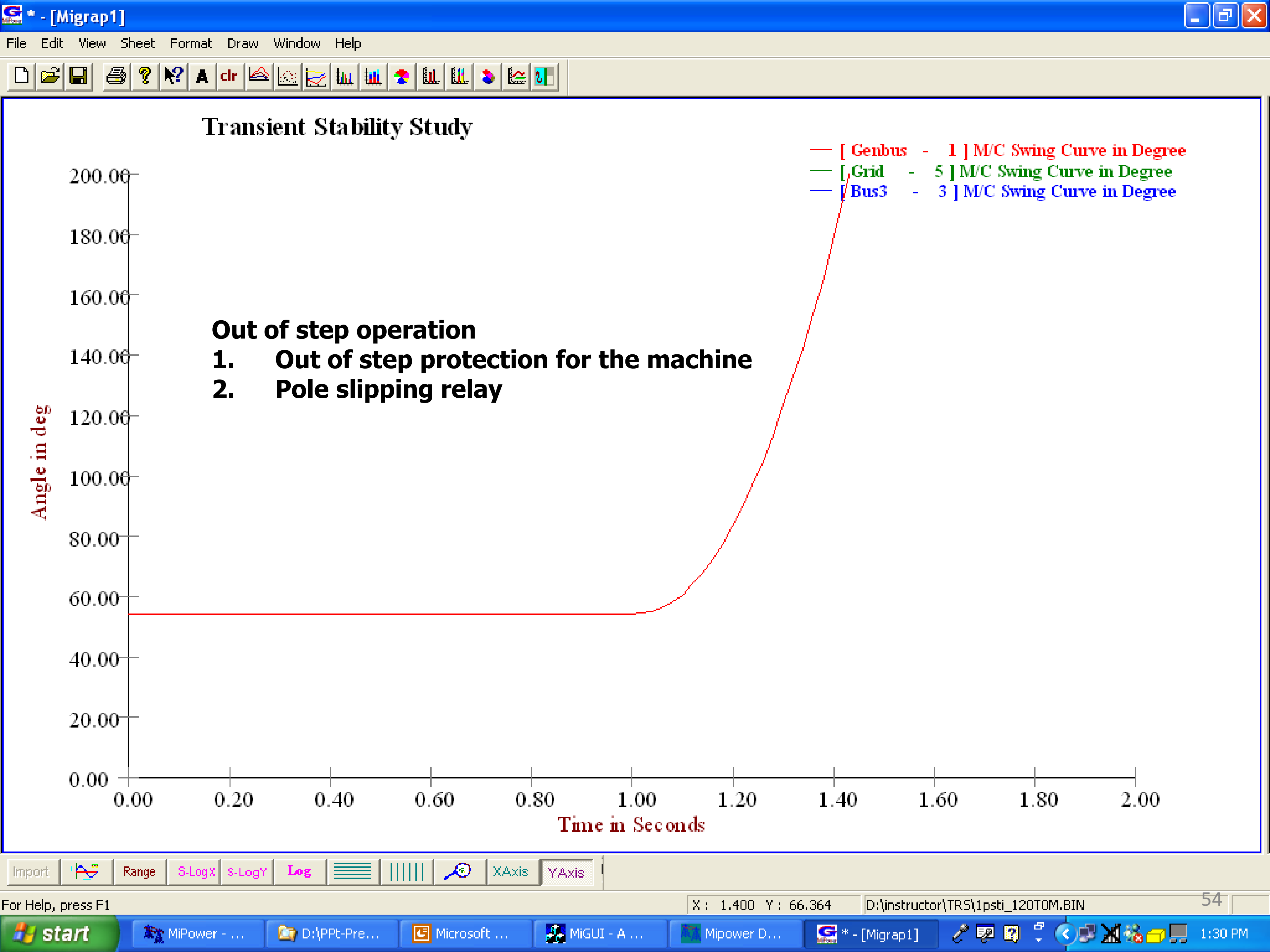


Out of step detected and generator tripped



Power reversal in the line
And the system is saved.

Understanding single pole auto re-closing facility



Out of step operation

1. **Out of step protection for the machine**
2. **Pole slipping relay**

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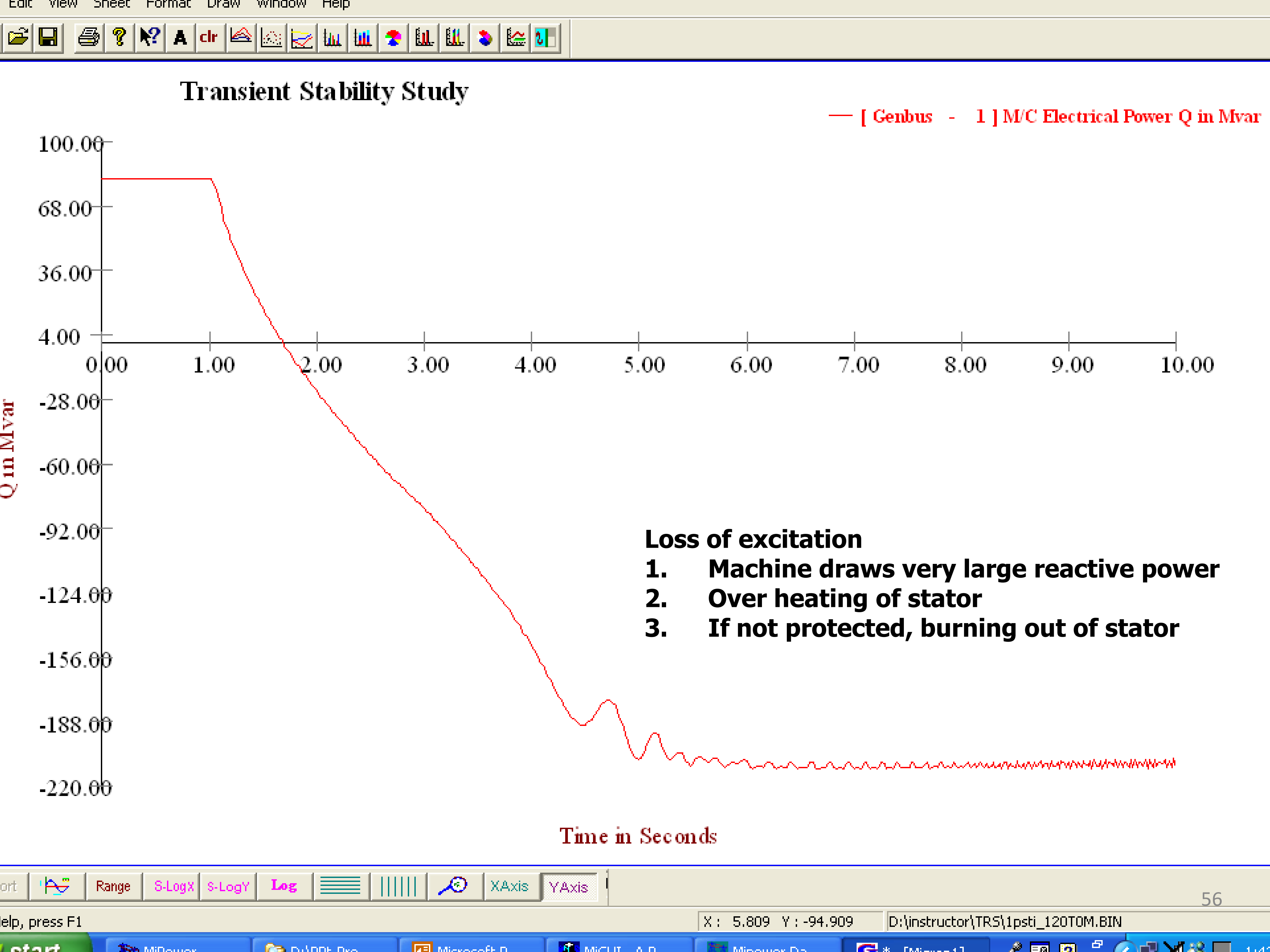
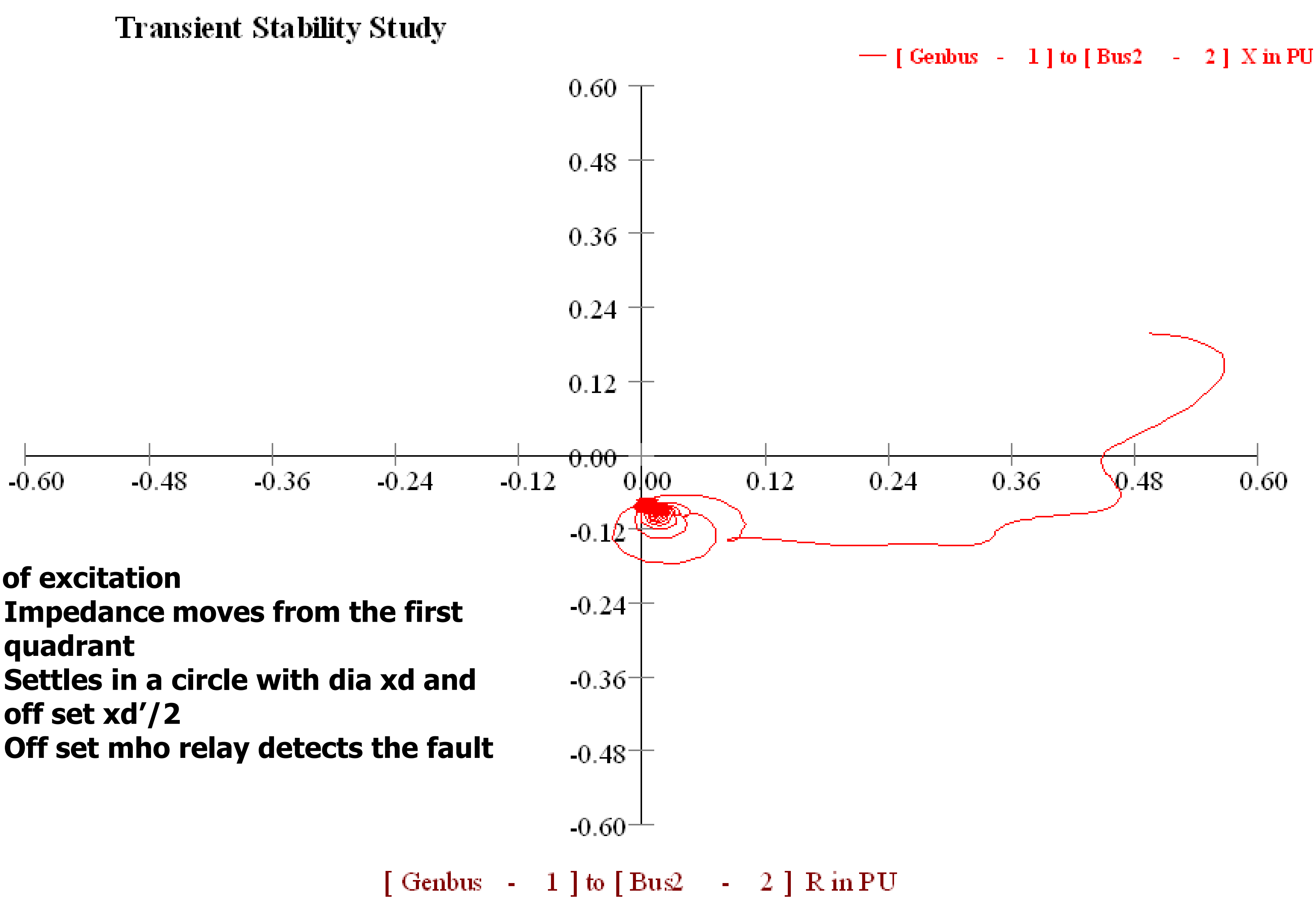
Protection Engineer designs the relay, based on system behavior



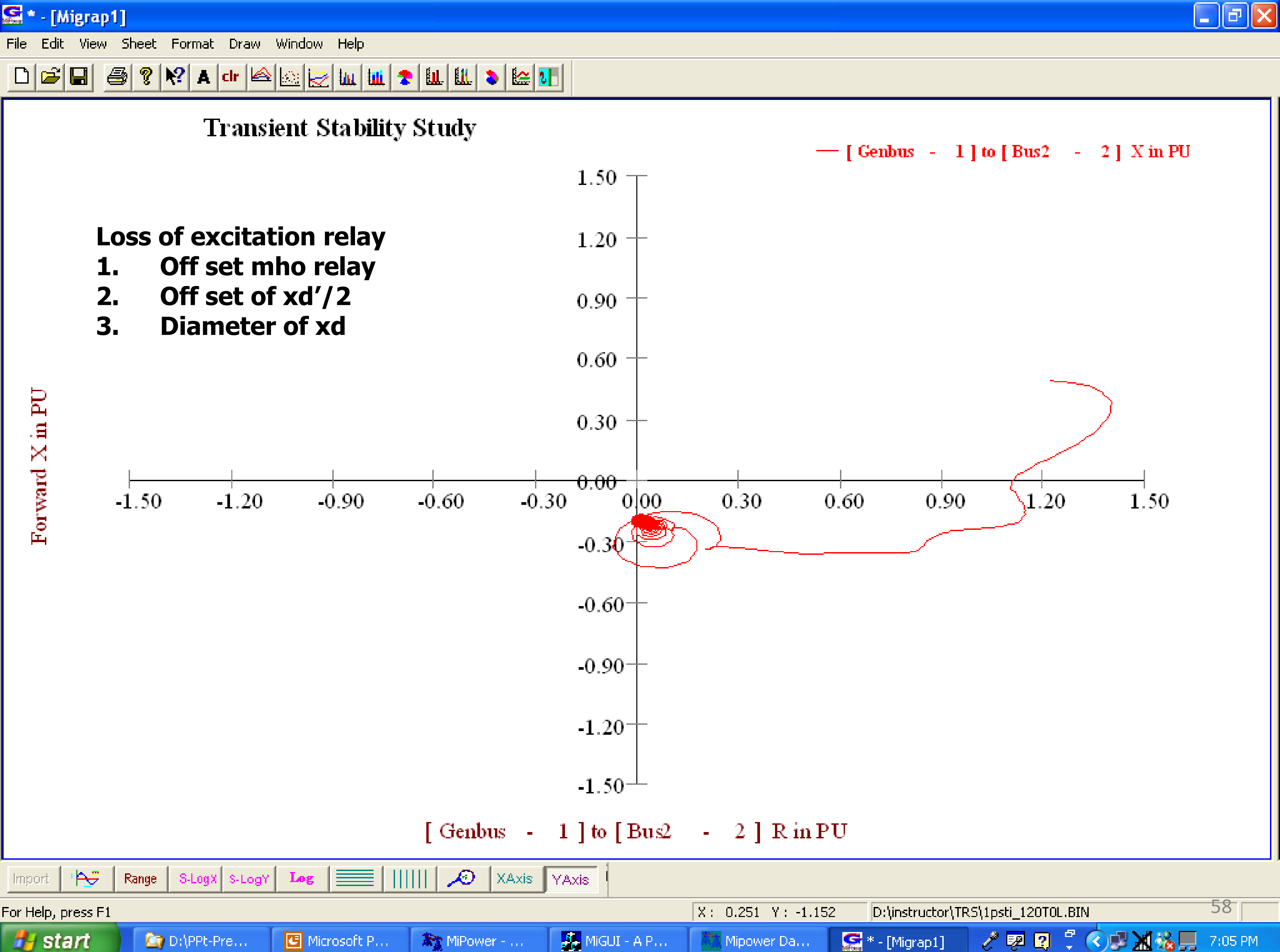
Loss of excitation

1. Machine draws very large reactive power
2. Over heating of stator
3. If not protected, burning out of stator

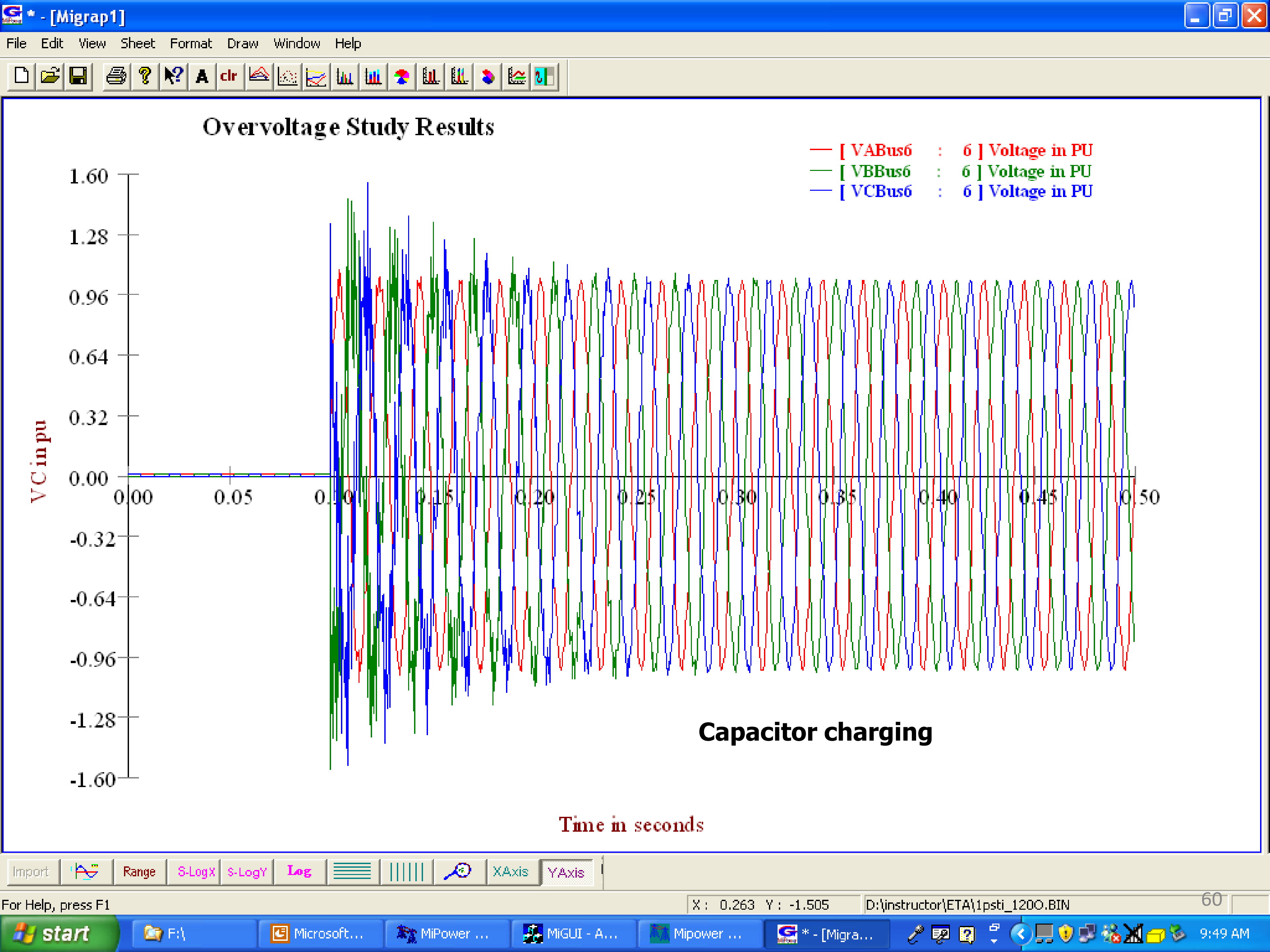


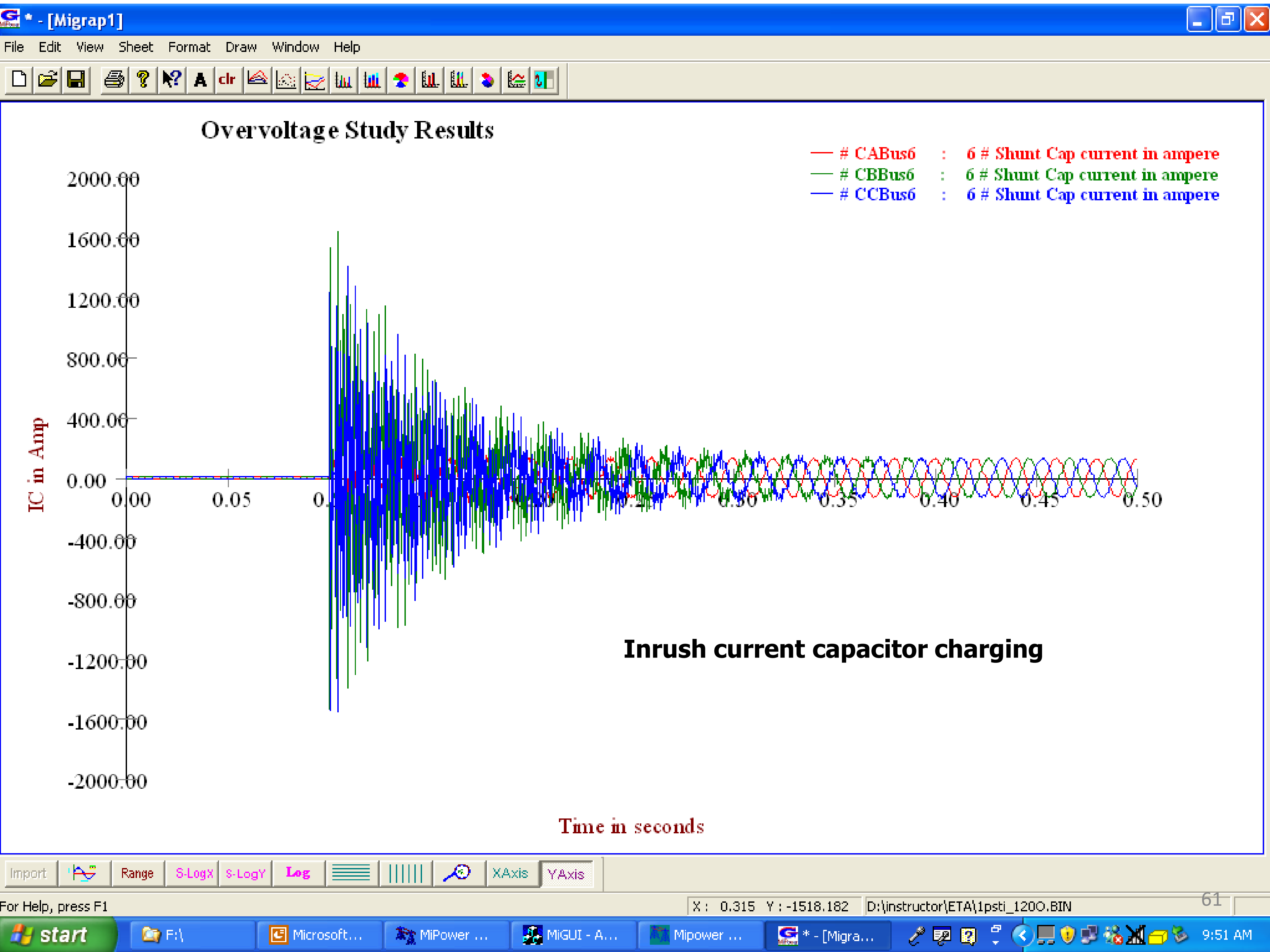
Loss of excitation

1. **Impedance moves from the first quadrant**
2. **Settles in a circle with dia xd and off set xd'/2**
3. **Off set mho relay detects the fault**

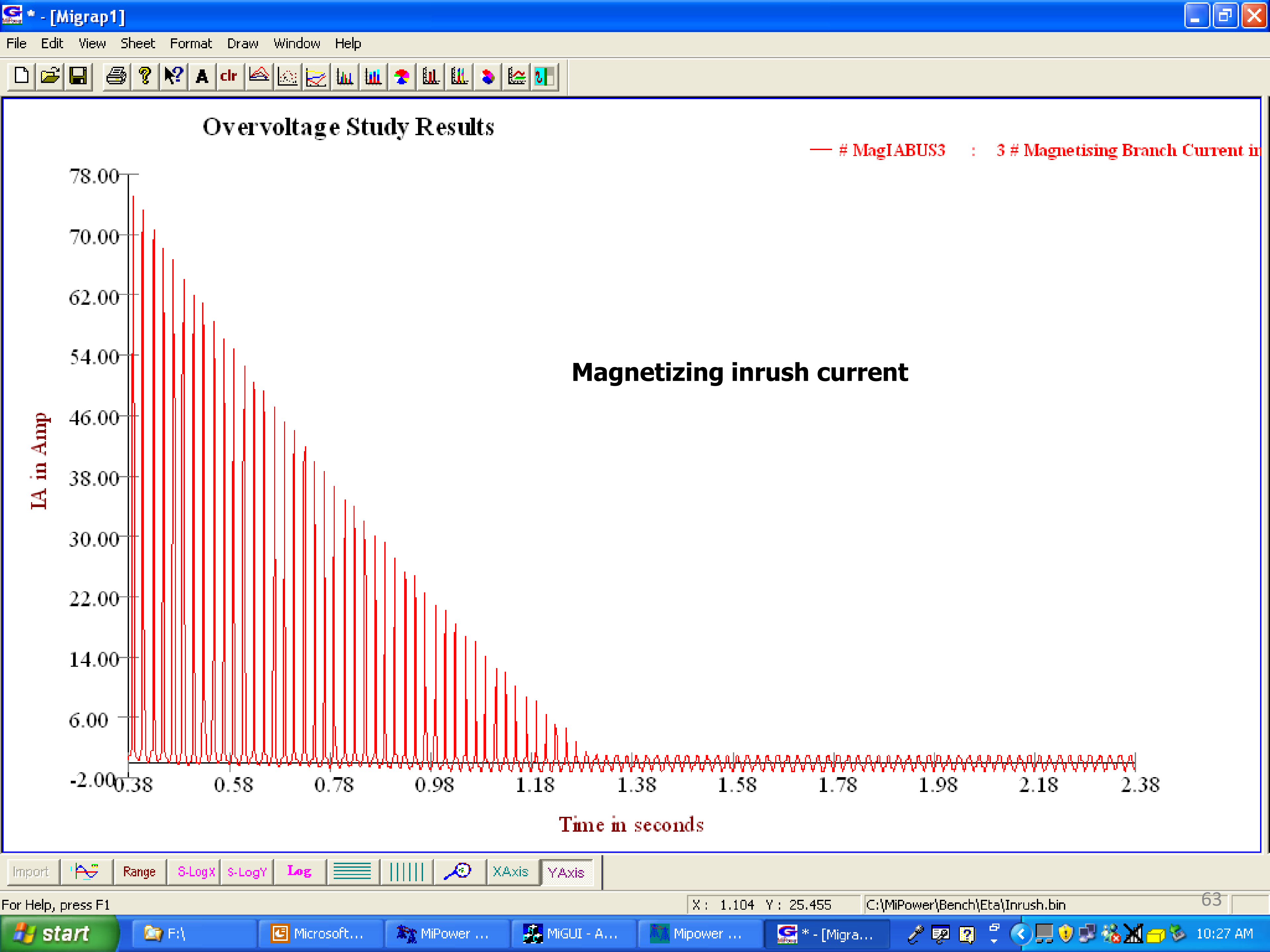

* - [Migrap1]
File Edit View Sheet Format Draw Window Help
Transient Stability Study
[Genbus - 1] to [Bus2 - 2] X in PU
Loss of excitation relay
1. Off set mho relay
2. Off set of xd'/2
3. Diameter of xd
Forward X in PU
1.50
1.20
0.90
0.60
0.30
0.00
-0.30
-0.60
-0.90
-1.20
-1.50
-1.50 -1.20 -0.90 -0.60 -0.30 0.00 0.30 0.60 0.90 1.20 1.50
[Genbus - 1] to [Bus2 - 2] R in PU
Import Range S-LogX S-LogY Log XAxis YAxis
For Help, press F1
X : 0.251 Y : -1.152
D:\instructor\TRS\1psti_120TOL.BIN
start D:\PPt-Pre... Microsoft P... MiPower - ... MiGUI - A P... Mipower Da... * - [Migrap1] 7:05 PM

Why current limiting reactor for capacitor banks?

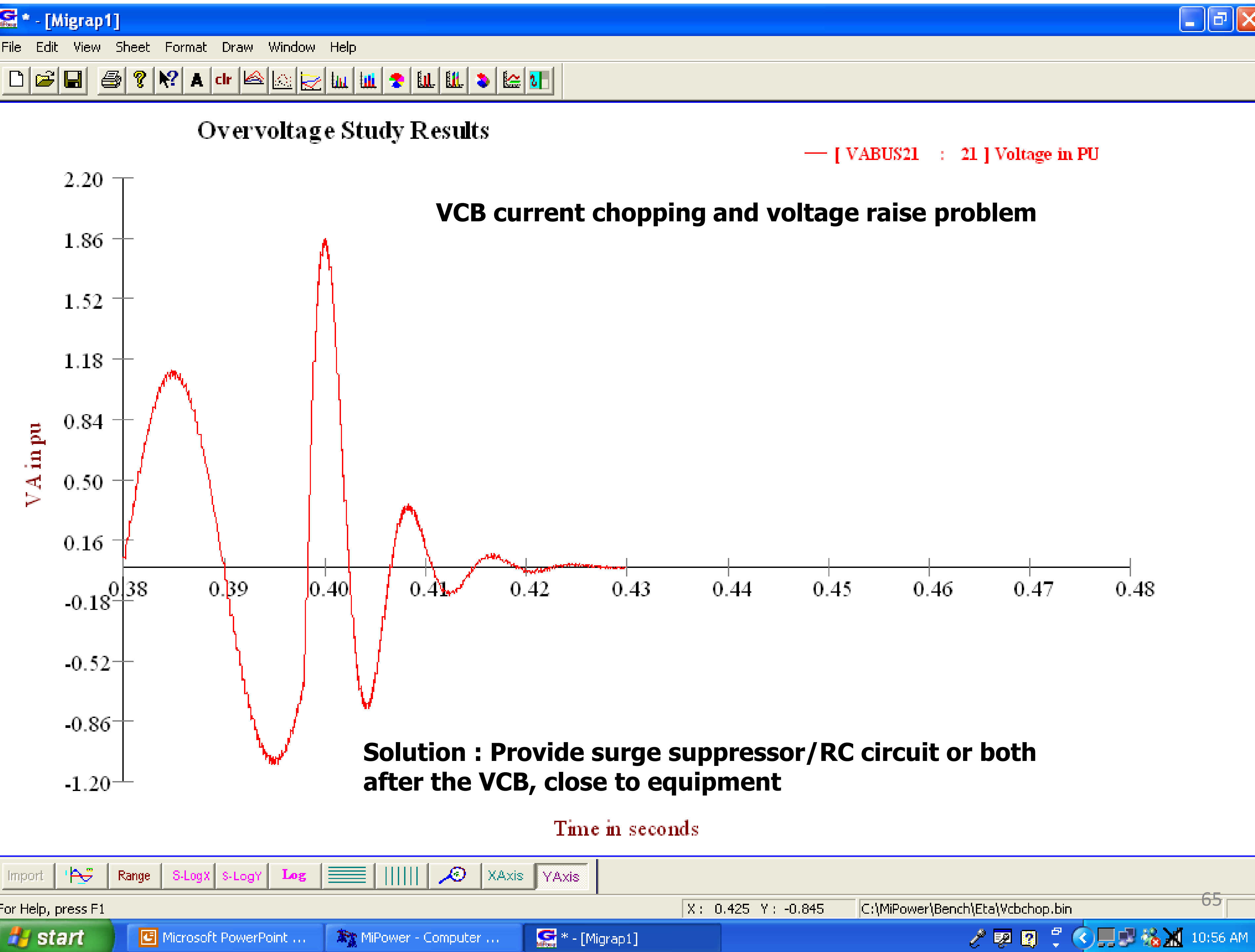

* - [Migrap1]
File Edit View Sheet Format Draw Window Help
Overvoltage Study Results
[VABus6 : 6] Voltage in PU
[VBBus6 : 6] Voltage in PU
[VCBus6 : 6] Voltage in PU
1.60
1.28
0.96
0.64
0.32
0.00
-0.32
-0.64
-0.96
-1.28
-1.60
VC in pu
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Capacitor charging
Time in seconds
Import
Range
S-LogX
S-LogY
Log
XAxis
YAxis
For Help, press F1
X : 0.263 Y : -1.505
D:\instructor\ETA\1psti_120O.BIN
start
F:\
Microsoft...
MiPower ...
MiGUI - A...
Mipower ...
* - [Migra...
9:49 AM


* - [Migrap1]
File Edit View Sheet Format Draw Window Help
Overvoltage Study Results
CABus6 : 6 # Shunt Cap current in ampere
CBBus6 : 6 # Shunt Cap current in ampere
CCBus6 : 6 # Shunt Cap current in ampere
IC in Amp
2000.00
1600.00
1200.00
800.00
400.00
0.00
-400.00
-800.00
-1200.00
-1600.00
-2000.00
0.00
0.05
0.30
0.35
0.40
0.45
0.50
Time in seconds
Inrush current capacitor charging
Import
Range
S-LogX
S-LogY
Log
XAxis
YAxis
For Help, press F1
X : 0.315 Y : -1518.182
D:\instructor\ETA\1psti_120O.BIN
start
F:\
Microsoft...
MiPower ...
MiGUI - A...
Mipower ...
* - [Migra...
9:51 AM

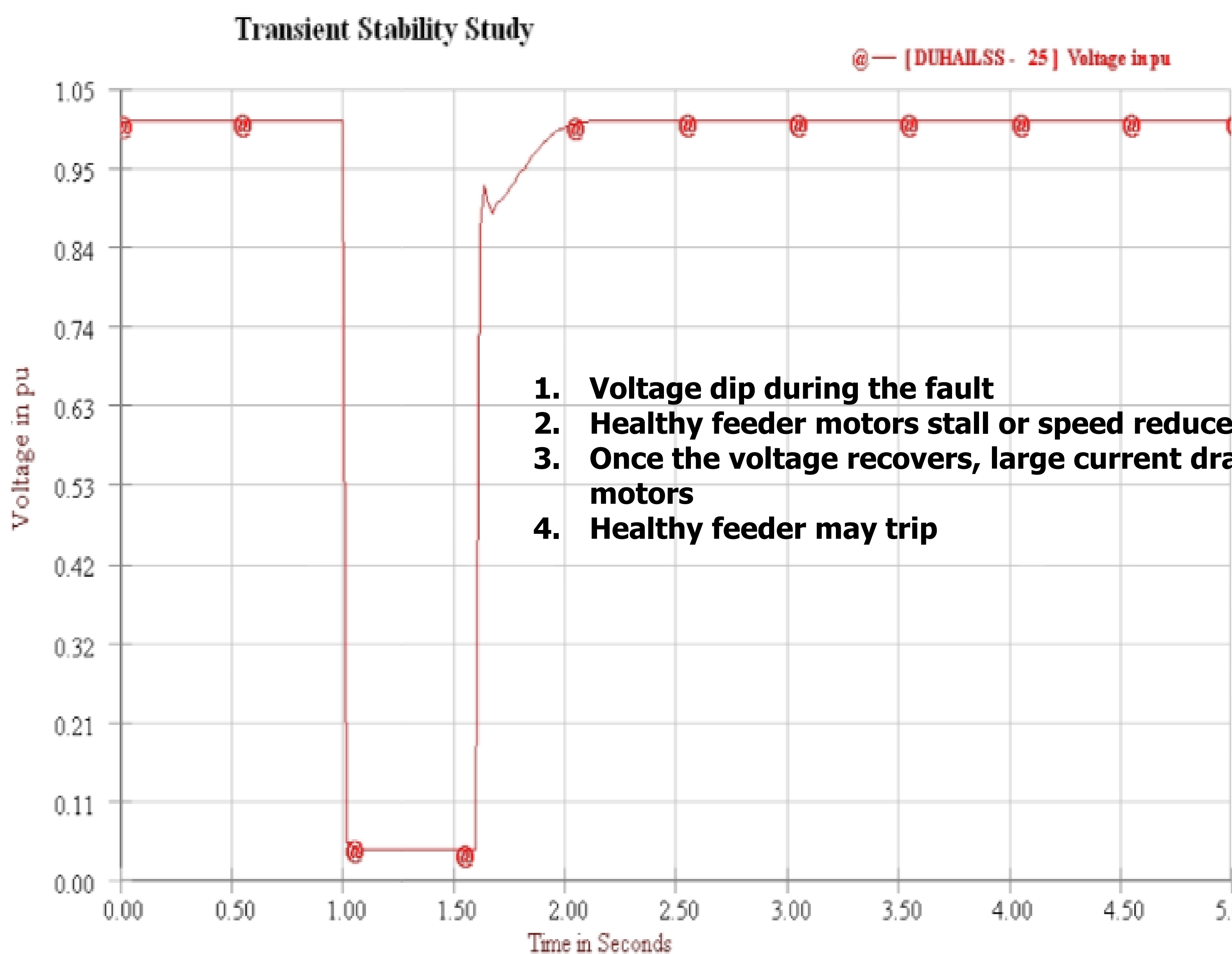
2nd Harmonic and 5th Harmonic restraint for transformer differential protection


* - [Migrap1]
File Edit View Sheet Format Draw Window Help
Overvoltage Study Results
MagIABUS3 : 3 # Magnetising Branch Current in
Magnetizing inrush current
IA in Amp
78.00
70.00
62.00
54.00
46.00
38.00
30.00
22.00
14.00
6.00
-2.00
0.38 0.58 0.78 0.98 1.18 1.38 1.58 1.78 1.98 2.18 2.38
Time in seconds
Import Range S-LogX S-LogY Log XAxis YAxis
For Help, press F1
X : 1.104 Y : 25.455
C:\MiPower\Bench\Eta\Inrush.bin
start F:\ Microsoft... MiPower ... MiGUI - A... Mipower ... * - [Migra... 10:27 AM

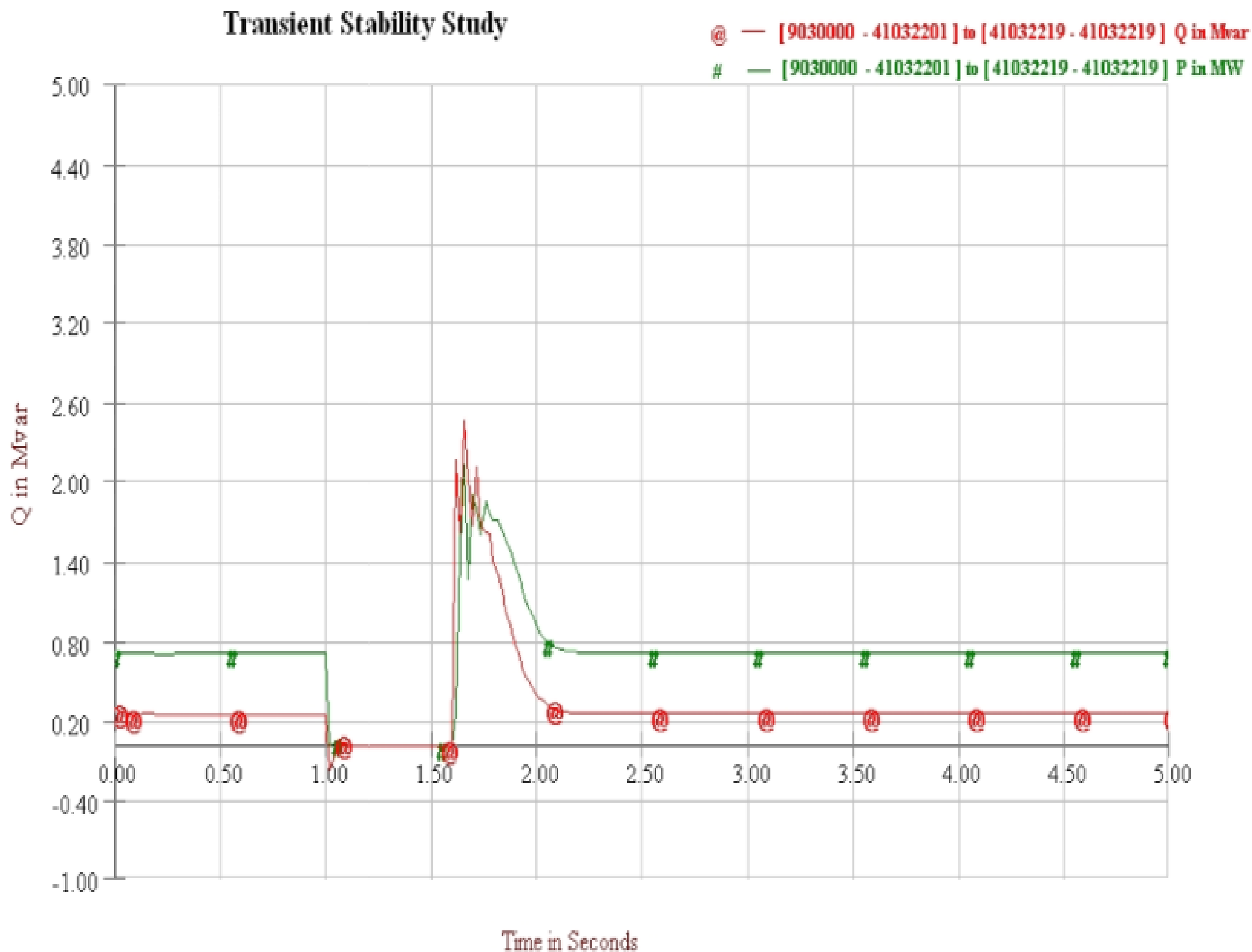
Why to provide surge arrestor and RC circuit for VCB switching


* - [Migrap1]
File Edit View Sheet Format Draw Window Help
Overvoltage Study Results
[VABUS21 : 21] Voltage in PU
VCB current chopping and voltage raise problem
2.20
1.86
1.52
1.18
0.84
0.50
0.16
-0.18
-0.52
-0.86
-1.20
VA in pu
0.38 0.39 0.40 0.41 0.42 0.43 0.44 0.45 0.46 0.47 0.48
Solution : Provide surge suppressor/RC circuit or both after the VCB, close to equipment
Time in seconds
Import Range S-LogX S-LogY Log XAxis YAxis
For Help, press F1
X : 0.425 Y : -0.845
C:\MiPower\Bench\Eta\Vcbchop.bin
start Microsoft PowerPoint ... MiPower - Computer ... * - [Migrap1]
10:56 AM

Sympathetic Tipping: What it means?



1. **Voltage dip during the fault**
2. **Healthy feeder motors stall or speed reduces**
3. **Once the voltage recovers, large current drawn by motors**
4. **Healthy feeder may trip**

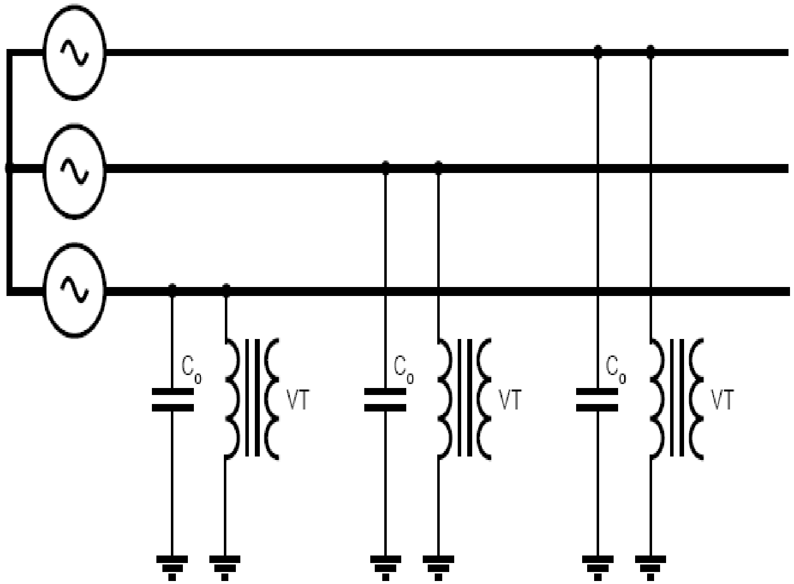

Transient Stability Study
@ — [9030000 - 41032201] to [41032219 - 41032219] Q in Mvar
# — [9030000 - 41032201] to [41032219 - 41032219] P in MW
5.00
4.40
3.80
3.20
2.60
2.00
1.40
0.80
0.20
-0.40
-1.00
Q in Mvar
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
Time in Seconds

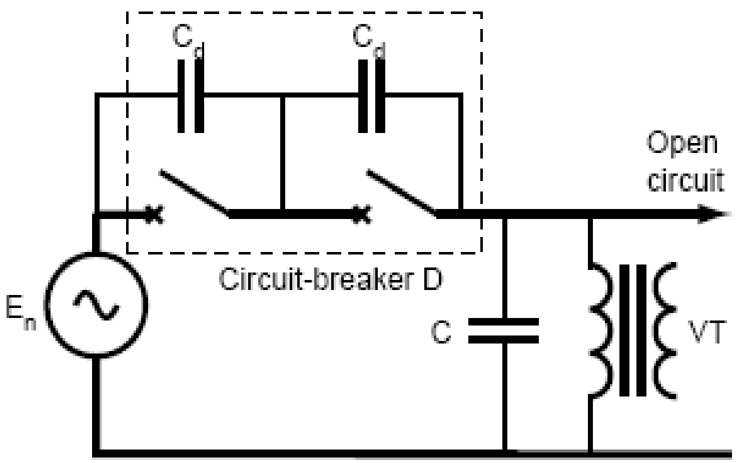
Ferroresonance: When and How?

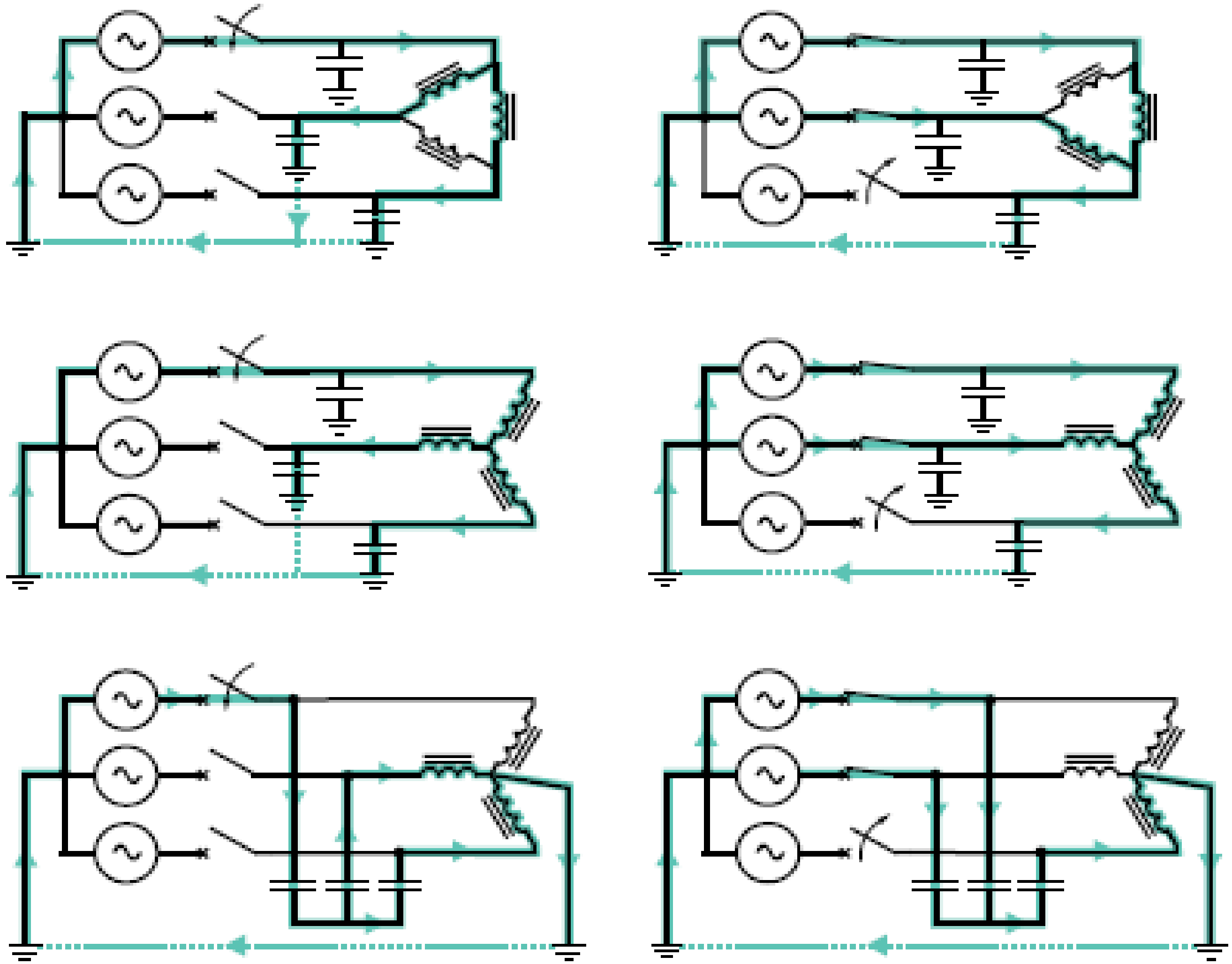
Ferroresonance (FR) TOV

- An oscillating phenomena occurring in an electric
- Circuit which must contain at least:
  - ✓ a non-linear inductance
  - ✓ a capacitor,
  - ✓ a voltage source (generally sinusoidal),
  - ✓ low losses.
- Transients, lightning over voltages, energizing or de-energizing transformers or loads, occurrence or removal of faults, etc...may initiate ferroresonance.
- The main feature of this phenomenon is that more than one stable steady state response is possible for the same set of the network parameters.

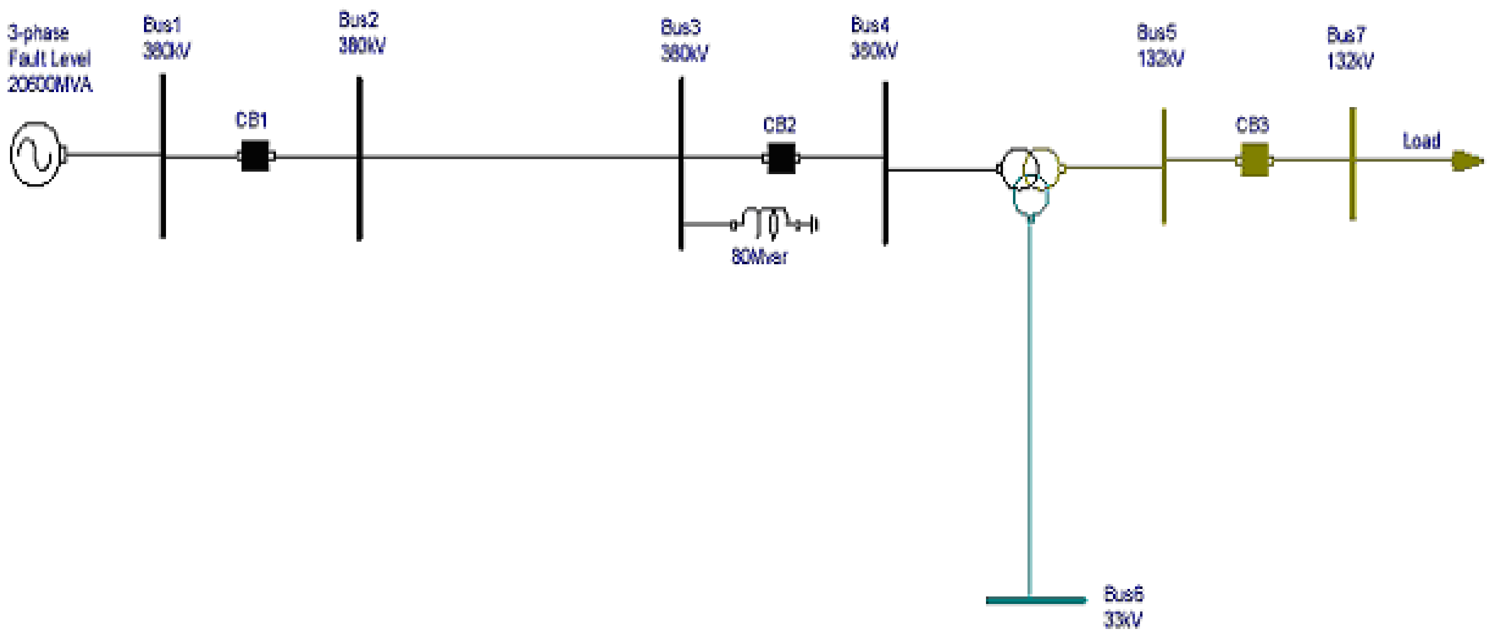
Examples of Systems at Risk from Ferroresonance.

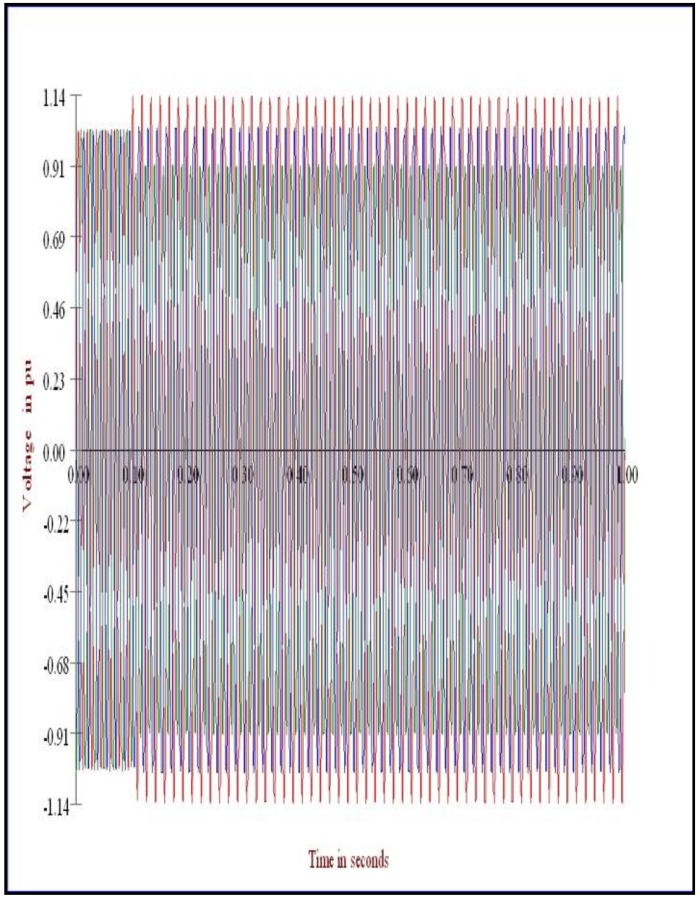




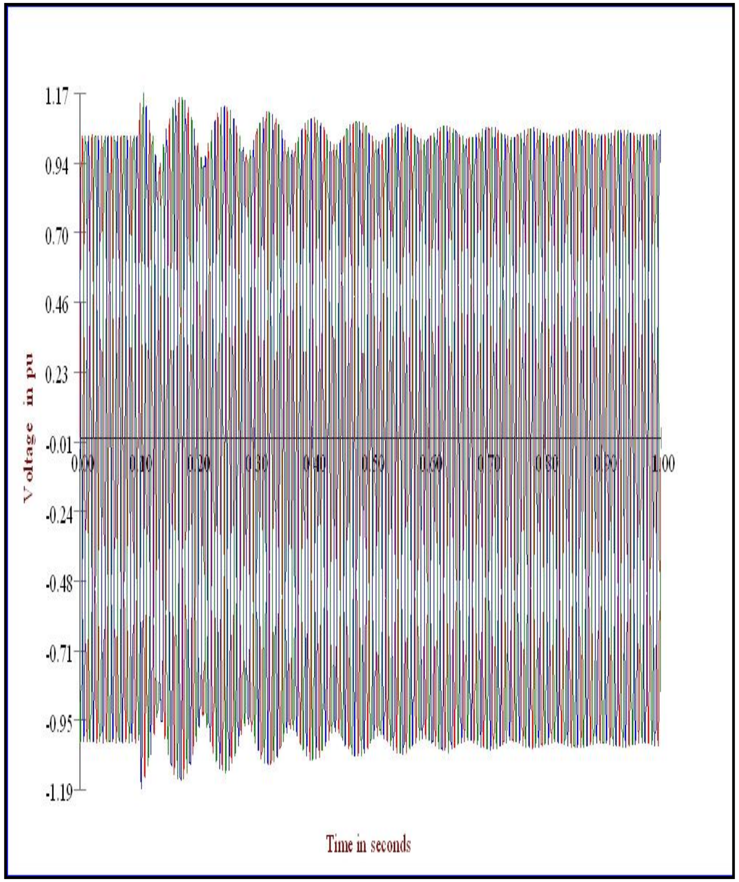


Case study for predicting and understanding of TOV and FR



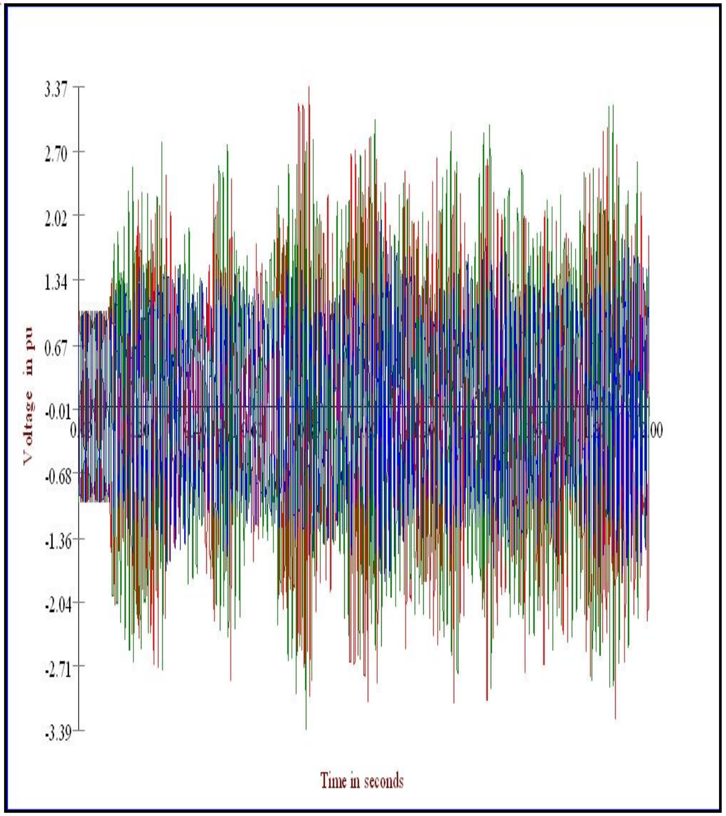


1-pole

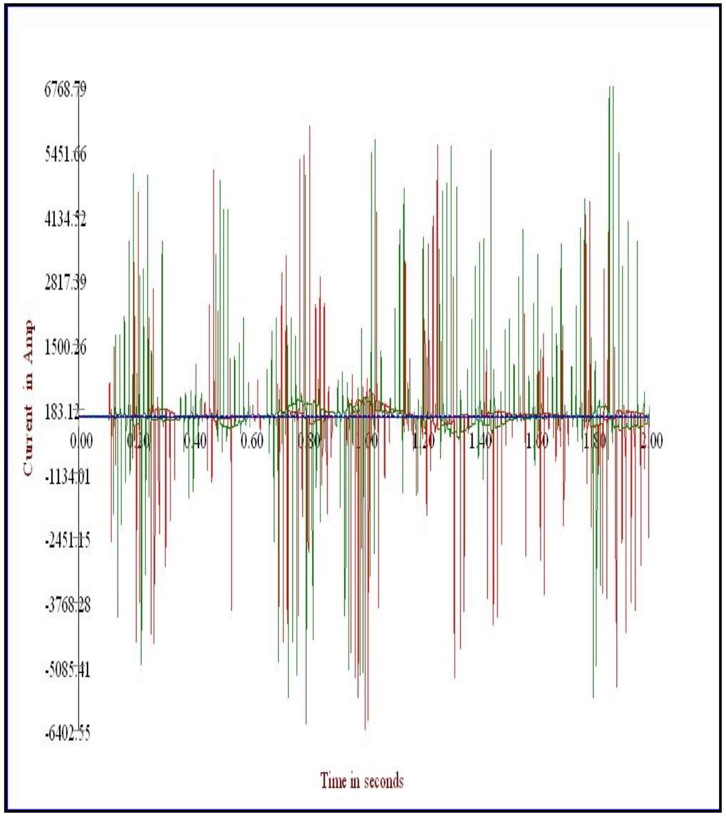


3-pole

HT side LR by opening CB2



Voltage



Current

FR existence when 2-poles opening of CB1

Conclusions

1. The various issues in the protection are discussed
2. It is concluded that close co-ordination for protection department with other departments are required.
3. The simulation tools help in learning the protection aspects
4. Automated fault analysis system will help in understanding the relay tripping incidences better.

Queries & Discussions

Thank You

PSCT | Protection Analytic tool

पूर्वी क्षेत्रीय विद्युत समिति

प्रगति के पथ को रोशन

MODELLING OF POWER SYSTEM ELEMENTS & LOAD FLOW STUDIES

PRDC®
विज्ञानेन जातानि जीवन्ति

PSCT | Protection Analytic tool

Per-unit Calculation

Power base : MVA

Voltage base : V_{LL} (kV)

Current base $= \dfrac{MVA x 1000}{\sqrt{3} V_{LL}}$

Impedance base $= Z_{base} = \dfrac{(kV)^2}{MVA}$

Base Conversion for Impedance:

MVA_{b1} is the old power base

MVA_{b2} is the new power base

kV_{b1} is the given voltage base

kV_{b2} is the new voltage base

Z_{pu1} is known $Z_{pu2} = ?$

$$Z_{base1} = \frac{(Kv_{b1})^2}{MVA_{b1}} \qquad Z_{base2} = \frac{(kV_{b2})^2}{MVA_{b2}}$$

$$Z_{act} = Z_{base1} . Z_{pu1} \qquad Z_{act} = Z_{base2} . Z_{pu2}$$

$$Z_{base1} . Z_{pu1} = Z_{base2} . Z_{pu2}$$

$$Z_{pu2} = \frac{Z_{base1} . Z_{pu1}}{Z_{base2}} = Z_{pu1} \frac{(kV_{b1})^2}{MVA_{b1}} . \frac{(MVA_{b2})}{(kV_{b2})^2}$$

$$If\, kV_{b1} = kV_{b2}, then$$

$$Z_{pu2} = Z_{pu1} \left(\frac{MVA_{b2}}{MVA_{b1}} \right)$$

Examples:

Base MVA: 100, Base kV : 220,
Base Current, I = 262.43 A, Base Z = 484 ohm

350 MW = 350/100 = 3.5 pu
220 MVAR = 220/100 = 2.2 pu
210 kV = 210/220 = 0.9545 pu
400 A = 400/262.43 = 1.524 pu

220 kV, 145 km line length, R = 0.06 ohm/km,
X = 0.4 ohm/km

In pu, for the entire line length,

R = 0.06x145/484 = 0.018 pu, X = 0.4x145/484 = 0.1198 pu

Examples:

500 MVA, 12.5% impedance
On 100 MVA, it is 0.125*100/500 = 0.025 pu

5 MVA, 8% impedance
On 100 MVA, it is 0.08*100/5 = 1.6 pu

Transmission line modelling:

1. Equivalent π Circuit.

2. Balanced operation
   No zero sequence.
   No mutual.
   Perfectly transposed.

3. Series compensation
   Series compensation factor X_c/X_L

4. Shunt compensation
   Shunt compensation factor B_L/B_c

Power quality – Voltage

- Voltage should be within the acceptable limit as per the grid code
- Acceptable voltage limits :

Voltage	Maximum	Minimum
33 kV	36.3 kV 1.1 pu	29.7 kV 0.96 pu
132 kV	145 KV 1.099 kV	122 kV 0.924 pu
220 kV	245 kV 1.114 pu	198 kV 0.900 pu
400 kV	420 kV 1.050 pu	380 kV 0.950 pu

Types of over voltages:

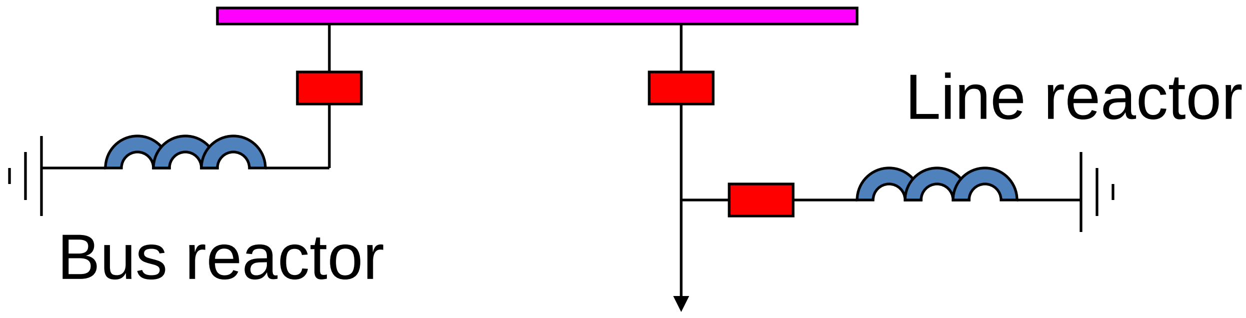
- Steady state over voltage
- Temporary over voltage
- Switching over voltage
- Lightning over voltage

Mitigation -

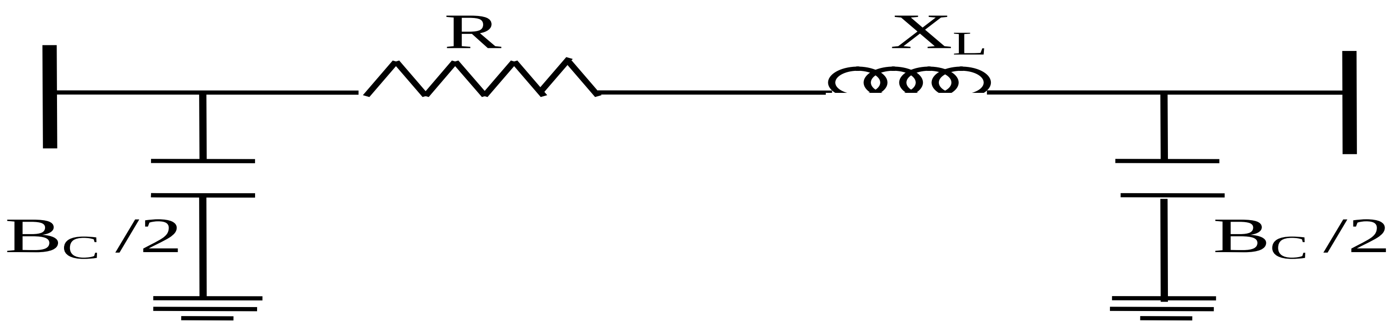
- Static var compensators
- Shunt capacitors and shunt reactors
- Strong transmission system

Types of Reactors:

- Bus reactor to mitigate the problem of steady state over voltage. Connected at the busbar to compensate for short lines terminated at a substation.
- Line reactors to mitigate the problem of steady state over voltage and switching over voltage. Connected as part of the transmission line, after the line breaker.



Types of Reactors:



400 kV / 100 MVA base; 350 km

R=0.0306 Ω / km --- 0.00669375 pu

X_L = 0.305 Ω / km --- 0.06672 pu

Bc = 3.4375 μ ℧ /km --- 1.925 pu

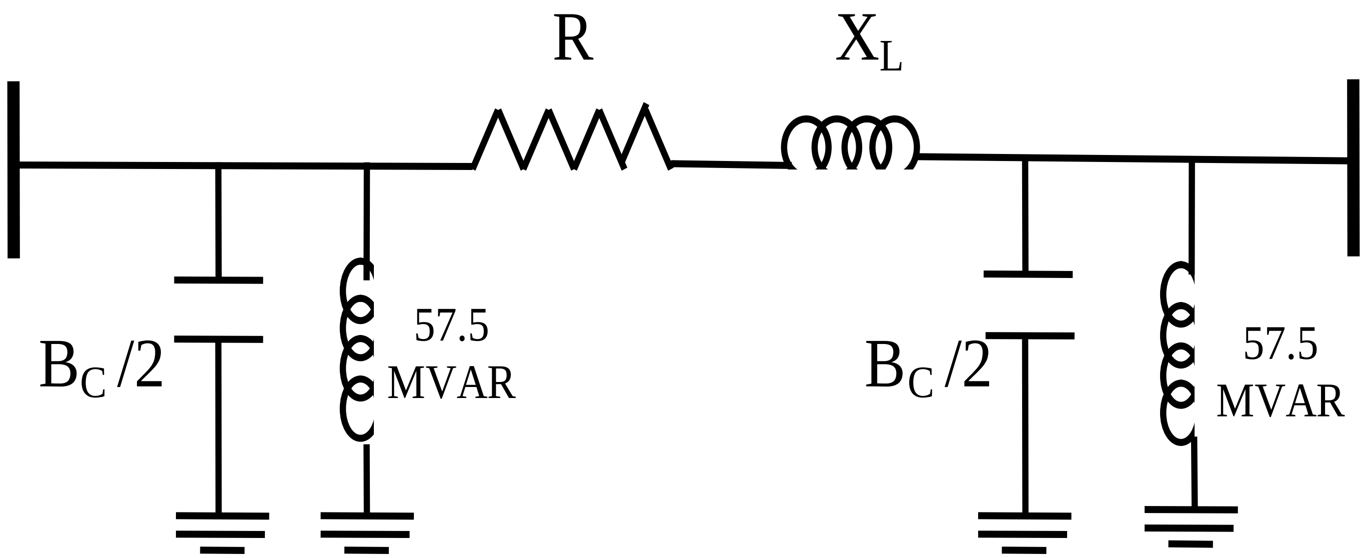
40% series compensation : Xc = 0.026688 pu

60% shunt compensation : B_L = 1.155 pu

≅ 115 MVAR

PSCT Protection Analytic tool

Types of Reactors:



Surge impedance :

Simple Expression : $\sqrt{\dfrac{L}{C}}$

Exact Equation:

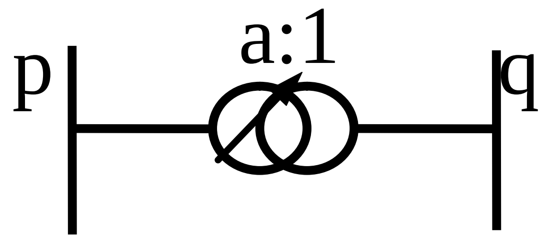
$$Z_c = \sqrt{\frac{z}{y}} = \sqrt{\frac{R + jX_L}{0 + jB_c}} \cong \sqrt{\frac{2\pi f L}{2\pi f C}} = \sqrt{\frac{L}{C}}$$

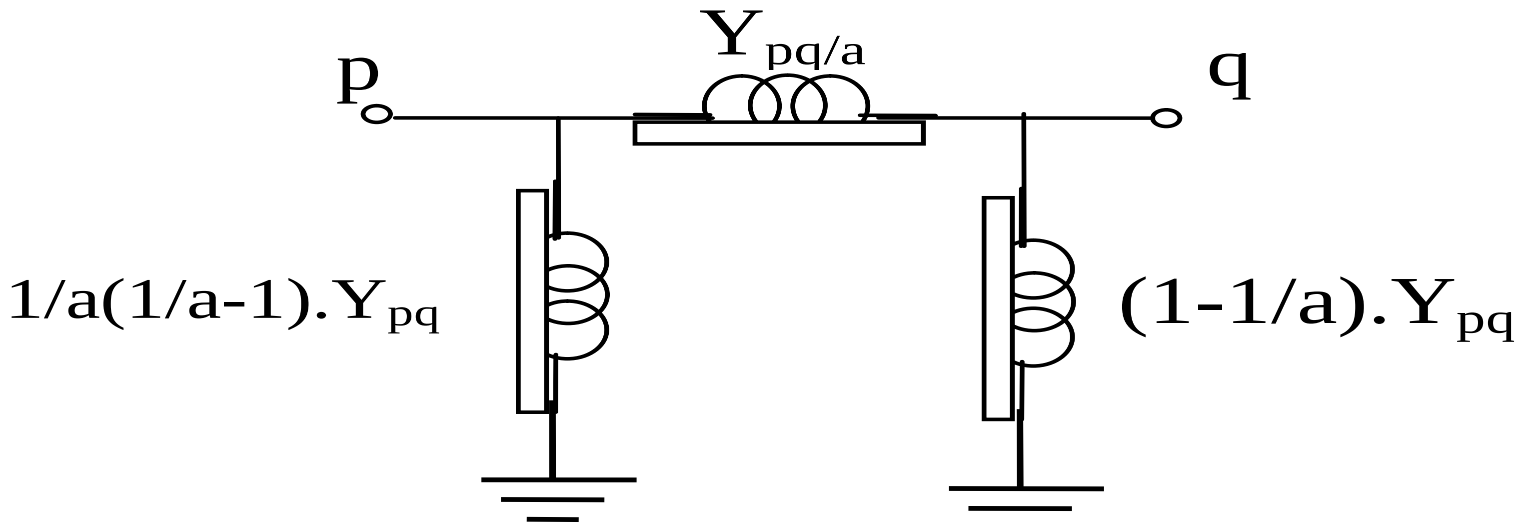
$$SIL = \frac{V^2}{SI} MW$$

Exercise:

For the given transmission line, load the line
1) Less than SIL
2) Equal to SIL
3) More than SIL
and plot the terminal voltage.

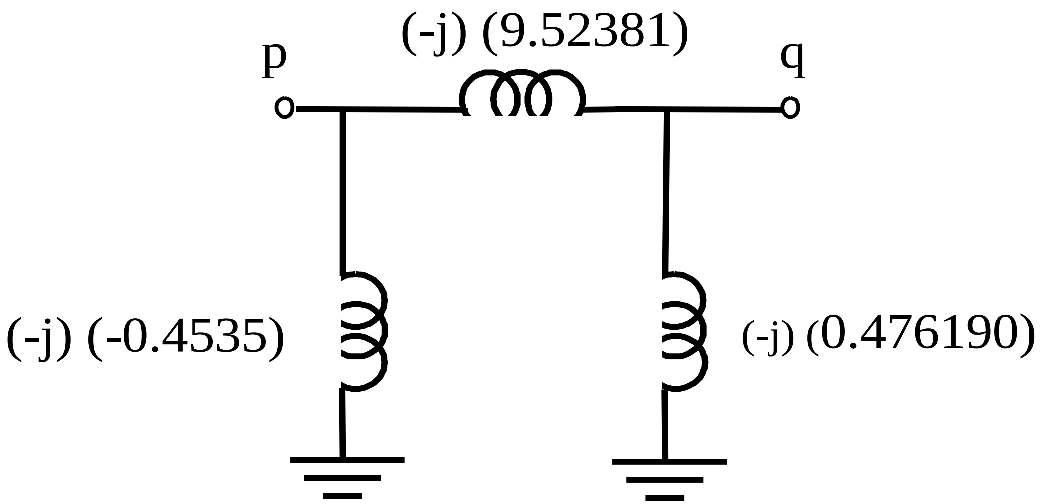
Transformer Modelling:

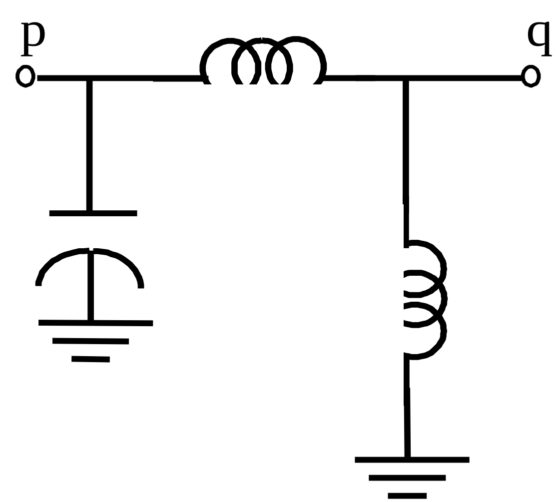




Transformer Modelling:

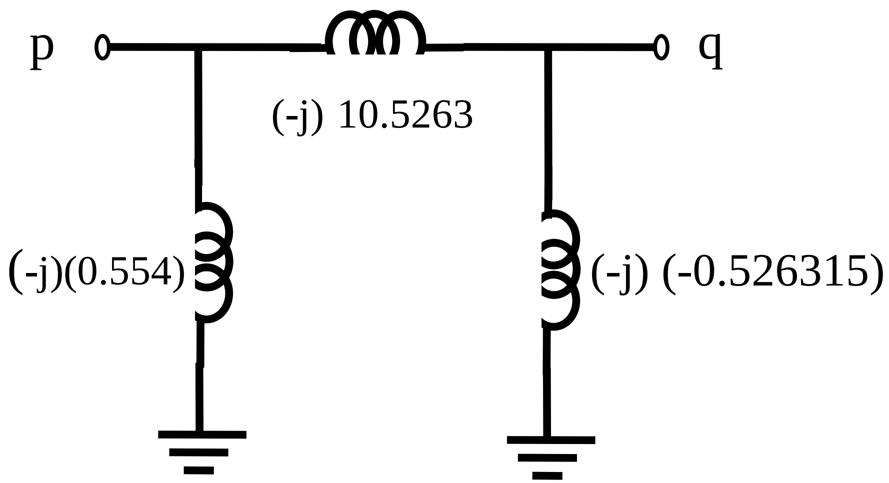
With R=0, a=1.05, X_t = 10%

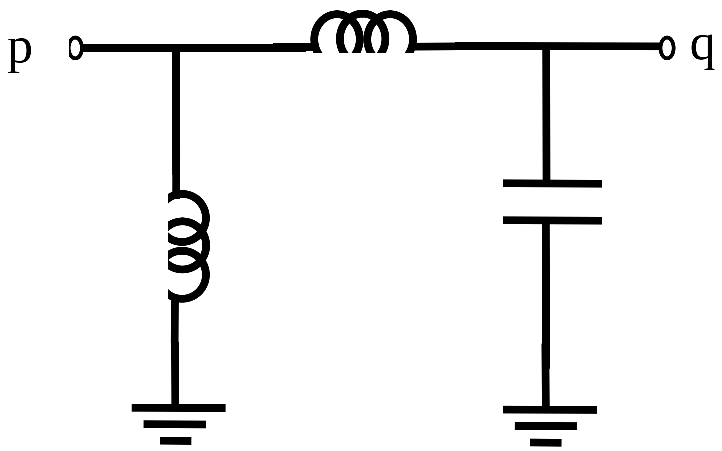




Transformer Modelling:

For a = 0.95,





Transformer Impedance

- Reactive power loss
- Voltage drop
- Fault level

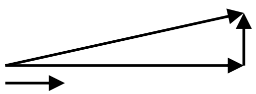
Reactive Power Loss

- 100 MVA, 10% Z, fully loaded, reactive power loss = 0.1*1*1 = 0.1 pu = 10 MVAR
- If it is 50% loaded, reactive power loss = 2.5 MVAR
- 500 MVA, 12.5 % impedance consumers 62.5 MVAR, when it is fully loaded.
- From generation to load at LT, there are about six transformation levels and at each level, there is reactive power loss.
- It is not just the load reactive power, we need to compensate the reactive power loss within the transformer.

Voltage Drop

- 100 MVA transformer, 10% impedance implies X is close to 10%, as the resistance is neglected.
- If the transformer is fully loaded at unity power factor, the voltage drop is negligible.
- If the transformer is fully loaded at zero power factor, the voltage drop is 10%.

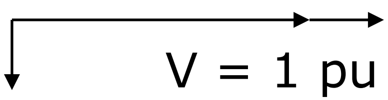
E   IX = 0.1 pu



E = sqrt (1*1+0.1*0.1) = sqrt(1.01), approximately = 1.0

I= 1pu   V = 1 pu   VR = (1-1)/1 = 0

IX = 0.1 pu



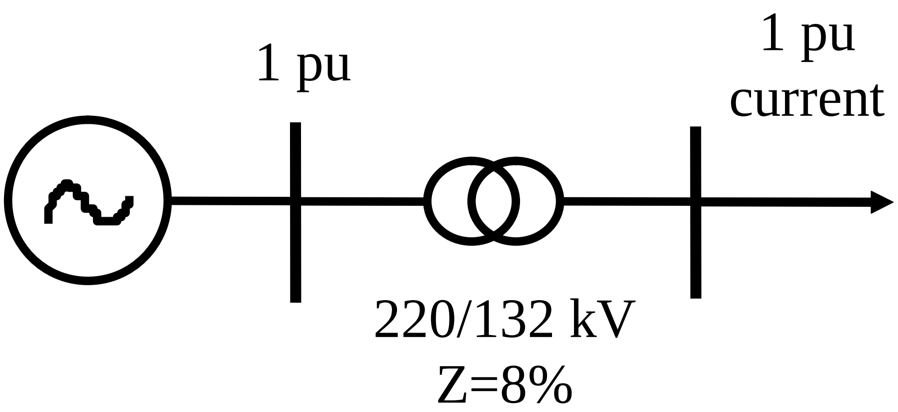
E = 1+0.1 = 1.1 pu

I= 1pu   V = 1 pu

VR = (1.1-1)/1 = 0.1=10%

Transformer Modelling:

220 kV/132 kV, 8% impedance on own rating of 115 MVA.



Transformer Modelling:

Points to Note :

- Usual impedance range.
- R considered or not.
- Number of units in parallel.
- Tap position.
- Tap reference.

Typical Transformer Data:

Transformer impedance on its own MVA rating:

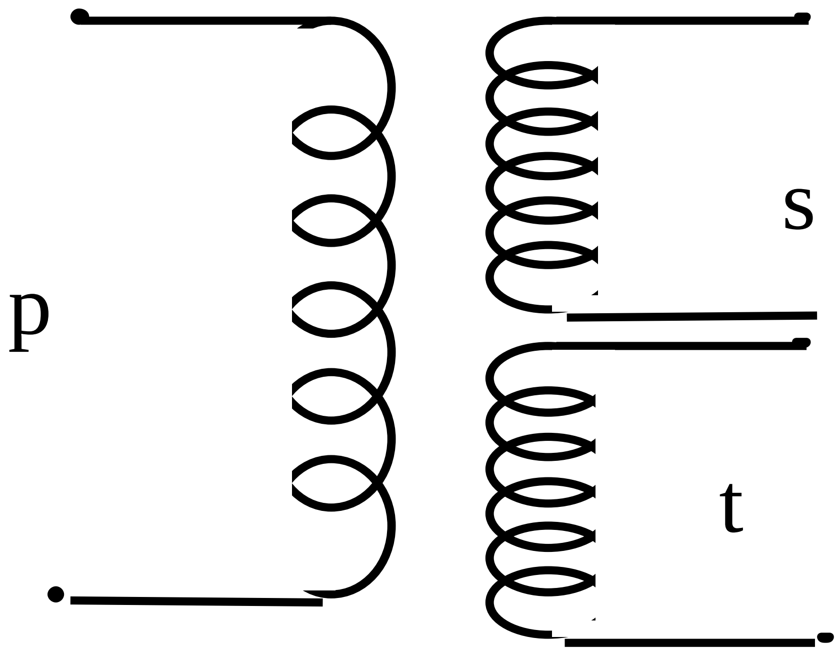
Generating unit : 14-15%

Interconnecting unit : 12.5%

Power transformers : 9-10%

Distribution transformers : 4.0-4.5% or even less

Three Winding Transformers:



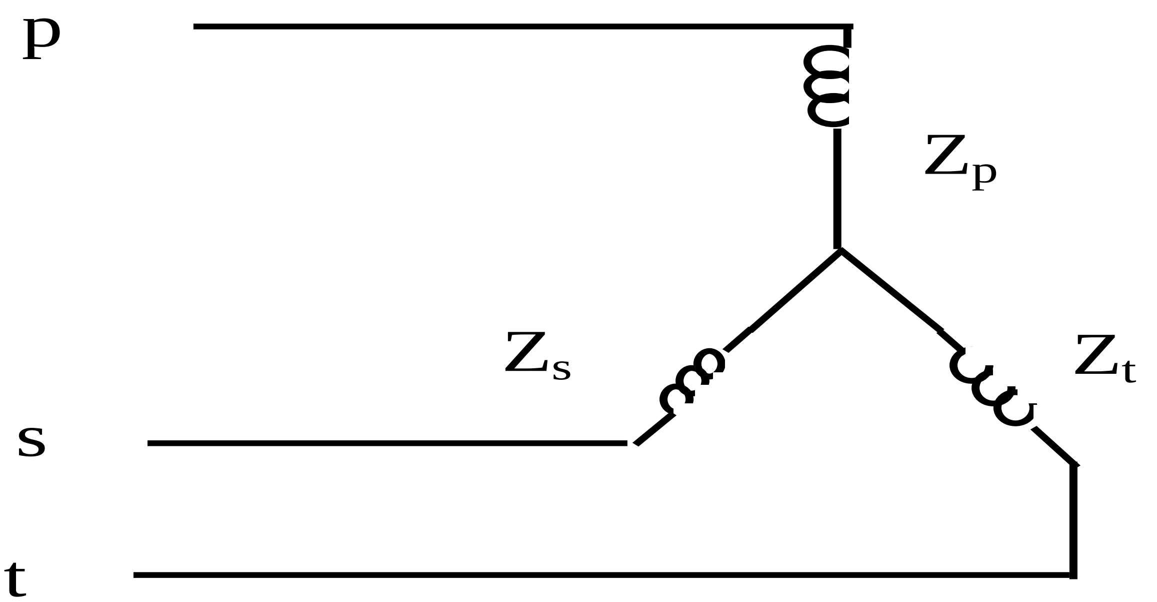
p-s - t
H - M - L

Three Winding Transformers :

$Z_{ps} = Z_p + Z_s$ ------------(1)

$Z_{st} = Z_s + Z_t$ ------------(2)

$Z_{pt} = Z_p + Z_t$ ------------(3)

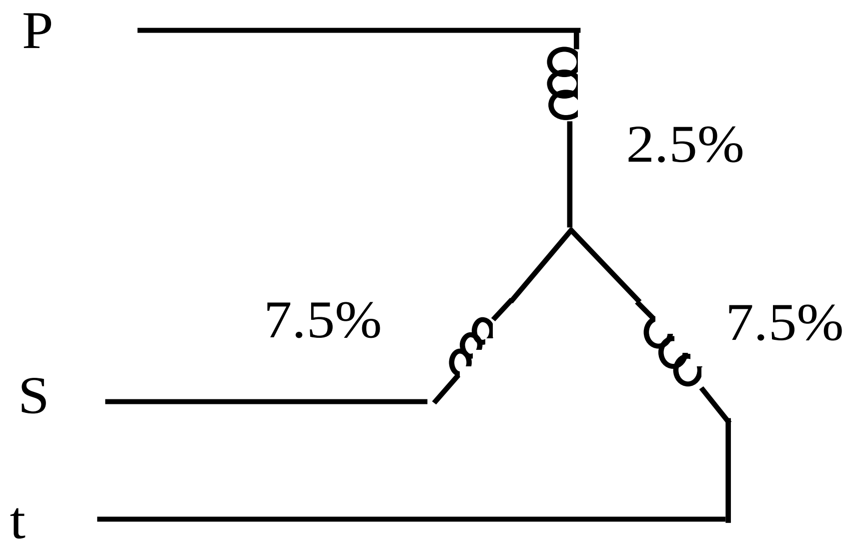


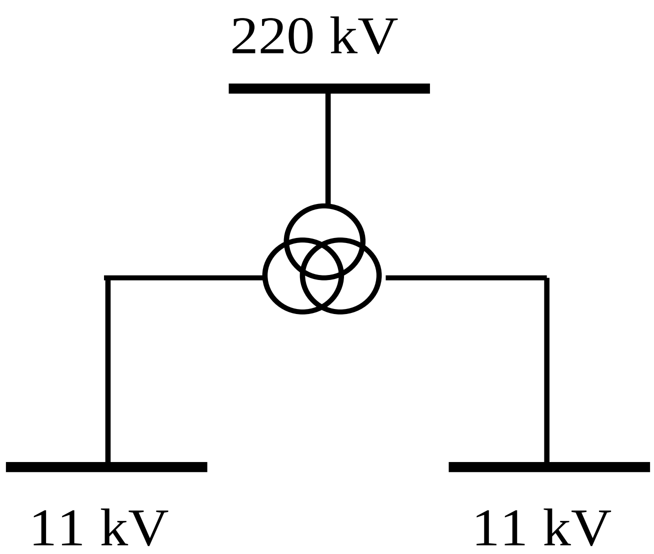
Example 1

220/11/11 kV ; 10%; 10%; 15% on 50 MVA rating

Zps = 10% Zpt = 10% Zst = 15%

Zp = 2.5% Zs = 7.5% Zt = 7.5%





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Example 2

220/132/11kV,
Primary-80 MVA, Secondary-60 MVA, Tertiary 20 MVA.
Zps = 9.5% on primary rating, Zpt = 11.5% on primary rating,
Zst = 16.5% on secondary rating

$$Z_{st} = 16.5 \times \frac{80}{60} = 22\%$$

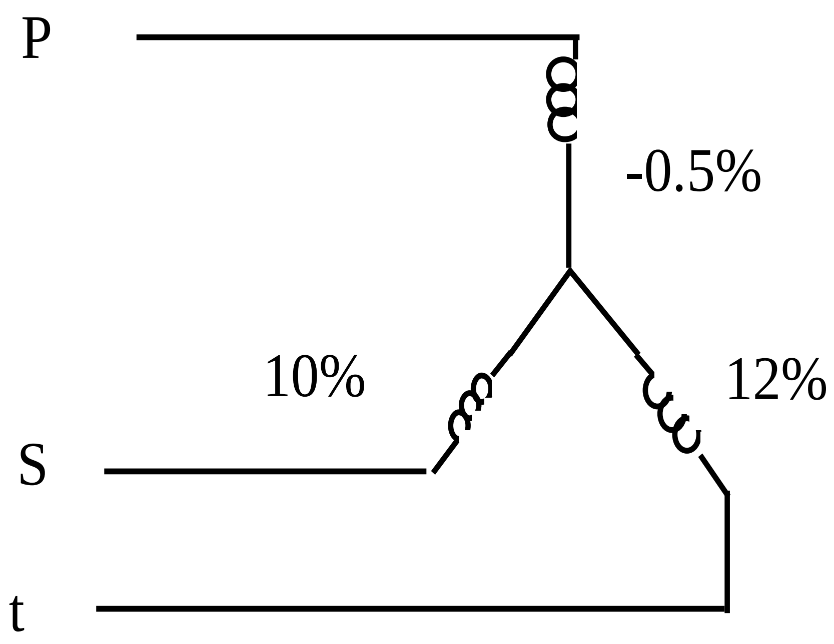
$$Z_p = \frac{1}{2}(9.5 + 11.5 - 22) = -0.5\%$$

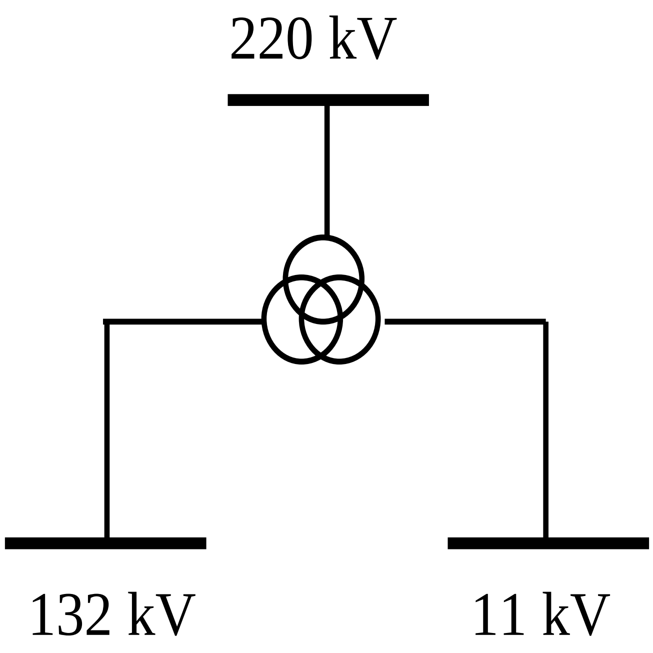
$$Z_s = \frac{1}{2}[22 + 9.5 - 11.5] = 10\%$$

$$Z_t = \frac{1}{2}(11.5 + 22 - 9.5) = 12\%$$

on primary rating

Example 2 : Equivalent Circuit





PSCT Protection Analytic tool

Types of Buses

Slack bus : P and Q are un-known, Voltage magnitude and angle are known. Voltage angle is generally taken as zero.

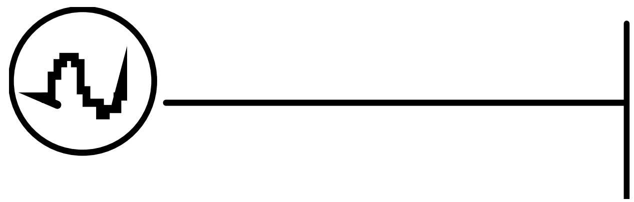
Load bus : P and Q are known, Voltage magnitude and angle are un-known

PV or generator bus : P and V are known. Voltage angle and Q are un-known. Q to be within the reactive power limit

Slack Bus:

- Can be one of the largest unit size, however, need not be. Any machine can be taken as slack bus.
- In the system, it corresponds to the physical generator or tie line or import/export point.
- The limits on the physical entity should be met.
- If the machine rating is 500 MW, and at the end of load flow, the slack bus generation is 550 MW, solution is not acceptable.
- If the machine rating is 250 MW, and at the end of load flow, the slack bus generation is (–50) MW, solution is not acceptable.
- The import and export limit should be within the slack bus generation, if the slack is taken as a tie line.
- In case of industrial system, import/export should be within the contract demand.

Generator Modelling

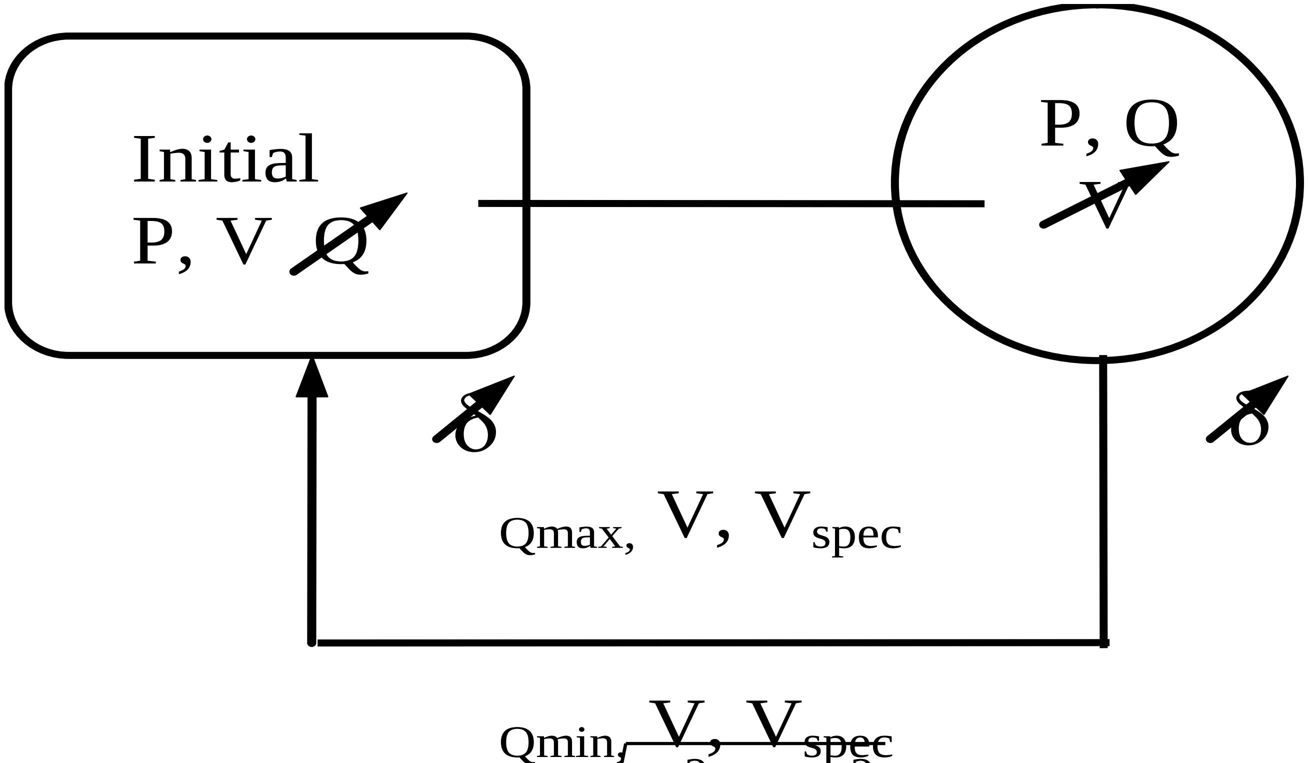


Terminal voltage and P scheduled known.
Q and angle to be determined
Q limits : Q_{min} to Q_{max}

V_{spec} $\rightarrow$ Voltage should increase
$Q = Q_{min}$

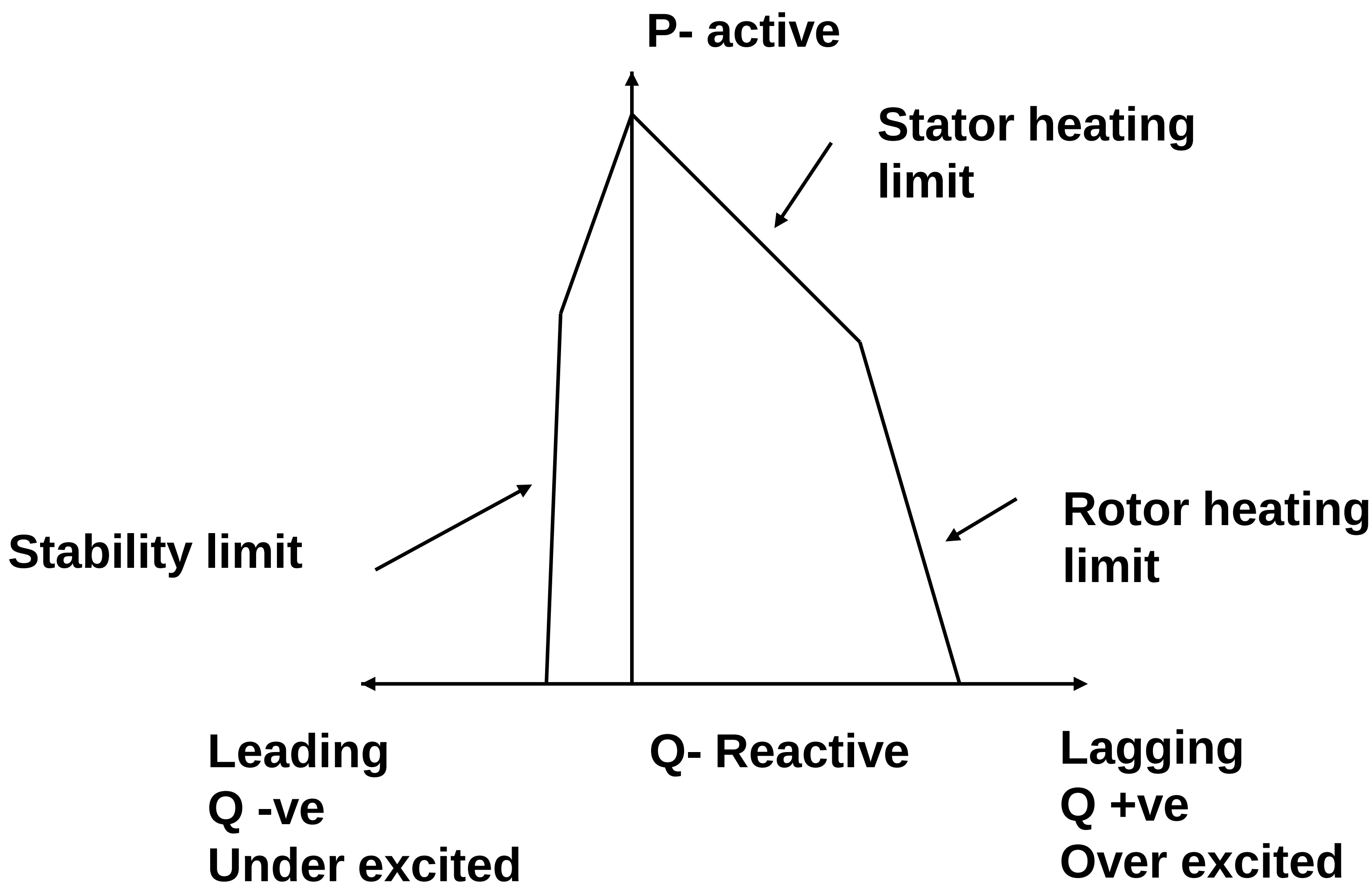
V_{spec} $\rightarrow$ Voltage should decrease
$Q = Q_{max}$

Generator Modelling

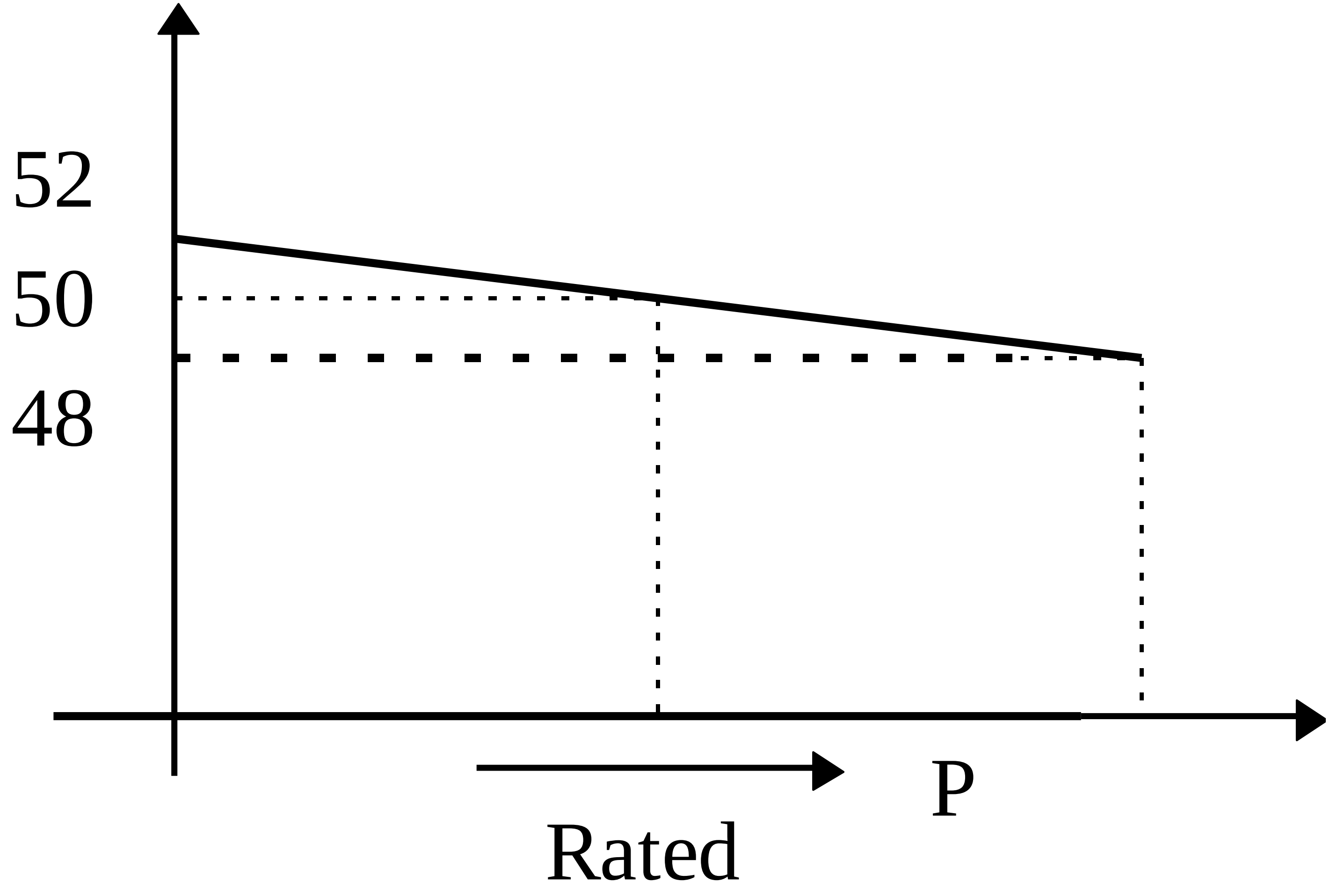


$$S = \sqrt{P^2 + Q^2}$$

Capability Curve



Generator Droop



Generator Droop

$$P_G = P_{G\,set} - \frac{\Delta f}{R} \qquad \Delta f = f - f_0$$

All units in per unit.

$$R = \frac{\Delta f_{p.u.}}{\Delta P_{p.u}} = \frac{\Delta f\,Hz \big| f_0\,Hz}{\Delta P_{MW} \big| P_{rate-MW}}$$

$$R = 4\% \quad \text{implies} \left(f - f_0\right) = 2H_Z. \qquad f_0 = 50H_Z$$

Real power changes by rated MW.

For 1Hz change;

$$0.04 = \frac{1/50}{\Delta P_{MW} / P_{rate\,MW}} \quad \therefore \quad \Delta P_{MW} = \frac{1/50 \cdot P_{rate\,MW}}{0.04} = \frac{P_{rate\,MW}}{2}$$

Generator Droop

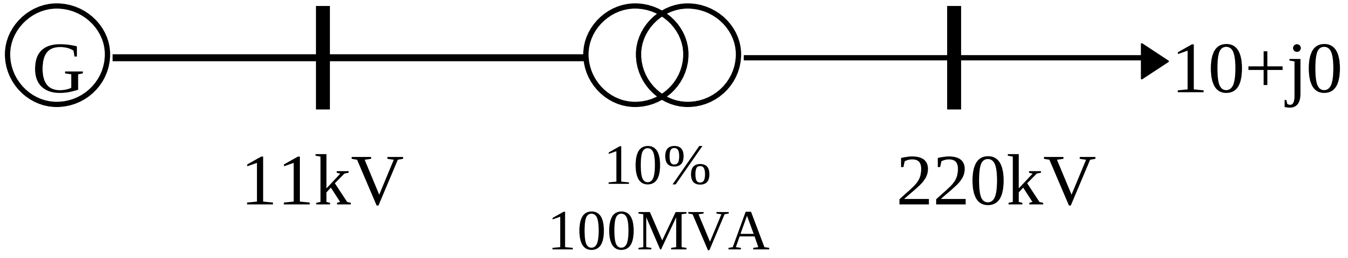
$$R = \frac{\Delta fHz \,/\, f_0 Hz}{\Delta P_{MW} \,/\, P_{rated-MW}}$$

$$\frac{R}{P_{rated-MW}} = \frac{\Delta f\ pu}{\Delta P pu \times New base MVA}$$

$$R\,.\,\frac{New\ base\ MVA}{P_{rated} - MW} = \frac{\Delta\, f\, pu}{\Delta P pu}$$

$$\therefore \quad R' = \frac{R\ New\ base\ MVA}{P_{rated} - MW}$$

CASE-1



Pmin = 0

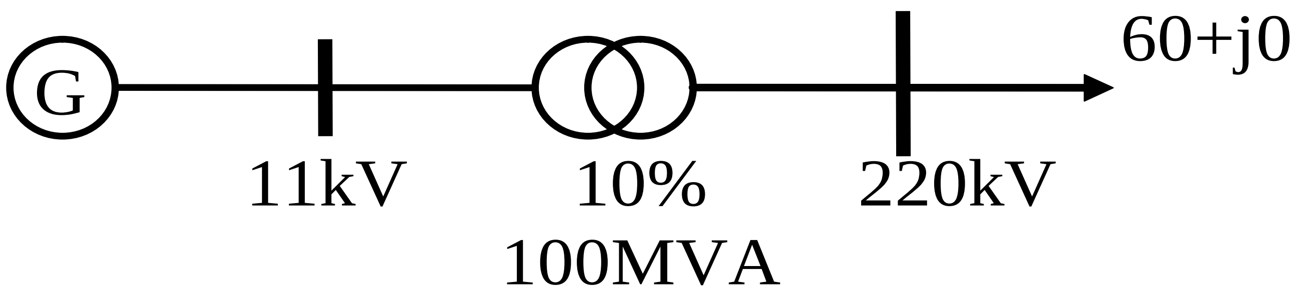
Pmax = 100 MW

Prated = 100 MW

Pscheduled = ? = X {Flat tie line control}

Droop = 5%

CASE-2



Pmin=0

Pmax=100MW   Droop=5%

Prated=100MW

Pscheduled=X

Generator Cost Curve

$C_{Rs} = C_0 + C_1P + C_2P^2$

C_0 =Constant cost in Rs

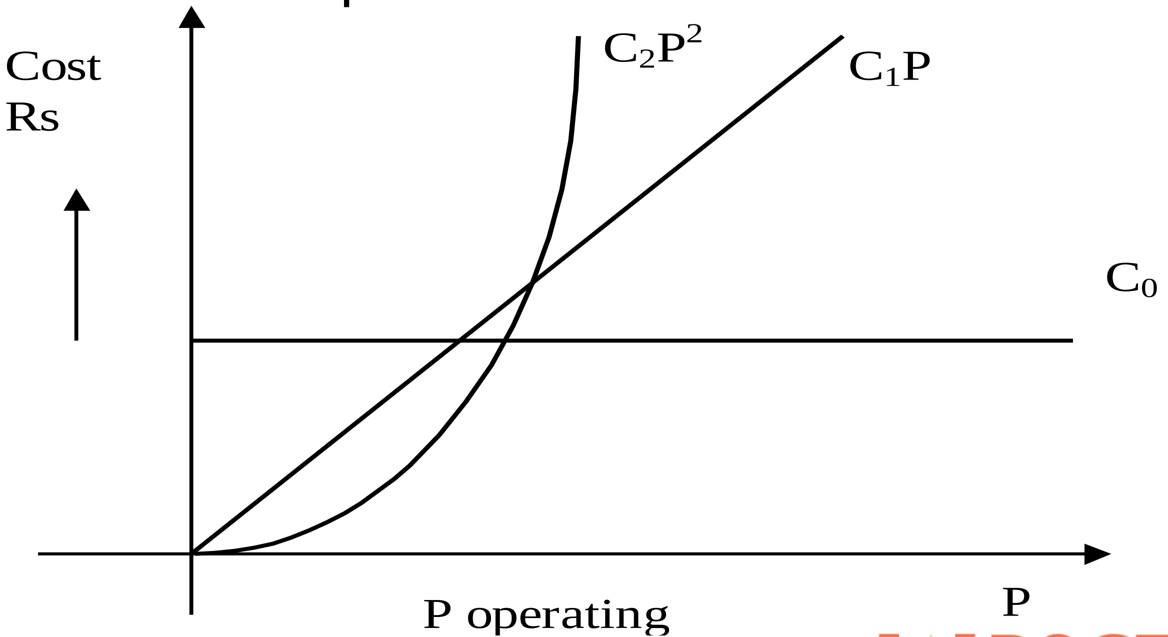
C_1= cost proportional to MW power in Rs/MW

C_2 = Cost proportional to MW^2 ($Power^2$) in Rs/MW^2

C0 $\Rightarrow$ Capital investment (Hydro, Thermal, Nuclear)

C1 & C2 $\Rightarrow$ Running cost

Used in economic despatch.



Load Modelling

$P_L = P_{L0}(1 + C_{pf}\ .\ \Delta f) * (C_{pp} + C_{pi}V + C_{pz}V^2)$

P_{L0} : Base load (Nominal load)

C_{pf} : Frequency dependence factor

Δf : Change in frequency

C_{pp} : Constant power factor

C_{pi} : Constant current factor

C_{pz} : Constant impedance factor

10,000 MW 7% change in load for 1 Hz change in frequency $C_{pf} = 3.5$ Exactly same analogy holds good for reactive load modelling also (Q).

Load Modelling

Load Modelling

Static

Dynamic
Induction Motor
Synchronous Motor

This model expresses the characteristic of the load at any instant of time as algebraic functions of the bus voltage magnitude & frequency

$$P = P_0\left[C_P^p + C_I^p.V + C_Z^p.V^2\right]\left[1 + K_f^p.\Delta f\right]$$

$$Q = Q_0\left[C_P^q + C_I^q.V + C_Z^q.V^2\right]\left[1 + K_f^q.\Delta f\right]$$

Load Modelling:

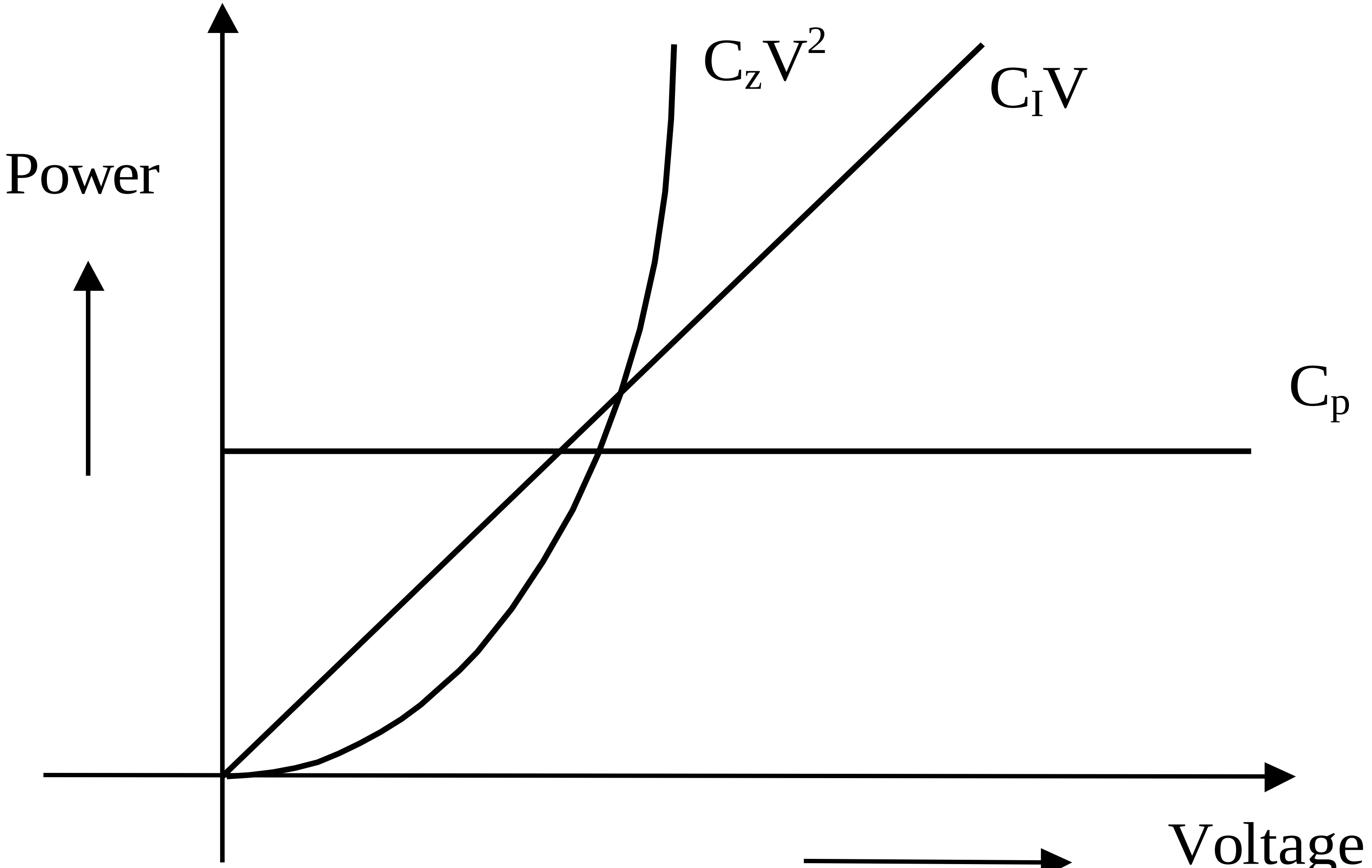
Loads are modelled as a function of Voltage and Frequency

$$P = P_0\left[C_P^p + C_I^p.V + C_Z^p.V^2\right]\left[1 + \Delta f.C_f^p\right]$$

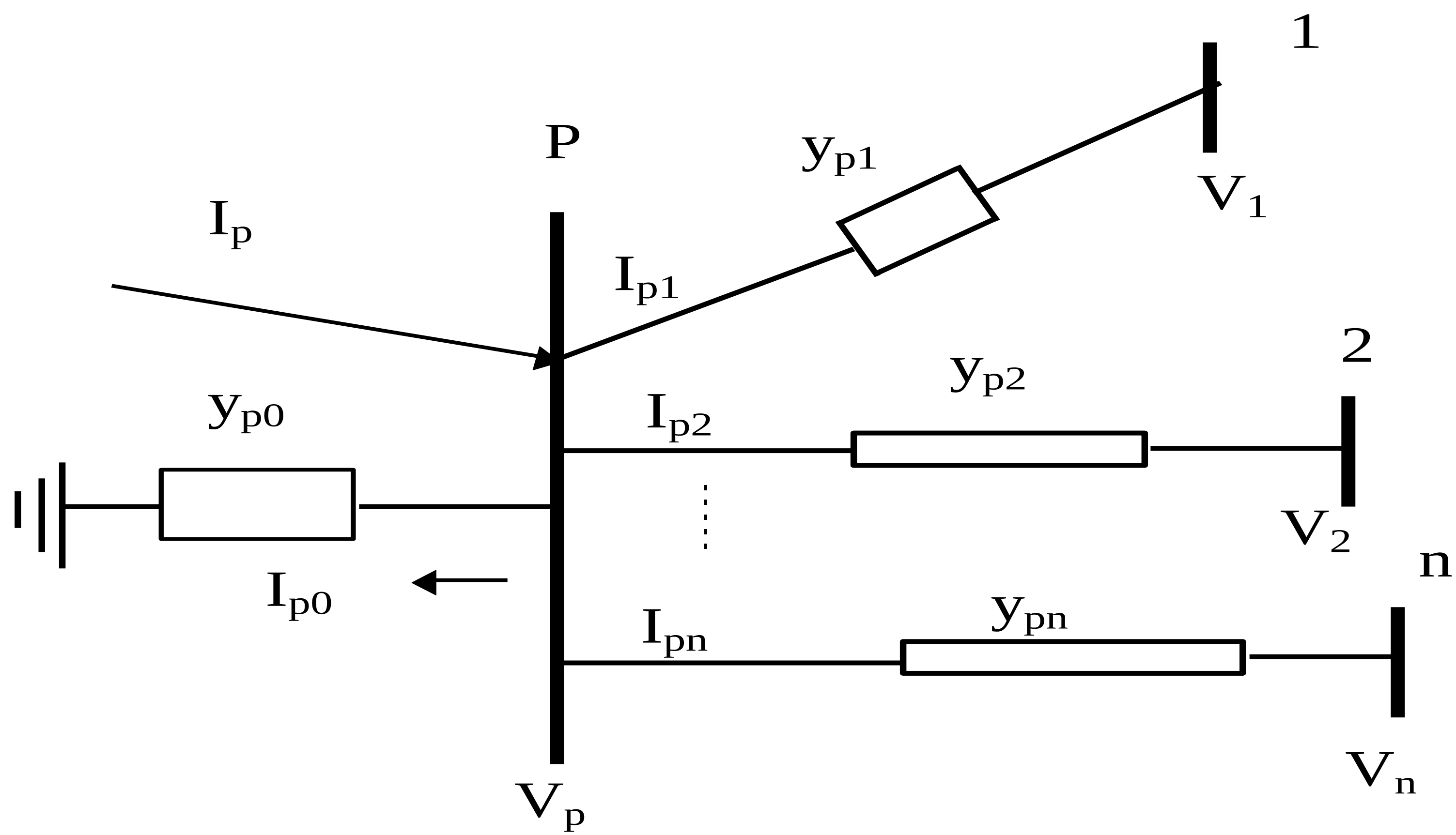
$$Q = Q_0\left[C_P^q + C_I^q.V + C_Z^q.V^2\right]\left[1 + \Delta f.C_f^q\right]$$

C_P =1	**C_I = 0.0**	**C_Z = 0.0**	**Constant power load**
C_P =0.0	**C_I = 1**	**C_Z = 0.0**	**Constant current load**
C_P =0.0	**C_I = 0.0**	**C_Z = 1**	**Constant impedance load**

Load Modelling:



Bus Admittance Matrix



Bus Admittance Matrix

$$I_p = I_{p0} + I_{p1} + I_{p2} + \cdots + I_{pn}$$

$$= V_p . y_{p0} + \left(V_p - V_1\right). y_{p1} + \left(V_p - V_2\right) y_{p2} + \cdots + \left(V_p - V_n\right) y_{pn}$$

$$I_p = \left(y_{p0} + y_{p1} + y_{p2} + \cdots + y_{pn}\right) V_p + \left(-y_{p1}\right). V_1 + \left(-y_{p2}\right) V_2 + \cdots + \left(-y_{pn}\right). V_n$$

$$I_p = Y_{p1} V_1 + Y_{p2} V_2 + \cdots + Y_{pp} V_p + Y_{pn} V_n$$

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_p \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1p} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2p} & \cdots & Y_{2n} \\ \vdots & & & & & \\ Y_{p1} & Y_{p2} & \cdots & Y_{pp} & \cdots & Y_{pn} \\ \vdots & & & & & \\ Y_{n1} & Y_{n2} & \cdots & Y_{np} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_p \\ \vdots \\ V_n \end{bmatrix}$$

$$\underset{nx1}{[I]_{bus}} = \underset{nxn}{[Y]_{bus}} \underset{nx1}{[V]_{bus}}$$

Iterative Techniques:

$$f_k\left(x_1, x_2, \cdots, x_k, \cdots, x_{n-1}, x_n\right) = Y_k$$

$$x_k = Y_k + f_k^{'}\left(x_1, x_{2,} \cdots, x_{k-1}, x_{k+2}, \cdots, x_{n-1}, x_n\right)$$

$$Gauss$$

$$x_k^i = Y_k + f_k^1\left(x_1^{i-1}, x_2^{i-1}, \cdots, x_{k-1}^{i-1}, x_{k+2}^{i-1}, \cdots, x_{n-1}^{i-1}, x_n^{i-1}\right)$$

$$Gauss - Seidel$$

$$x_k^i = Y_k + f_k^1\left(x_1^i, x_2^i, \cdots, x_{k-1}^i, x_{k+2}^{i-1}, \cdots, x_{n-1}^{i-1}, x_n^{i-1}\right)$$

Application to Power Systems

$$S_p = V_p I_p^{\ *} \qquad I_p = \frac{P_p - jQ_p}{V_p^*} \qquad ----------(1)$$

$$I_p = Y_{p1}V_1 + Y_{p2}V_2 + \cdots + Y_{pp}V_p + \cdots + Y_{pn}V_n \qquad ---------(2)$$

$$\mathrm{V_p} = \frac{1}{\mathrm{Y_{pp}}}\left(\mathrm{I_p} - \sum_{\substack{q=1\\ q\neq p}}^{n} \mathrm{Y_{pq}}\,\mathrm{V_q}\right)$$

$$\mathrm{V_p} = \frac{1}{\mathrm{Y_{pp}}}\left(\frac{\mathrm{P_p} - j\mathrm{Q_p}}{\mathrm{V_p^*}} - \sum_{\substack{q=1\\ q\neq p}}^{n} \mathrm{Y_{pq}}\,\mathrm{V_q}\right)$$

$$V_p^i = \frac{1}{Y_{pp}}\left[\frac{P_p - jQ_p}{V_p^{*\,i-1}} - \left(\sum_{q=1}^{p-1} Y_{pq}V_q^i + \sum_{q=p+1}^{n} Y_{pq}V_q^{i-1}\right)\right]$$

NR – Method

$$f_k\left(x_1^{i-1}+\Delta x_1, x_2^{i-1}+\Delta x_2,\ldots\ldots+x_k^{i-1}+\Delta x_k+\ldots\ldots+x_n^{i-1}+\Delta x_n\right)=y_k$$

$$f_k\left(x_1^{i-1},x_2^{i-1},\ldots.x_k^{i-1},\ldots.x_n^{i-1}\right)+\Delta x_1\left.\frac{\partial f_k}{\partial x_1}\right|_{i-1}+\Delta x_2\left.\frac{\partial f_k}{\partial x_2}\right|_{i-1}+\ldots\ldots+\Delta x_k\left.\frac{\partial f_k}{\partial x_k}\right|_{i-1}+\ldots..+\Delta x_n\left.\frac{\partial f_k}{\partial x_n}\right|_{n}=y_k$$

$$y_k-f_k\left(x_1^{i-1},x_2^{i-1},\ldots.x_k^{i-1},\ldots.x_n^{i-1}\right)=\Delta x_1\left.\frac{\partial f_k}{\partial x_1}\right|_{i-1}+\Delta x_2\left.\frac{\partial f_k}{\partial x_2}\right|_{i-1}+\ldots\ldots+\Delta x_k\left.\frac{\partial f_k}{\partial x_k}\right|_{i-1}+\ldots\ldots.+\Delta x_n\left.\frac{\partial f_k}{\partial x_n}\right|_{i-1}$$

$$\Delta y_k=\Delta x_1\left.\frac{\partial f_k}{\partial x_1}\right|_{i-1}+\Delta x_2\left.\frac{\partial f_k}{\partial x_2}\right|_{i-1}+\ldots\ldots+\Delta x_k\left.\frac{\partial f_k}{\partial x_k}\right|_{i-1}+\ldots\ldots.+\Delta x_n\left.\frac{\partial f_k}{\partial x_n}\right|_{i-1}$$

$$
\begin{bmatrix} \Delta y_1 \\ \\ \Delta y_k \\ \vdots \\ \\ \Delta y_n \end{bmatrix}
\begin{bmatrix}
\frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} \cdots\cdots\cdots & \frac{\partial f_1}{\partial x_k} & \frac{\partial f_1}{\partial x_n} \\
\vdots & \vdots \quad \cdots\cdots\cdots & \vdots & \vdots \\
\frac{\partial f_k}{\partial x_1} & \frac{\partial f_k}{\partial x_2} \cdots\cdots\cdots & \frac{\partial f_k}{\partial x_k} & \frac{\partial f_k}{\partial x_n} \\
\frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & \frac{\partial f_n}{\partial x_k} & \frac{\partial f_n}{\partial f_n}
\end{bmatrix}_{i-1}
\begin{bmatrix} \Delta x_1 \\ \\ \vdots \\ \Delta x_k \\ \\ \Delta x_n \end{bmatrix}
$$

$$
S_k = V_k . I_k^*
$$

$$
= V_k \sum_{m=1}^{n} \left(V_m Y_{km} \right)^*
$$

$$
= V_k \angle \delta_k . \sum_{m=1}^{n} V_m \angle -\delta_m . Y_{km} \angle -\theta_{km}
$$

$$P_k + jQ_k = \sum_{m=1}^{n} V_k V_m Y_{km} \angle \delta_k - \delta_m - \theta_{km}$$

$$P_k = \sum_{m=1}^{n} V_k V_m Y_{km} \cos(\delta_k - \delta_m - \theta_{km})$$

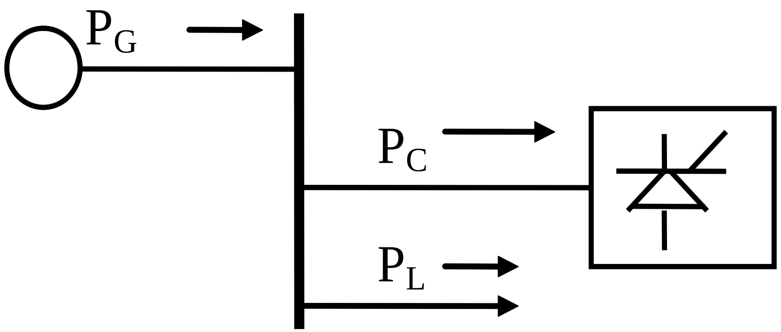
$$Q_k = \sum_{m=1}^{n} V_k V_m Y_{km} \sin(\delta_k - \delta_m - \theta_{km})$$

When the solution is obtained

$$\sum_{m=1}^{n} V_k^{'} V_m^{'} Y_{km} \cos(\delta_k^{'} - \delta_m^{'} - \theta_{km}) = P_{spec}$$

$$V_k^{'} \angle \delta_k^{'}, V_m^{'} \angle \delta_m^{'} \rightarrow solution\ set$$

P_{spec}: *Net injected real power at the bus*



P_G : Net Generation (MW)

P_L : Net Load (MW)

P_C : Net Convertor power drawn (MW)

$$P_{spec} = P_G - P_C - P_L$$

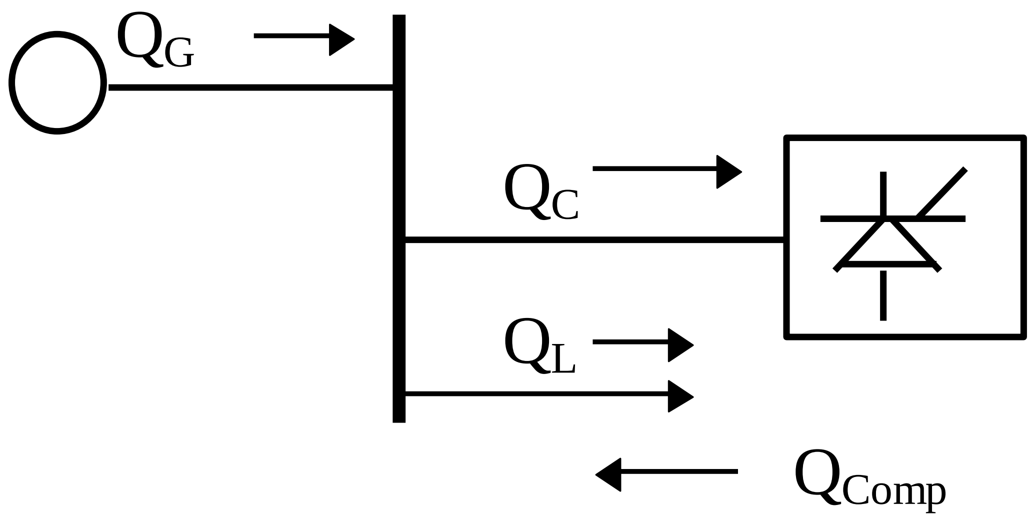
P_G : After generator regulation characteristic

P_L : After load modelling

$$\Delta P_k = P_{spec} - P_k$$

$$\sum_{m=1}^{n} V_k^{'} V_m^{'} Y_{km} \sin\left(\delta_k^{'} - \delta_m^{'} - \theta_{km}\right) = Q_{spec}$$

Q_{spec} : Net injected reactive power at a bus



$Q_{spec} = Q_G - Q_c - Q_L + Q_{comp}$

Q_G = After Q checking

Q_L = After load modelling

Q_{comp} = Fixed compensation given along with load data.

$\Delta Q_k = Q_{spec} - Q_k$

$$
\underbrace{\begin{bmatrix}
\frac{\partial P_2}{\partial \delta_2} \cdots \frac{\partial P_2}{\partial \delta_k} \cdots \frac{\partial P_2}{\partial \delta_n} & \frac{\partial P_2}{\partial V_2} \cdots \frac{\partial P_2}{\partial V_k} \cdots \frac{\partial P_2}{\partial V_n} \\
\vdots & \\
\frac{\partial P_k}{\partial \delta_2} \cdots \frac{\partial P_k}{\partial \delta_k} \cdots \frac{\partial P_k}{\partial \delta_n} & \frac{\partial P_k}{\partial V_2} \cdots \frac{\partial P_k}{\partial V_k} \cdots \frac{\partial P_k}{\partial V_n} \\
\vdots & \\
\frac{\partial P_n}{\partial \delta_2} \cdots \frac{\partial P_n}{\partial \delta_k} \cdots \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial V_2} \cdots \frac{\partial P_n}{\partial V_k} \cdots \frac{\partial P_n}{\partial V_n} \\
\multicolumn{2}{c}{Q\ deravitives}
\end{bmatrix}}_{2(n-1) \times 2(n-1)}
\underbrace{\begin{bmatrix}
\Delta\delta_2 \\ \vdots \\ \Delta\delta_k \\ \vdots \\ \Delta\delta_n \\ \Delta V_2 \\ \vdots \\ \Delta V_k \\ \Delta V_n
\end{bmatrix}}_{2(n-1)\times 1}
=
\underbrace{\begin{bmatrix}
\Delta P_2 \\ \vdots \\ \Delta P_k \\ \vdots \\ \Delta P_n \\ \Delta Q_2 \\ \vdots \\ \Delta Q_k \\ \Delta Q_n
\end{bmatrix}}_{2(n-1)\times 1}
$$

$$
P_k = \sum_{m=1}^{n} V_k V_m Y_{km} \cos\left(\delta_k - \delta_m - \theta_{km}\right)
$$

$$\frac{\partial P_k}{\partial \delta_k} = \sum_{\substack{m=1 \\ m \neq k}}^{n} V_k V_m Y_{km} \sin\left(\delta_k - \delta_m - \theta_{km}\right)(-1)$$

$$\frac{\partial P_k}{\partial \delta_m} = V_k V_m Y_{km} \sin\left(\delta_k - \delta_m - \theta_{km}\right)(-1)(-1)$$

$$\frac{\partial P_k}{\partial V_k} = \sum_{\substack{m=1 \\ m \neq k}}^{n} V_m Y_{km} \cos\left(\delta_k - \delta_m - \theta_{km}\right) + 2V_k . Y_{kk} \cos\left(\delta_k - \delta_k - \theta_{kk}\right)$$

$$\frac{\partial P_k}{\partial V_m} = V_k Y_{km} \cos\left(\delta_k - \delta_m - \theta_{km}\right)$$

$$Q_k = \sum_{m=1}^{n} V_k V_m Y_{km} \sin\left(\delta_k - \delta_m - \theta_{km}\right)$$

$$\frac{\partial Q_k}{\partial \delta_k} = \sum_{\substack{m=1 \\ m\neq k}}^{n} V_k V_m Y_{km} \cos\left(\delta_k - \delta_m - \theta_{km}\right)$$

$$\frac{\partial Q_k}{\partial \delta_m} = \sum_{m=1}^{n} V_k V_m Y_{km} \cos\left(\delta_k - \delta_m - \theta_{km}\right)(-1)$$

$$\frac{\partial Q_k}{\partial V_k} = \sum_{\substack{m=1 \\ m\neq k}}^{n} V_m Y_{km} \sin\left(\delta_k - \delta_m - \theta_{km}\right) + 2V_k Y_{kk} \sin\left(\delta_k - \delta_k - \theta_{kk}\right)$$

$$\frac{\partial Q_k}{\partial V_m} = V_k Y_{km} \sin\left(\delta_k - \delta_m - \theta_{km}\right)$$

$$\begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

Decoupled N-R Method

$$[J_1][\Delta\delta] = [\Delta P] \quad |\theta - | \quad V \ iteration$$

$$[J_4][\Delta V] = [\Delta Q]$$

Fast Decoupled Load Flow:

$$(\delta_k - \delta_m) \cong \phi$$

$$\frac{\partial P_k}{\partial \delta_m} = V_k V_m Y_{km} \sin(\delta_k - \delta_m - \theta_{km})$$

$$= V_k V_m Y_{km} \sin(-\theta_{km}) = -V_k V_m \theta_{km}$$

$$\frac{\partial P_k}{\partial \delta_k} = \sum_{\substack{m=1 \\ m \neq k}}^{n} V_k V_m B_{km} = V_k \sum_{\substack{m=1 \\ m \neq k}}^{n} V_m B_{km}$$

$$\frac{\partial Q_k}{\partial V_m} = -V_k B_{km}$$

$$\frac{\partial Q_k}{\partial V_k} = \sum_{\substack{m=1 \\ m \neq k}}^{n} -V_m B_{km} + 2V_k(-B_{kK})$$

Fast Decoupled Load Flow:

$$\begin{bmatrix} \sum\limits_{m\neq k} V_m B_{1m} - V_2 B_{12} \cdots - V_k B_{1k} \cdots - V_n B_{1n} \\ \vdots \\ -V_1 B_{k1} - V_2 B_{k2} \cdots \sum\limits_{m\neq k} V_m B_{km} \cdots - V_n B_{kn} \\ -V_1 B_{n1} - V_2 B_{n2} \cdots \sum V_k B_{nk} \cdots \sum\limits_{m\neq 1} V_m B_{nm} \end{bmatrix} \begin{bmatrix} \Delta\delta_1 \\ \vdots \\ \Delta\delta_k \\ \vdots \\ \Delta\delta_n \end{bmatrix} = \begin{bmatrix} \frac{\Delta P_1}{V_1} \\ \frac{\Delta P_k}{V_k} \\ \frac{\Delta P_n}{V_n} \end{bmatrix}$$

Assuming voltage as 1 pu in the Jacobian terms, since neglecting shunt ;

$$\sum_{m\neq 1} B_{1m} = -B_{11} \,;$$

$$\begin{bmatrix} -B_{11} & -B_{12} \cdots\cdots & -B_{1k} \cdots & -B_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ -B_{k1} & -B_{k2} \cdots\cdots & B_{kk} & -B_{kn} \\ \vdots & \vdots & \vdots & \vdots \\ -B_{n1} & -B_{n2} \cdots\cdots & -B_{nk} \cdots & -B_{nn} \end{bmatrix} \begin{bmatrix} \Delta\delta_1 \\ \vdots \\ \Delta\delta_k \\ \vdots \\ \Delta\delta_n \end{bmatrix} = \begin{bmatrix} \frac{\Delta P_1}{V_1} \\ \frac{\Delta P_k}{V_k} \\ \frac{\Delta P_n}{V_n} \end{bmatrix}$$

$-ve\,of\,imaginary\,of\,Y bus$

Fast Decoupled Load Flow:

Since the shunt reactance to ground are neglected, transformers tap as unity, above approximation can be done.

Iteration :

$|\theta$-$|V$ iteration.

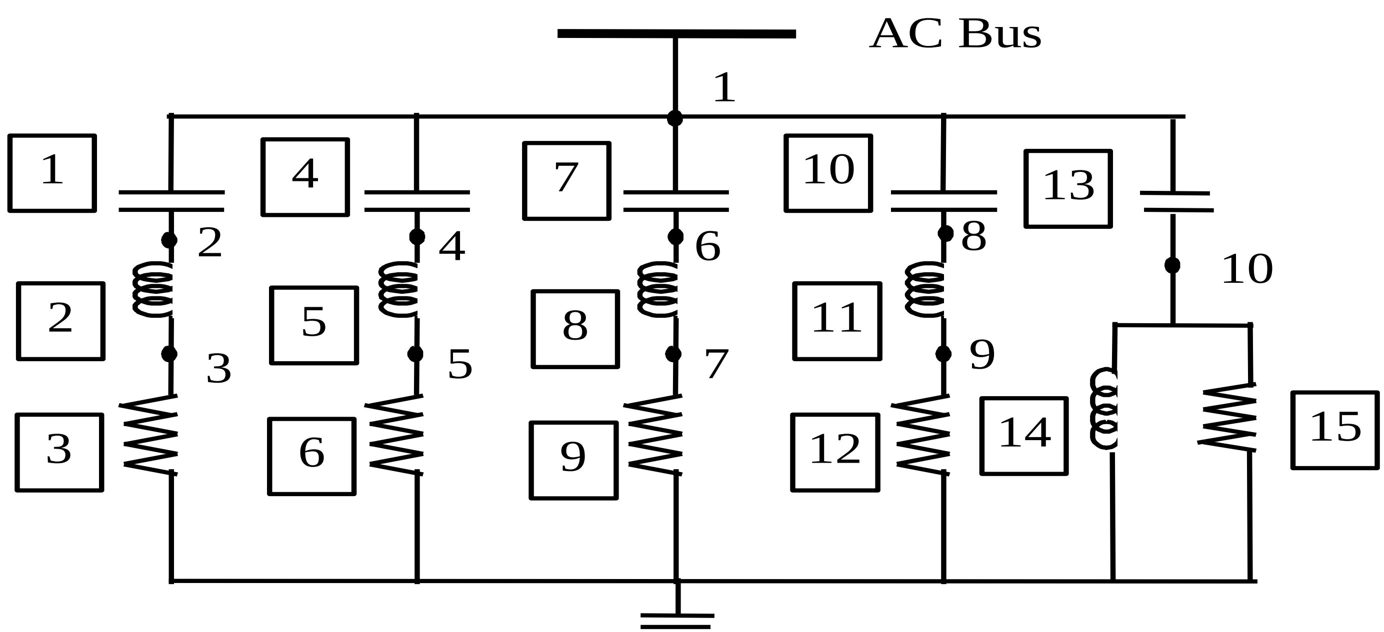
1. Solve for $\Delta\delta$; from ΔP
2. Re-compute ΔQ. solve for ΔV.
3. With new V, compute ΔP & go to 1.

repeated till convergence.

User Defined Filters:

At fundamental frequency capacitive in nature.

1. HVDC converters
2. Harmonic elimination
3. Industrial plants



PSCT Protection Analytic tool

User Defined Filters:

Branch	Expression - Y
R	$\left(\dfrac{1}{R + j0}\right)$
L	$\left(\dfrac{1}{0 + j2\pi fL}\right)$
C	$\left(0 + j2\pi fC\right)$

R = 1, L = 2, C = 3

$X_L = 2\pi fL$ and $X_C = 1/2\pi fC$

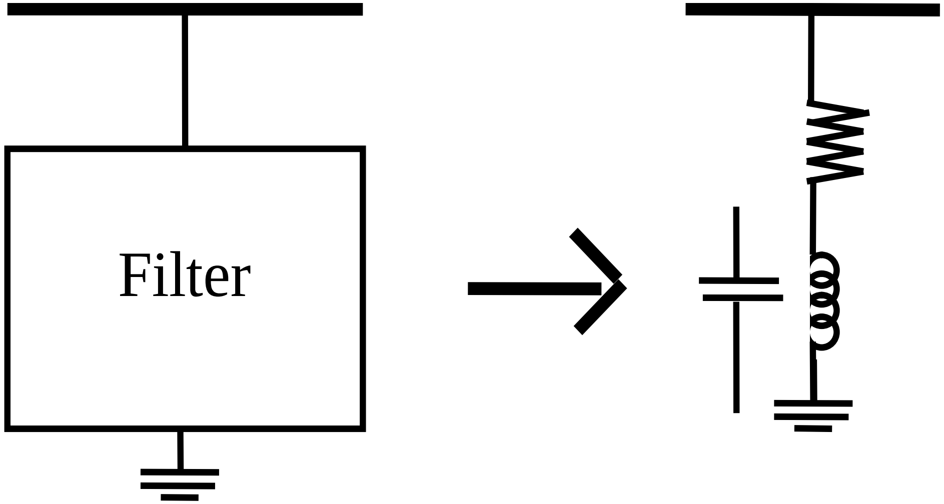
f : system frequency

PRDC

विज्ञानेन जातानि जीवन्ति

PSCT Protection Analytic tool

User Defined Filters:



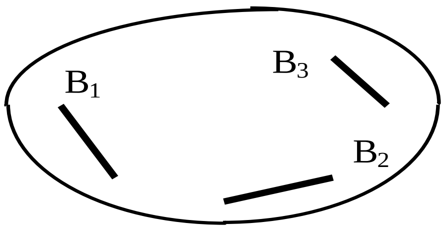
R +jX
G+jB
B +ve for C
B -ve for L

Contingency Ranking

When (n-1) contingency is considered for the outage of series elements.

- Exact load flow is performed.
- Weightage for buses and lines can be given.
- Ranks on voltage performance index and overload performance index.

Bus Weightage



- Normal weightage is unity (Default).
- Tells how important is the requirement to maintain the bus voltage at the specified bus.
- If at B_1 weightage is 1, B_2 weightage is 3, and B_3 weightage is 4, say then for same voltage deviation, B_3 is 4 times important compared to B_1, while B_2 is 3 times important, in terms of maintaining the voltage.

Bus Weightage

$$PIV = \sum_{i=1}^{nb} W_i \left[\frac{\left|V_{inew}\right| - \left|V_i\right|_{sp}}{\Delta V_{i\max}} \right]^2$$

nb : number of buses

Wi : Contingency weightage at bus i

$|Vi|$ new : Post voltage magnitude at bus i

$|Vi|$ sp : Specified voltage magnitude at bus i = 1 pu

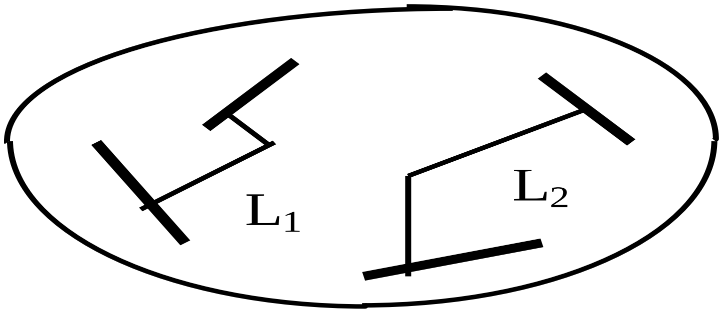
Δ Vmax : Maximum allowable voltage change

Δ Vmax = Vmax - Vspec if $V_i >$ Vmax

= Vmin - Vspec if $V_i <$ Vmin

PSCT Protection Analytic tool

Line Weightage:



- Normal weightage is unity.
- Weightage is given high value > 1, if it is not desired to overload.
- Tie lines can be given higher weightage, so that over loading on those lines will result in higher ranking.

Line Weightage:

$$PIP = \sum_{i=1}^{nl} W_i \left[\frac{P_{inew}}{P_{ilimit}} \right]^2 \quad i \notin contingency\ line$$

where,

nl : Total number of series elements.

Wi : Line weightage for i[th] line

P_{inew} : New real power flow in the line

P_{ilimit} : Real power flow limit on the line

Contingency Analysis Methodology Exact Load Flow:

Instead of real power loading MVA loading is considered.

Features added:

- Multiple contingencies

Reactive Power Optimisation:

Data Requirements:

1. Normal load flow data.
2. Voltage (minimum and maximum) at buses.
3. Compensation constraints.
4. Minimum, maximum and step size
5. Cost details
   - Probable compensation buses.
   - Substation space constraint.
   - Sizing constraints.

Methodology

Minimise the voltage deviation at buses

$$i.e. Minimize \sum_i \left| V_{spec} - V_{act} \right| i. \in \{comp\}$$

$$where \quad V_{spec} = V_{\max}, if\, V_{act} \rangle V_{\max}$$

$$= V_{\min}, if\, V_{act} \langle V_{\min}$$

Subject to:

- Voltage is within the specified limits.
- Tap is within the limits.
- Compensation is within the limits

Methodology

At each compensation iteration,

- Load flow is performed.
- Losses are determined.

Program termination:

- Voltages are within the limits
- No more VAR source is available

Present Worth of An Annuity:

$$P.W. = \left\{ \frac{(1+i)^n - 1.0}{i(1+i)^n} \right\} * X$$

where,

X is the annual expenditure / income.

i : interest rate per annum.

n : Scheme period in years.

Present Worth of An Annuity:

Capital investment :

Cost per MVAR * MVAR installed

Annual expenditure :

Capital investment * (O & M)

Annual benefit :

Reduced loss(in MW)*loss load factor * 8760*1000 * Unit charge in Rs. (kwhr)

Present Worth of An Annuity:

$$L_{lf} = \frac{average\,power\,loss}{power\,loss\,at\,peak\,load}$$

$$L_{lf} = 0.3(Lf) + 0.7(Lf)^2$$

$$L_f : Load\ factor$$

$$L_{lf} : Loss\ load\ factor$$

Project is economically feasible if net present worth is +ve

Net present worth =

(net annual savings present worth - capital investment)

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Economic Scheduling

1 **Data Requirement:**

- Normal load flow data
- Minimum & Maximum generator schedules.
- Generator cost curve.
- Unit charge (cost details)

2 **Methodology:**

- Minimize: The total cost (generation + cost).
- Subject to: Generation schedule being within minimum & maximum limits.

Economic Scheduling

3 **Technique :**

- Linear Programming technique
- Minimize the objective function (total cost)
- Subject to equality and inequality constraints

Economic Scheduling

Generation cost function

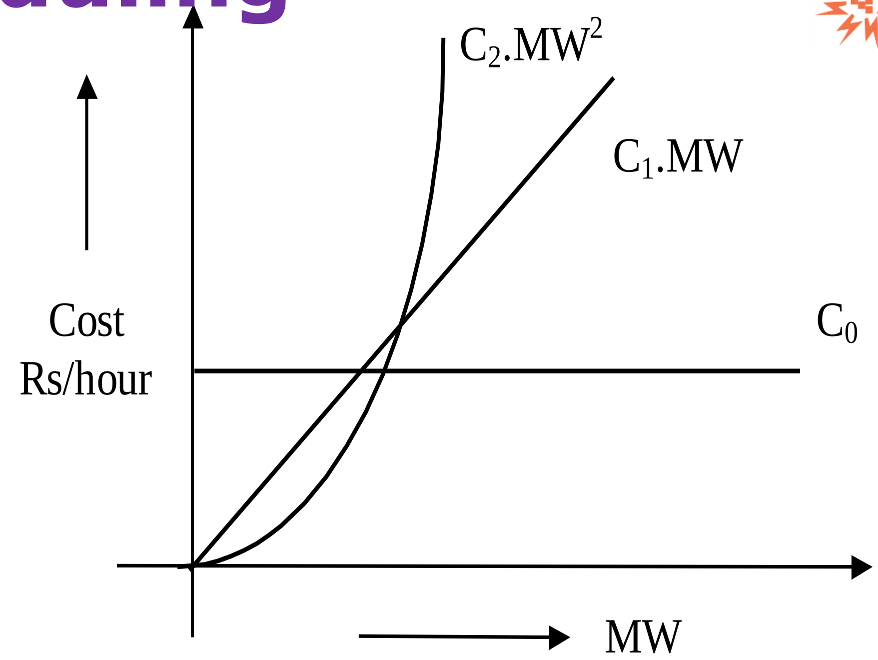
$G_{cost} = C_0 + C_1\ MW + C_2\ MW^2$

G_{cost} = Rupees per hour

C_0 : Constant cost, Rs/hour

C_1 : Cost in Rs/MW . hour

C_2 : Cost in Rs/(MW)^2 hour



Loss cost :

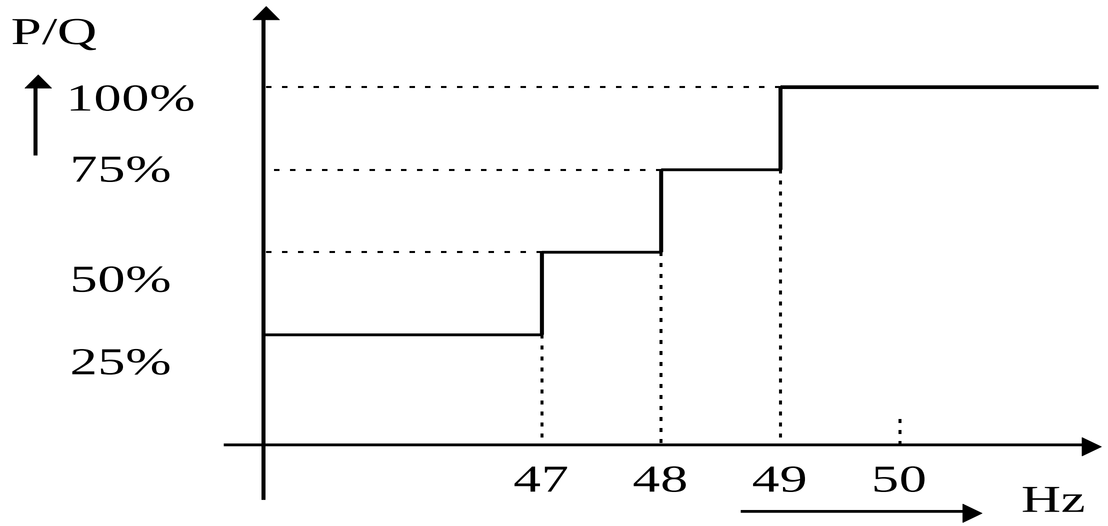
Loss in MW * 1000 x Energy charge in Rs.

Note :

Schedule for particular hour & operating condition. Hence no loss load factor is considered.

Loss cost is per hour.

Frequency Relay (Load Shedding):

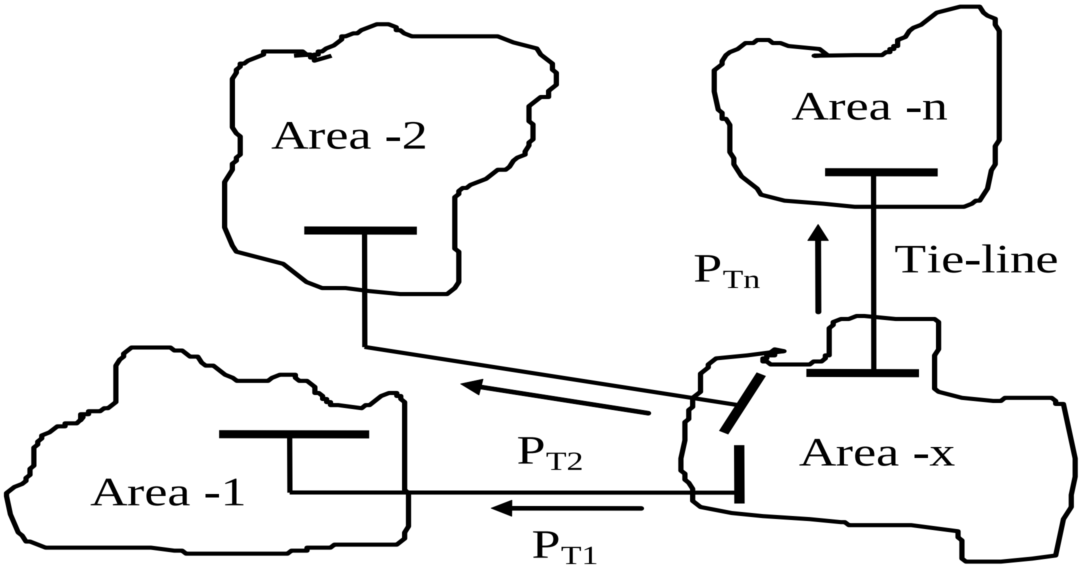


f - Hz	Shedding (S)	Actual load
49	0.25	0.75P
48	0.50	0.50P
47	0.75	0.25P

$$f_3 \leq f_2 \leq f_1 \quad f: frequency$$

$$S_3 \geq S_2 \geq S_1 \quad S: shedding$$

Tie Line Scheduling:

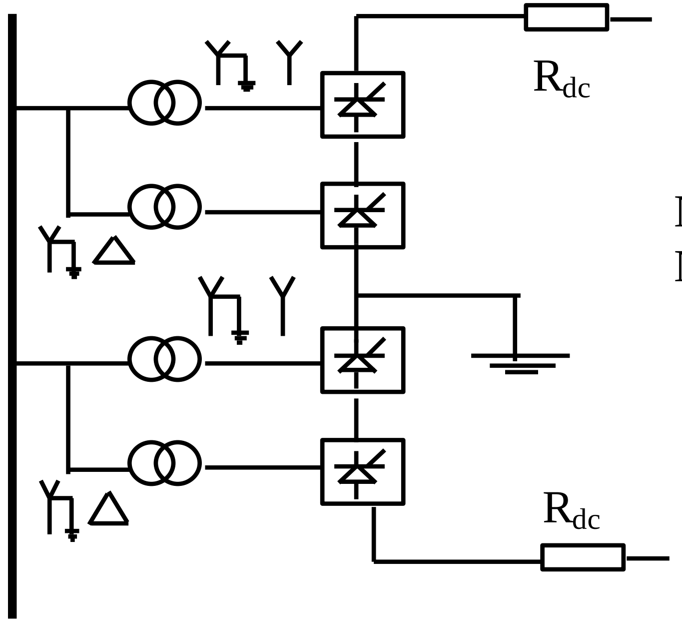


$$P_{T\,scheduled} = P_{T1} + P_{T2} + \cdots + P_{Tn}$$

$$= \sum_{i=1\ ,n} PT_i$$

$$P_{T\,actual} = P_{T\ \ scheduled} + \Delta P_T \quad \Delta P_T : Tolerance$$

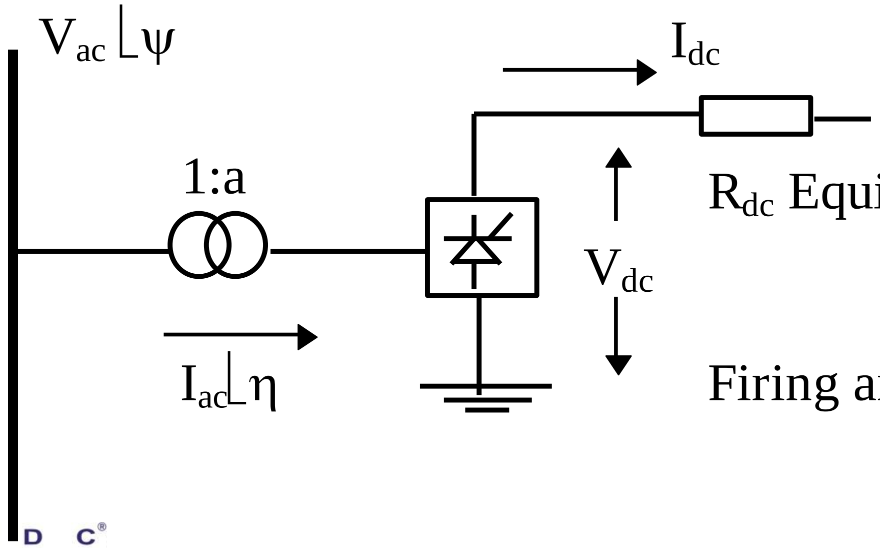
HVDC



No. of poles = 2
No. of bridges = 2

$$R_c = \frac{3X_C}{\pi}$$

Xc = Transformer reactance on own MVA rating



R_{dc} Equivalent

Firing angle α

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Base Quantities:

$P_{ac\ base}$: 3 phase power

$V_{ac\ base}$: line to line rms value of AC voltage

$$I_{ac\ base} = \frac{P_{ac\ \ \ base}}{\sqrt{3}V_{ac\ base}}$$

In DC System:

$P_{dc\ base} = P_{ac\ base}$

$V_{dc\ base} = K_b\ .V_{ac\ base}\ .\ np$

$K_b = (3\sqrt{2}/\pi)nb$

$I_{dc\ base} = P_{dc\ base}/V_{dc\ base}$

$Z_{dc\ base} = V_{dc\ base}/I_{dc\ base}$

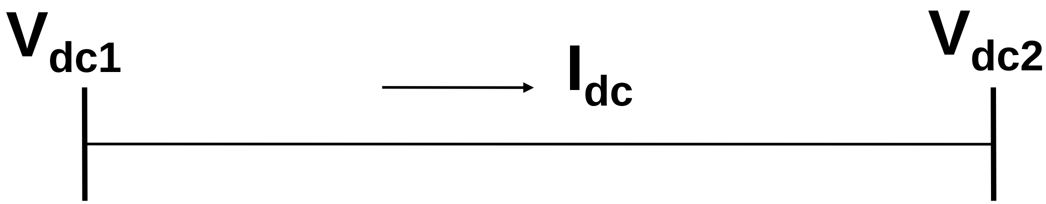
$$R_C = X_C\left(\pi/6\right)\frac{baseMVA}{T_r.MVA}x\left(\frac{1}{nb\times np}\right)$$

Types of Controls:

- Constant voltage control - Vdc
- Constant current control - Idc
- Constant power control - Pdc

Types of Controls:

1. Current is controlled and voltage is regulated in the DC link - why?
2. Why voltage is maintained at designed value?



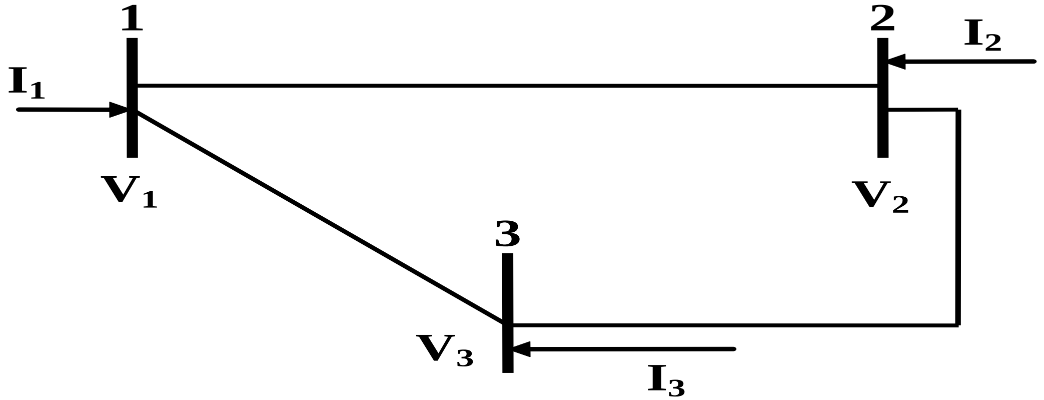
$P_{dc} = V_{dc} * I_{dc}$,When V_{dc} is less I_{dc} has to be more for same P_{dc} . $\mathbf{I_{dc}^2R_{dc}}$ is the loss

Types of Controls:

Current Control - Rectifier

1. P $_{increase}$ - α_r is reduced $\rightarrow$ Q decreases
2. Inverter can operate with minimum γ (extinction angle) $\rightarrow$ Q decreases.

Voltage control - Inverter



Voltage Control:

With voltage control bus as reference,

$V_{bus} = R_{bus}\ I_{bus} + V_m$

V_m : voltage control bus V_{dc}

$V_{dc} = M\ (a\ .\ V_{ac} \cos\alpha\ -\ R_c\ .I_{dc})$

Vdc : DC bus voltage

a : Tap

α : Control angle (firing angle, extinction angle)

R_c : commutation reactance

I_{dc} : DC current

M : Constant = 0.97 for 3% voltage margin

Voltage Control:

$$aV_{ac} \times \cos\alpha = \frac{V_{dc}}{M} + R_c I_{dc}$$

$$aV_{ac} = \frac{\frac{V_{dc}}{M} + R_c I_{dc}}{\cos\alpha}$$

$$P_{ac} = P_{dc} = V_{dc} I_{dc}$$

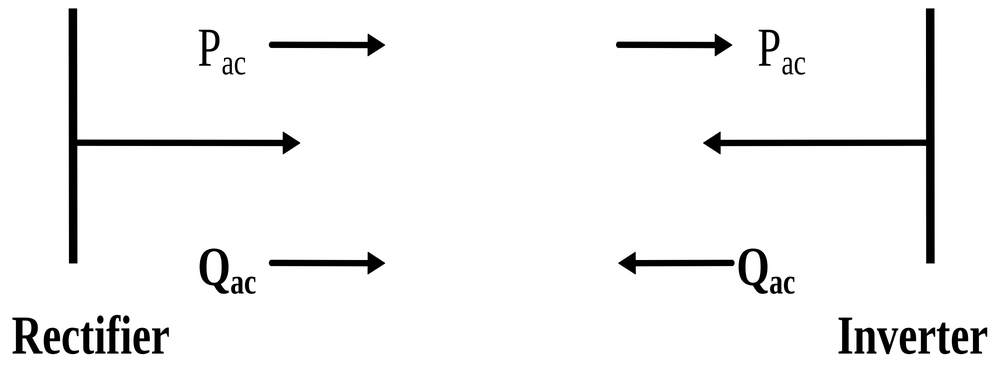
$$V_{dc} = aV_{ac}\cos(\psi - \xi) = aV_{ac}\cos\phi$$

$$\cos\phi = \frac{V_{dc}}{aV_{ac}}$$

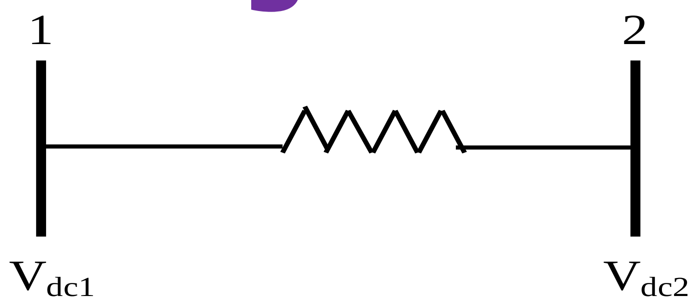
$$Q_{ac} = Q_{dc} = P_{ac}\tan\phi$$

Note:

Q_{ac} is always positive



Modelling of DC Link:



Steady state operation : R alone L & C not considered

$$I_{dc} = \frac{(V_{dc1} - V_{dc2})}{R_{dc}}$$

$$P_{dc1} = V_{dc1} * I_{dc}$$

$$P_{dc2} = V_{dc2} * I_{dc}$$

$$our\, approach\, P_{dc}, I_{dc} + ve\, for\, rectifier\, , - ve\, for\, inverter\, , V_{dc} : always + ve$$

$$R_{dc} \text{ is accepted in ohms}$$

$$R_{dc\ pu} = \frac{R_{dc\,ohm}}{Z_{dc-base}}$$

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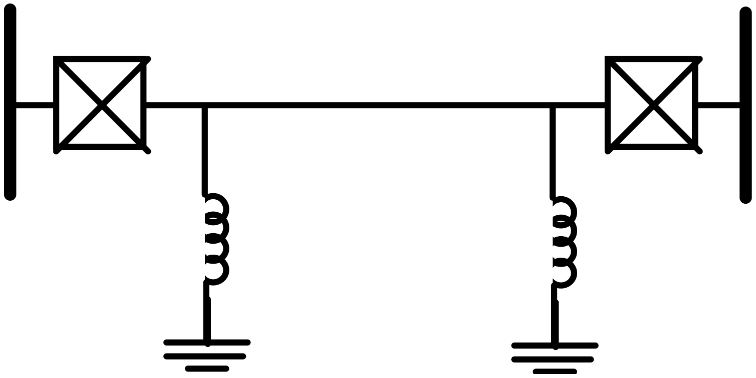
Modelling of DC Link:

Line Reactors:



Major references used in the development of Load Flow Studies Module

1. Stott and O.Alsac, "Fast Decoupled Load Flow", IEEE Transaction on Power Apparatus and Systems, vol PAS-93, May 1974, PP : 859-869.

2. D.Thukaram, K.Parthasarthy etal., "Steady State Power Flow Analysis Incorporating Load and Generator Regulation Characteristics", Journal of the Institution of Engineers(1),Vol.64, pt.El.5, April 1984, PP : 274 - 279.

3. H.Fudeh, C.M.Ong etal., "A Simple and Efficient AC-DC Load-Flow Method For Multi-terminal DC Systems", IEEE PES summer Meeting, Portland, Oregon, July 1981, PP : 26 - 31.

Major references used in the development of Load Flow Studies Module

4. D.Thukaram, K.Parthasarthy etal., "Optimum Allocation of Reactive Power in AC-DC Power Systems", Proceedings of The 53rd Research and Development sessions, Bhuvaneshvar, May 1986, pp : 39 - 47.

5. R.Nagaraja, S.A.Soman, K.Parthasarathy, D.Thukaram etc, "Fast Decoupled Power flow Incorporating Load and Generation regulating Characteristics", Eighth National Power systems conference. New Delhi, Dec. 1994.

6. Stagg and A.H. El-Abiad, "Computer Methods in Power System Analysis", Mcgraw- Hill, 13th print, New Delhi, 1988.

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Queries & Discussions

Thank You

POWER FLOW SOLUTION PRACTICAL CONSIDERATIONS

Data to be collected

1. Single line diagram of the system

2. Transformer Name plate details

   - Voltage rating, MVA rating
   - Impedance on own rating

3. Transformer Tap details

   - Tap no. : 1 to 19
   - Voltage at minimum tap no.
   - Voltage at Maximum tap no.
   - Type of tap change : OLTC/OFTC

Typical data for a Transformer

- MVA rating : 145
- Voltage rating : 132kV/66kV
- Number of taps : 6
- Minimum tap voltage : 122.1 kV
- Maximum tap voltage : 138.6 kV
- Impedance on own rating : 11%
- Type of tap change : OLTC

Line or Cable details

- Number of circuits
- Positive sequence resistance - ohms/km
- Positive sequence reactance - ohms/km
- Positive sequence susceptance - mho/km
- Line length
- Loading capability

Typical values for line

Voltage KV	R ohm/km	X ohm/km	B mho/km	Bp 100 km
400	0.02640	0.329440	3.365e-6	0.5384
220	0.07986	0.399784	2.867e-6	0.1388
132	0.102	0.401	1.46e-6	0.0254
110	0.18906	0.398961	2.834e-6	0.0343
66	0.31882	0.466684	2.892e-6	0.0127
33	0.201	0.395	2.72 e-6	0.0029

Per unit susceptance value for the package B or B/2 is always a confusion.

Load data

- Real and Reactive Power at all the load buses

Or

- Real Power and Power Factor

Shunt Reactor and Capacitor Data

- Rated kV and MVAR at rated kV
- 400 kV bus/line reactors are rated at 420 kV
- 11 kV capacitors are rated at 12.5 kV

Generator Data

- Scheduled real power and voltage
- Reactive power limits
- Capability curve

Node Numbering and Naming

Node numbers are for easy understanding

Ex :

1 - 100 : Generator buses

101 - 200 : 400 kV buses

201 - 400 : 220 kV buses

401 - 600 : 132 kV buses

601 - 800 : 66 kV buses

Node Numbering and Naming

Further,

1 - 1000 : Area 1 buses

1001 - 2000 : Area 2 buses

2001 - 3000 : Area 3 buses

3001- 4000 : Area 4 buses

Naming

Close to the user

Last digit to indicate the voltage level

Say,

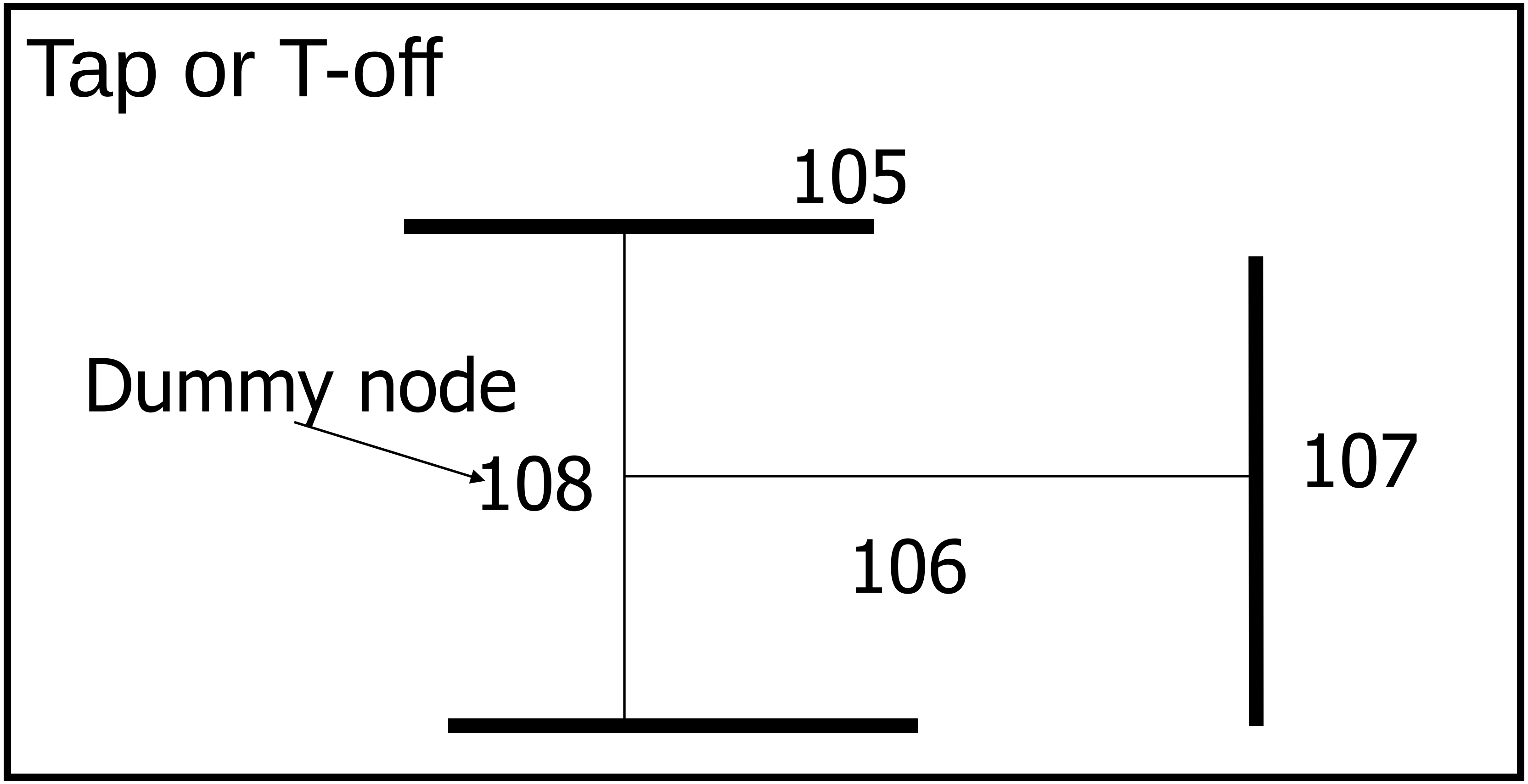
NLMG400 - Nelamangala 400 kV

NLMG220 - Nelamangala 220 kV

NLMG66 - Nelamangala 66 kV

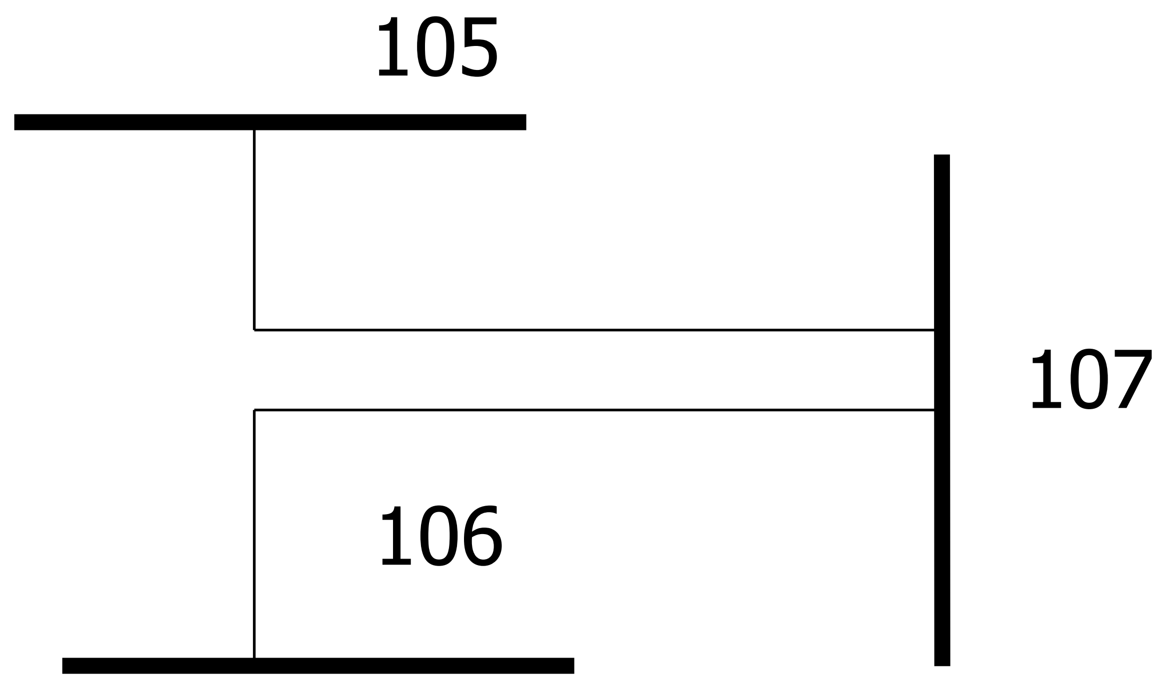
RAWI132 - Rarawai 132 kV

New substation arrangement



New substation arrangement

Loop in and Loop out (LILO)



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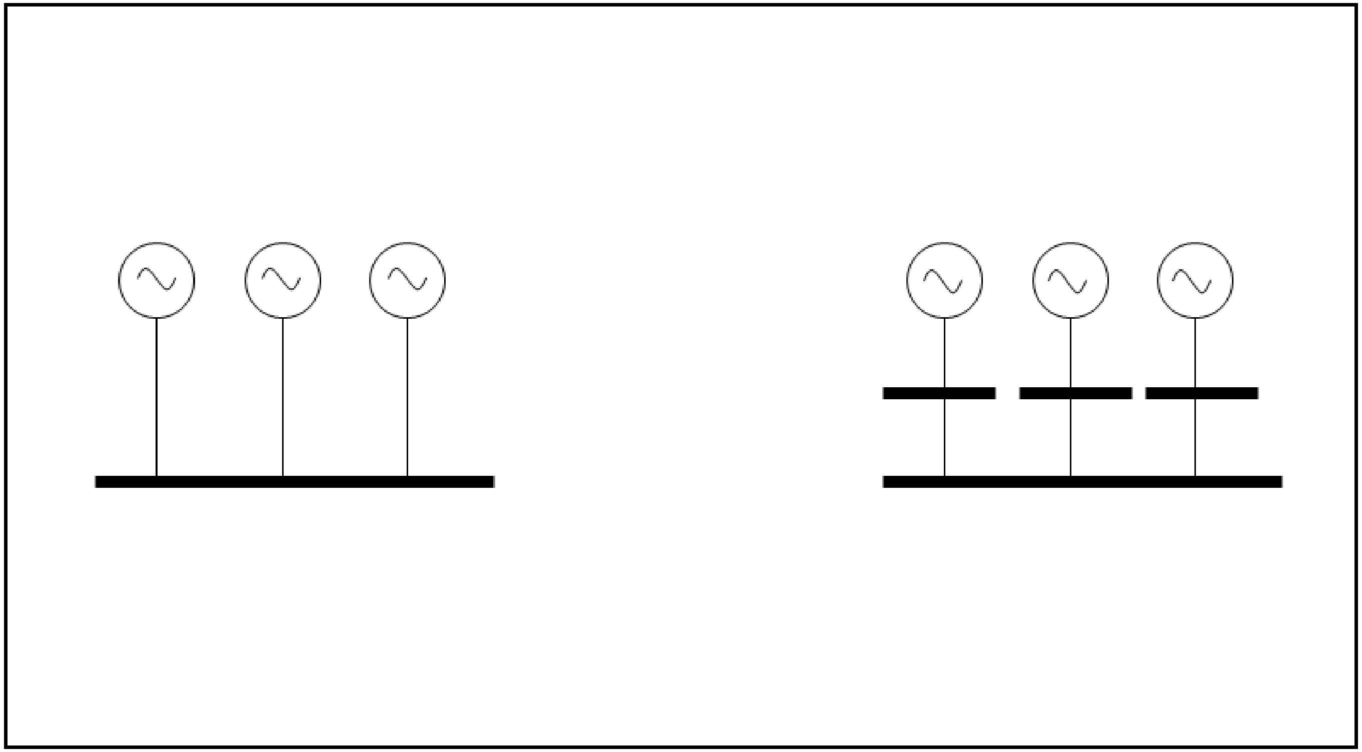
Generator Arrangement



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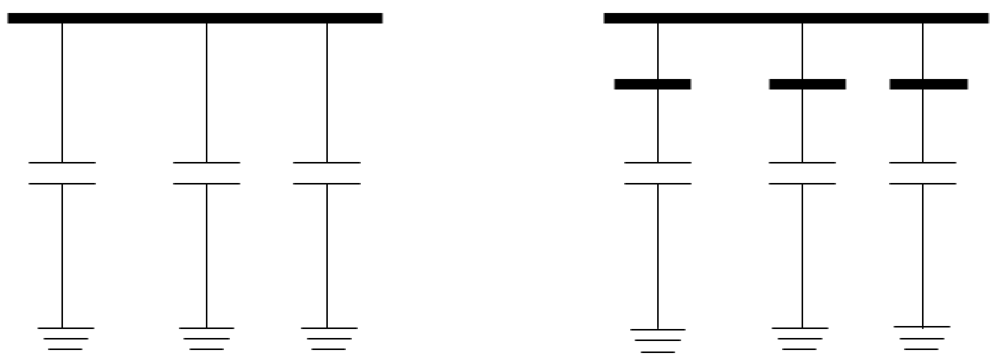
Shunt Arrangement

If voltage rating is same



Selection of base MVA

- For utility networks : 100 MVA
- For distribution networks : 10 or 1 MVA
- Industrial system : 20 MVA, 50 MVA, based on incoming transformer rating
- Depends on largest MVA equipment and smallest MVA equipment
- Depends on largest load and smallest load

Per Unit calculation

Most of the packages convert the name plate details to PU internally. No additional calculations are involved by the user

However, knowledge of pu calculation and conversion is very important.

$Z\ base = (kV)^2/MVA$

$Zpu = Z\ actual\ /\ Z\ base$

Voltage base remaining same,

$Zpu(new)=Zpu(old)*[MVA(new)/MVA(old)]$

Per Unit calculation

Thumb Rule

Conversion from smaller MVA base to larger MVA base : Zpu_new increases

Conversion from larger MVA base to smaller MVA base : Zpu_new decreases

Ex.

10 MVA, 8% on own base : 80% on 100 MVA base

500 MVA, 10% on own base, 2% on 100 MVA base

Special Consideration for Transformer

kV rating : 220/34.5

Base voltage on primary : 220 kV

Base voltage on secondary : 33 kV

Even for nominal tap of unity, transformer tap need to be different, i.e., 0.95652

+/- 5% becomes : 0.908694 to 1.004346

Basic Checks for Load Flow Analysis

1. Load and generation balance

Total scheduled generation : 3000 MW
Total scheduled load : 2800 MW

Total scheduled generation : 3000 MW
Total scheduled load : 1000 MW

Total scheduled generation : 3000 MW
Total scheduled load : 4000 MW

Basic Checks for Load Flow Analysis

2. Line charging susceptance

3. Transformer pu value on own Rating

4. Line and cable parameters ohm/km

   - High voltage lines : R << X
   - Cable and medium voltage lines : R~=X
   - LT cables and LT lines : R >> X

Basic Checks for Load Flow Analysis

5. MVAR limits on generators

Load MVAR 2000,
Generator Qmin : -1000 MVAR
Generator Qmax : 3000 MVAR

Load MVAR 2000,
Generator Qmin : -1000 MVAR
Generator Qmax : 1000 MVAR

Convergence

1. Validity of the data

2. Reactive power support in the system

In case of convergence problem, to get some acceptable convergence which will enable to check the results

Disable reactive power limit checking on generators

Reduce reactive power load in the system

Convergence

Model reactive power load as a function of voltage

Reduce both real and reactive power load

Model both real and reactive power load as a function of voltage

Check for over voltage and low voltage in some pockets of the system

Convergence

Over voltage in some pockets :

Line reactors and bus reactors might not have been modelled

Shunt susceptance value may be wrong

Shunt capacitance value may be wrong

Convergence

Low voltage in some pockets :

Bus reactors which are normally opened at peak load may be present

Some ICT connections may be left out

Double circuit line data may be given as single circuit

Reactive power support in the network may not be adequate

Convergence

Every thing perfect, but unable to converge

X/R ratio : uniform, no problem

X/R ratio : Non uniform, normally transmission and distribution networks represented together

Try to separate and solve independently

Long and short lines at a bus

Neglect the short line and merge the buses

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Convergence

Tolerance value for convergence

Base MVA : 100

Smallest load at the bus, P = 50MW

Smallest load at bus, Q = 25 MVAR

Tolerance value of 0.01 on P : error = 0.01*100 = 1 MW on 50 MW is acceptable.

Tolerance value of 0.005 on Q : error = 0.005*100 = 0.5 MVAR on 25 MVAR is acceptable.

Convergence

Tolerance value for convergence

Base MVA : 100

Smallest load at the bus, P = 5 MW

Smallest load at bus, Q = 2.5 MVAR

Tolerance value of 0.01 on P : error = 0.01*100 = 1 MW on 5 MW is not acceptable.

Tolerance value of 0.005 on Q : error = 0.005*100 = 0.5 MVAR on 2.5 MVAR is not acceptable.

Convergence

Select the tolerance based on smallest real and reactive power loads.

Tolerance value : 0.001,
minimum mismatch at the end of the iterations = 0.002

Message : Load flow is unable to converge to given tolerance

Values can be accepted if the actual error is small.

Check the trend and increase the iterations, if required

Analysis of Results

- Voltage should be within the acceptable limits

Voltage	Max	Min
33kV	36.3kV 1.1 p.u	29.7kV 0.9 p.u
132 kV	145 kV 1.099 p.u	122 kV 0.924 p.u
220 kV	245 kV 1.114 p.u	198 kV 0.900 p.u
400 kV	420 kV 1.050 p.u	380 kV 0.950 p.u

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Analysis of Results

Generator Q limits

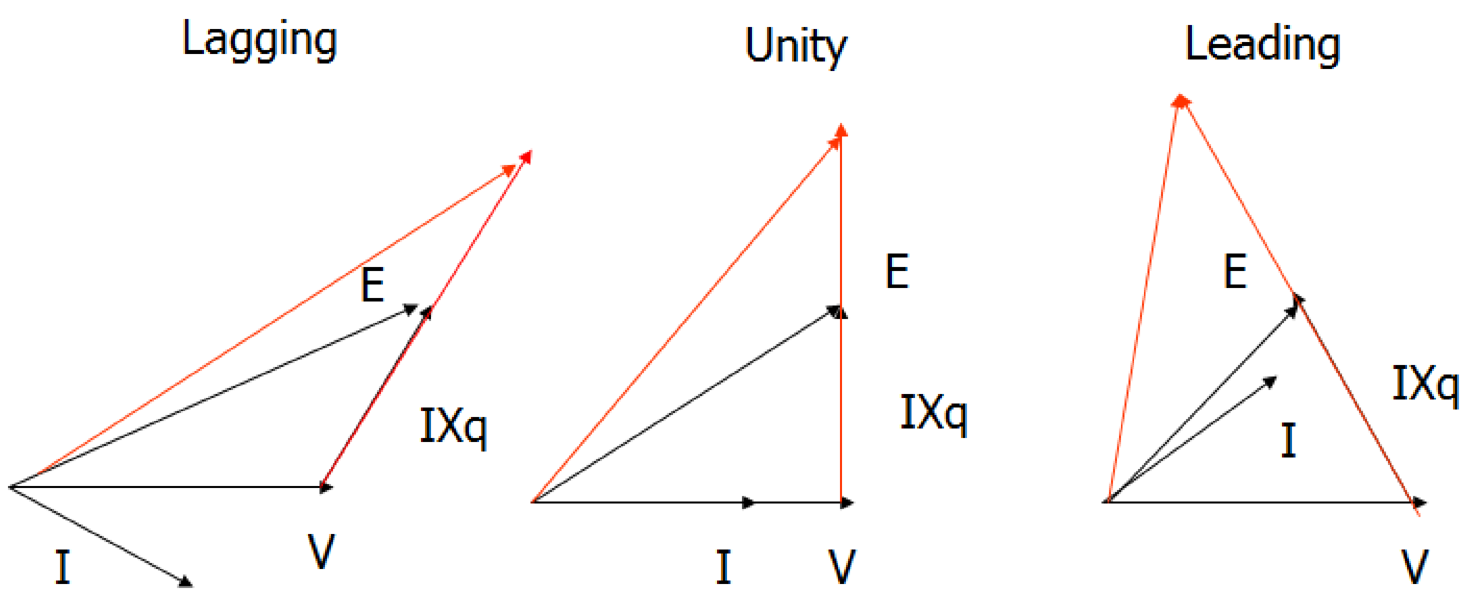
Thermal and nuclear units should never be operated in the leading power factor,

i.e., absorbing reactive power, even though the capability exists

Analysis of Results

Hydro units : X_q = 0.4 to 1 pu on own rating

Thermal units : X_q = 1 to 2 pu on own rating



Analysis of Results

Line loading

Permissible line loading depends on

- Voltage regulation
- Stability
- Thermal (current carrying) capacity

Voltage regulation : 5% and phase angle difference less than 30 degrees

Analysis of Results

- Thermal capacity
- Design practice
- Ambient temperature
- Maximum permissible conductor temperature
- Wind velocity

Analysis of Results

- Short lines can be loaded above SIL and long lines should be loaded less than SIL because of stability limitations.

- Double circuit line should not be loaded more than 50% of its capacity to account for one circuit outage

- For generating stations and important lines, tower outage (n-2 contingency) should be considered.

Queries & Discussions

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Thank You