Caribbean Colloquium on Power Quality

June 24-27, 2003, Dorado - Puerto Rico

Power Quality Studies Using Digital Simulation

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Power Quality Studies Using Digital Simulation

Introduction

Definitions

- **Power quality** : The concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment
  - This term refers to a wide variety of electromagne-tic phenomena that characterize the voltage and current at a given location of a pwer system
- **Electromagnetic compatibility** : The ability of a device, equipment, or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment
- **Electromagnetic environment** : The totality of electromagnetic phenomena existing at a given location

Introduction

- Two main concerns :
  - proliferation of contaminating equipment
  - proliferation of sensitive equipment
- Disturbance causes are well identified, but there is a lack of experience on their effects and how to quantify them
- There is also an increasing number of techniques for mitigating their effects

Introduction

- Disturbances
  - Causes, effects, mitigation
- Disturbance characterization
- Standards
  - IEC, CENELEC, IEEE (ANSI)
- Simulation tools for PQ studies
  - Transformed methods, Frequency- and Time-domain methods
- New techniques
  - Wavelets , Neural Networks

Contents

- Introduction
- Power Quality Disturbances
  - Causes, Effects, Characterization
- EMTP-type tools
  - Algorithms and Capabilities
- The ATP package
- Power Quality Studies using the ATP
- Illustrative Examples

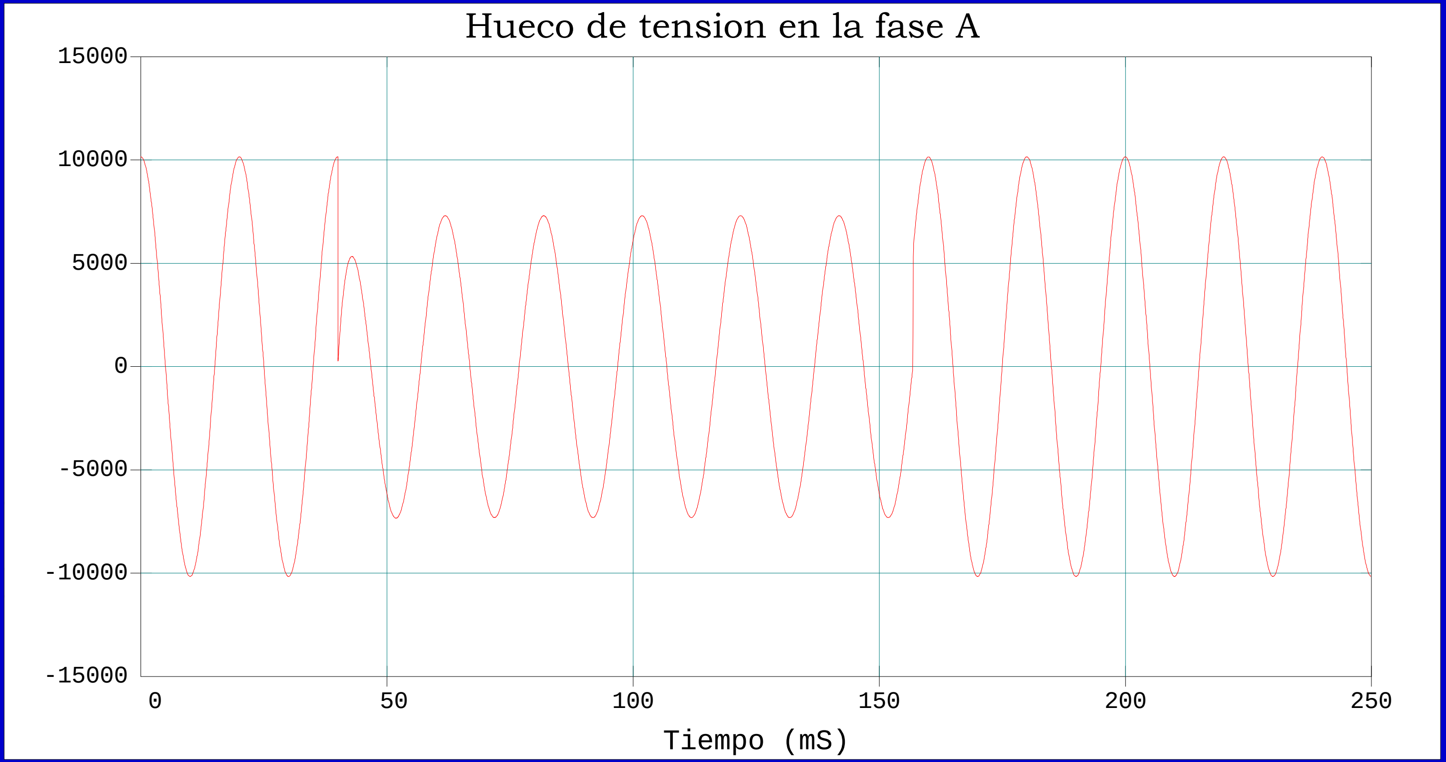
Power Quality Studies Using Digital Simulation

Disturbances : Causes, Effects and Characterization

Disturbances

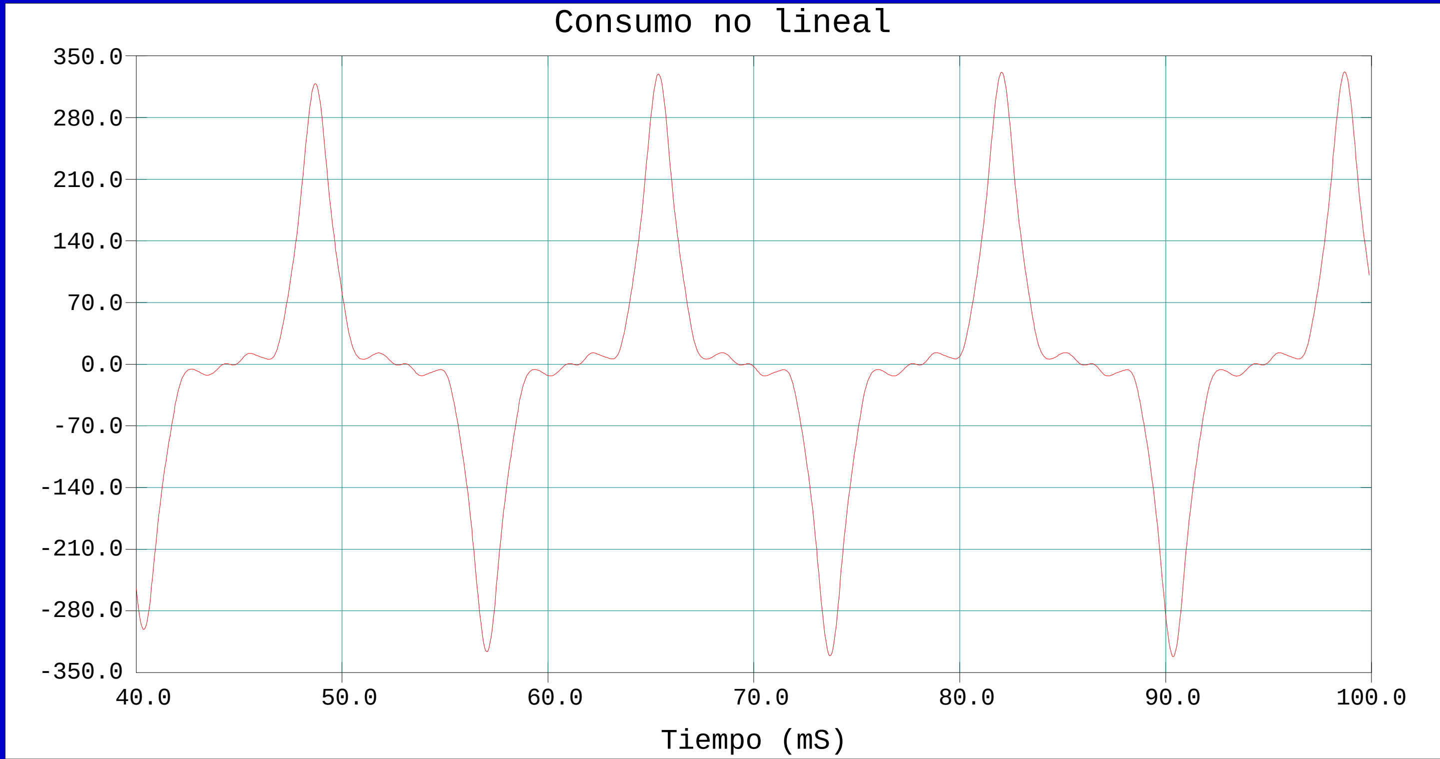
- Voltage dips
- Harmonics
- Flicker
- Transients
- Unbalances
- Other disturbances (notches, noise, ...)

Voltage Dips



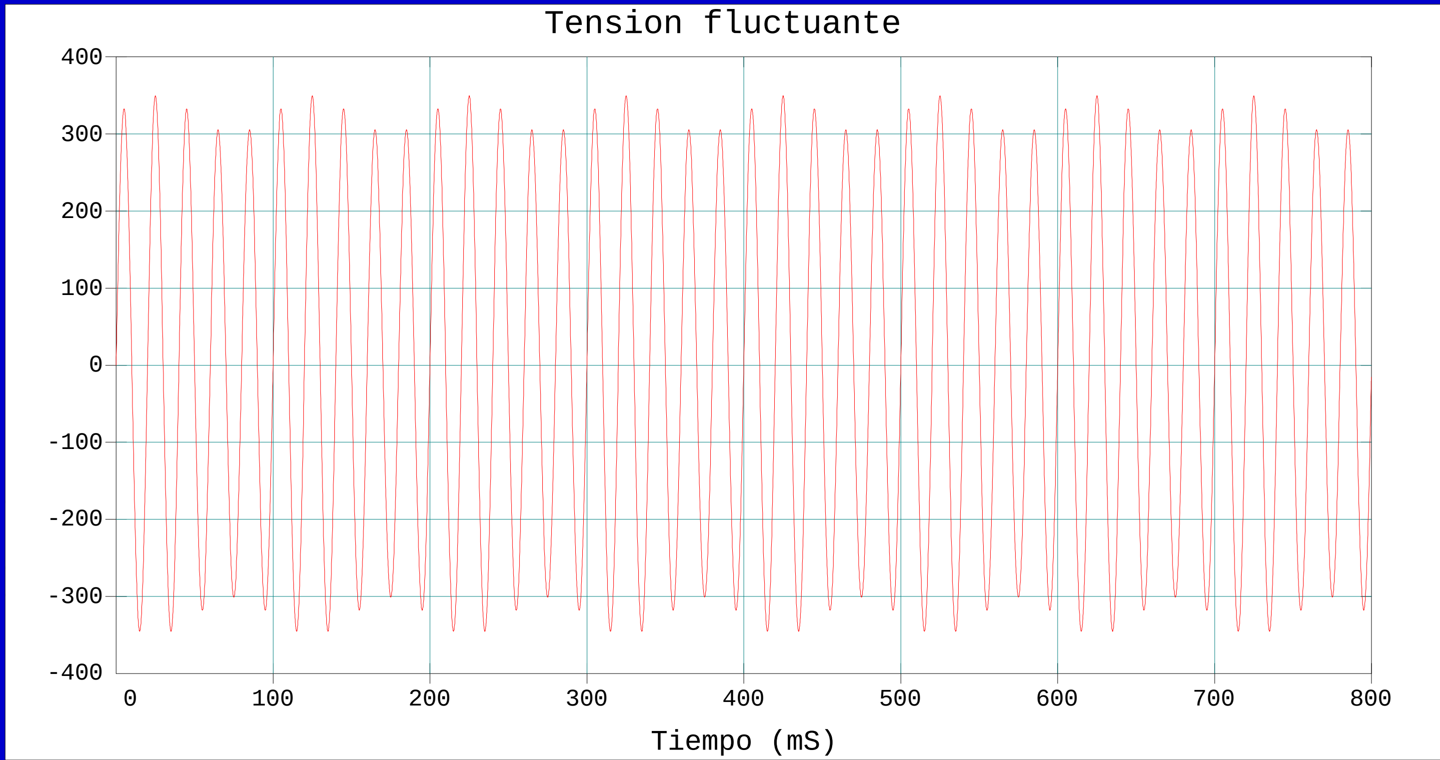
- **Causes**
  - shortcircuits
  - large motor startup
  - transformer energizing
  - sudden load variations
- **Effects**
  - equipment trip
  - energy lost

Harmonics



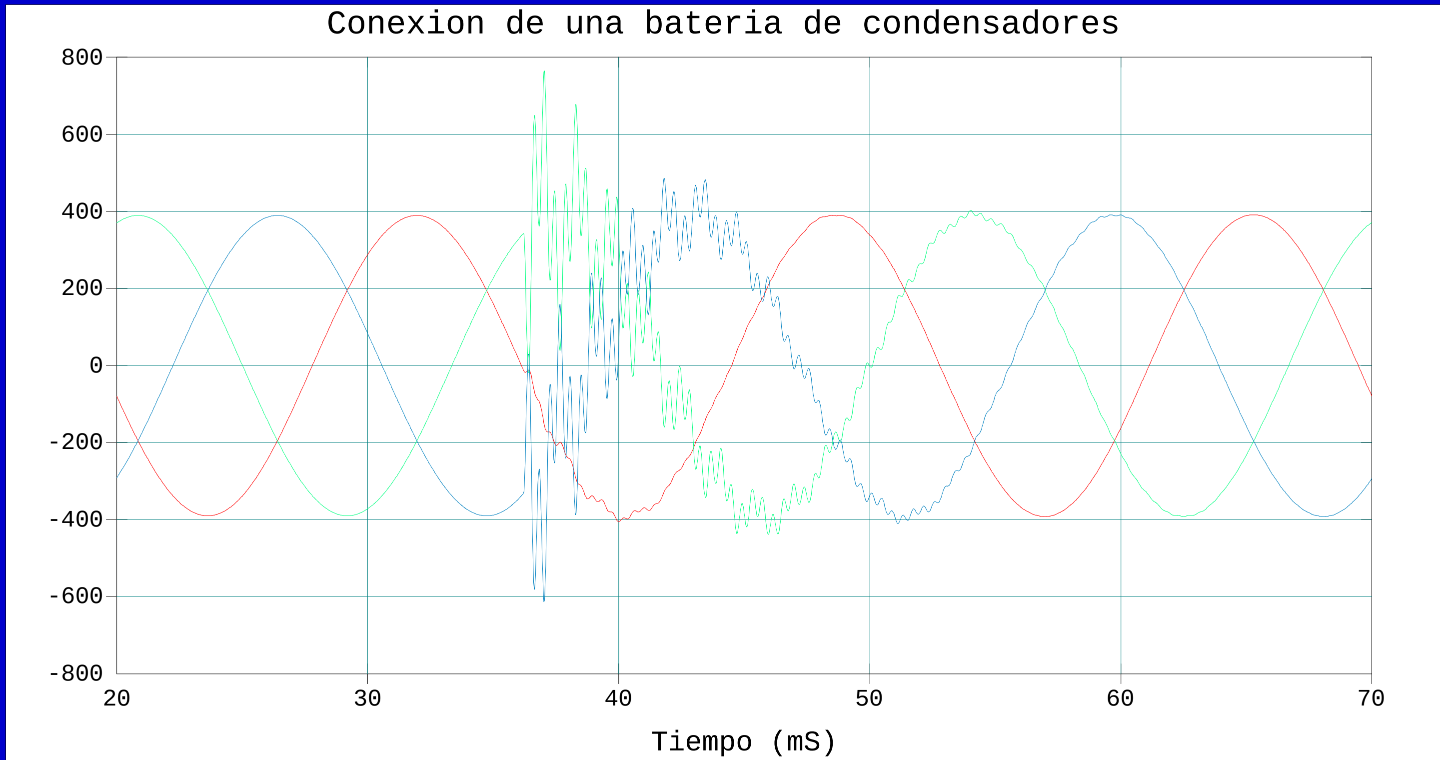
- **Causes**
  - nonlinear loads
  - saturable reactances
  - variable topology converters
- **Effects**
  - resonances
  - overheating
  - equipment maloperation

Flicker



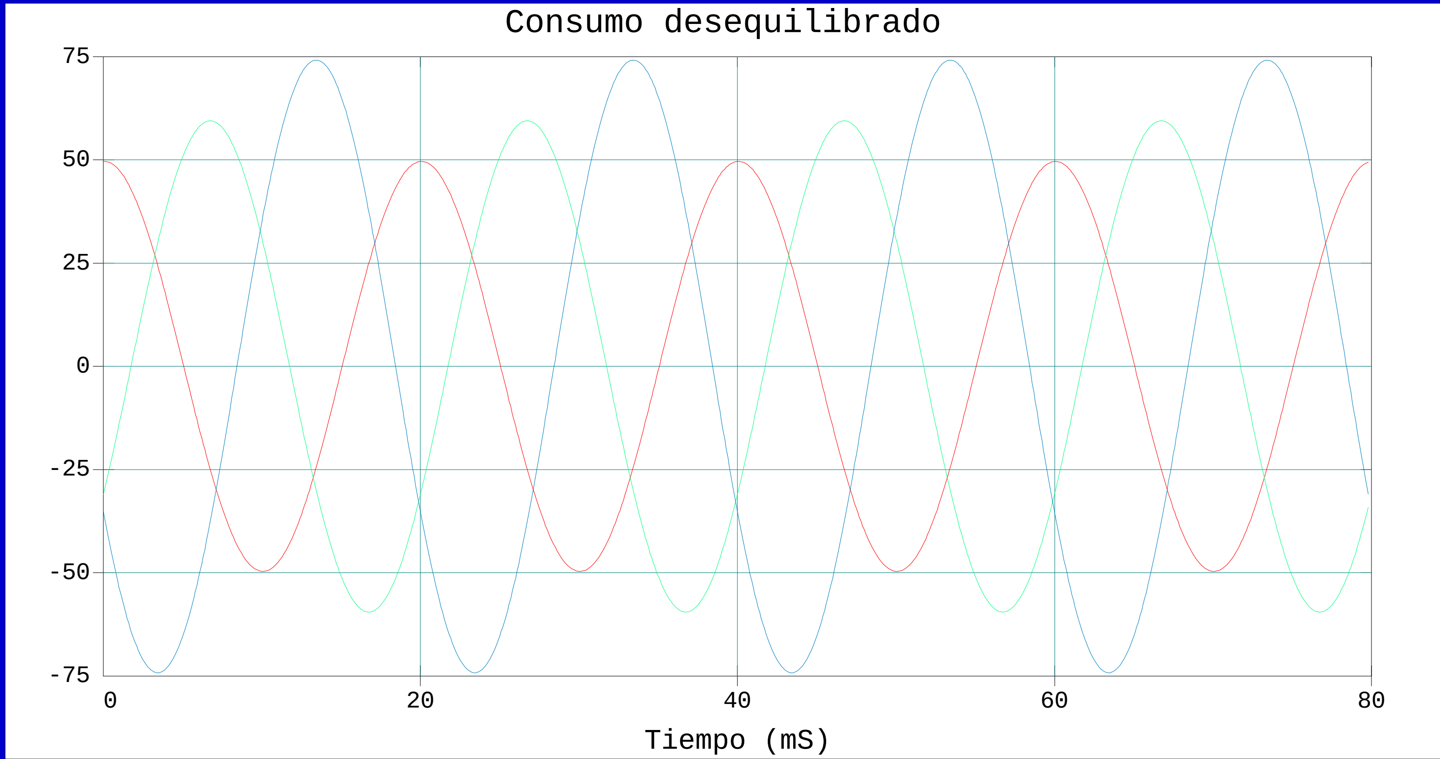
- **Causes**
  - arc furnaces
  - large motor startup
- **Effects**
  - human eye problems
  - maloperation of sensitive equipment

Transients



- **Causes**
  - shortcircuits
  - switching operations
  - lightning strokes
- **Effects**
  - overcurrents
  - equipment aging and breakdown

Unbalances



- **Causes**
  - single-phase loads
  - faulty three-phase loads
- **Effects**
  - maloperation of three-phase equipment

Power Quality Disturbances

TYPE OF DISTORSION	DURATION	METHOD OF CHARACTERIZING
Harmonics	Steady state	Harmonic spectrum Harmonic distortion
Phase-unbalance	Steady state	Unbalance factor
Interruptions	-------------	Duration
Notches	Steady state	Duration Magnitude
Voltage flicker	Steady state	Variation magnitude Frequency of occurrence Modulation frequency
Sags/Swells	Transient	Magnitude Duration Rms vs. time
Oscillatory transients	Transient	Waveform Peak magnitude Frequency range
Impulsive transients	Transient	Rise time Peak magnitude Duration
Noise	Steady state/ Transient	Magnitude Frequency spectrum

Digital Simulation

Benefits from digital simulation

Digital simulation can be useful

- to understand how disturbances propagate
- to determine waveform distortion
- to quantify the impact of disturbances
- to test mitigation techniques
- to design power conditioning equipment
- for educational applications

What should be represented?

Power quality simulations require the representation of

- power components
- disturbances (their stochastic nature, if necessary)
- protective devices (breakers, relays, reclosers, fuses)
- monitoring devices (characteristics, indices)
- mitigation devices (including dispersed generation and energy storage)

Types of digital tools

- Power flow
- Short-circuit calculations
- Frequency-domain
  (Harmonic Power Flow)
- Time-domain
  (ElectroMagnetic Transients Programs)

Capabilities of a digital tool

- Accurate modelling
- Multi-level modelling
- Development of custom-made models
- Numerical stability to avoid run-off problems
- Multiple run option
  (parametric studies, statistical analysis)
- Post-processing capabilities
- Interface to external tools - Open systems

Power Quality Studies Using Digital Simulation

Introduction to ElectroMagnetic Transients Programs

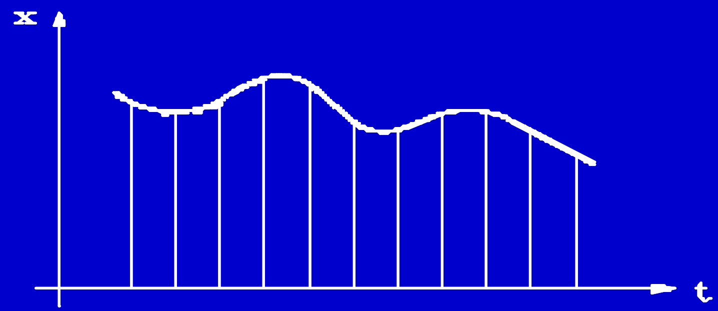
EMTP-Type Tools

- Circuit-oriented tools based on a time-domain technique
- The Dommel's scheme: A combination of the Trapezoidal rule and the Bergeron's method
- Advantages: simplicity, numerical stability
- Important aspects
  - Basic solution methods
  - Built-in models
  - Modelling guidelines
  - Applications

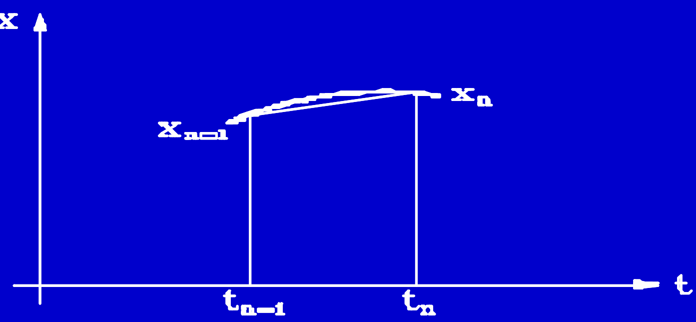
EMTP Solution Methods: Transient Solution

- The trapezoidal rule

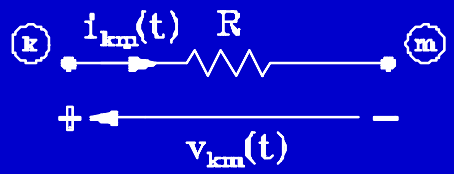
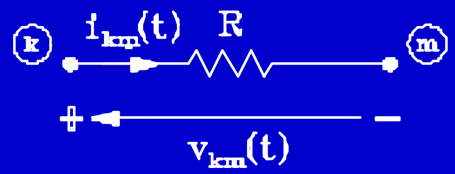
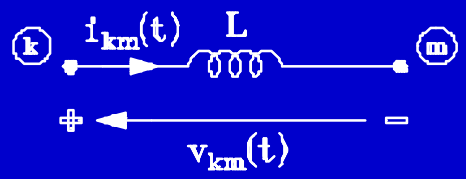
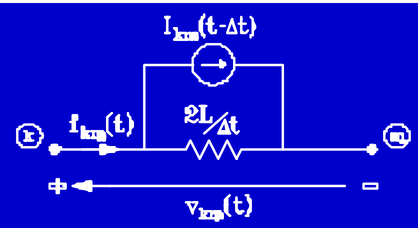
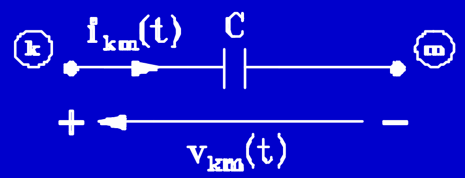
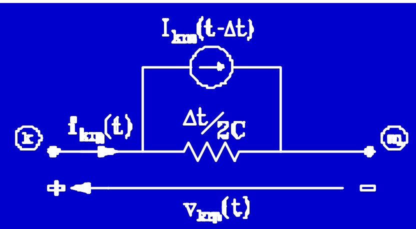
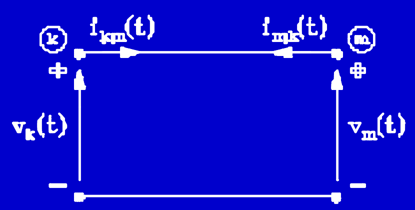
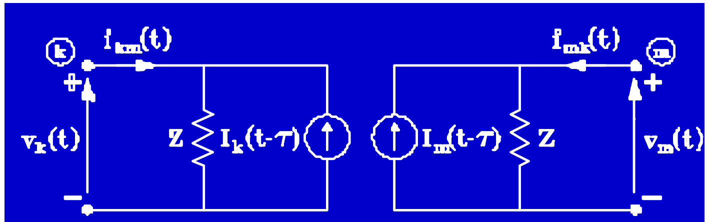
$$\frac{dy}{dt} = x(t)$$



$$y(t+D\ t) = y(t) + \frac{D\ t}{2}[x(t+D\ t) + x(t)]$$



Discrete Models

COMPONENT	TIME-DOMAIN REPRESENTATION	DISCRETE MODEL
RESISTOR		
INDUCTOR		
CAPACITOR		
IDEAL LINE		

EMTP Solution Methods: Transient Solution

- Equations are assembled using a nodal approach

$$[G]\ [v(t)] = [i(t)] - [I]$$

$$[G_{AA}]\ [v_A(t)] = [i_A(t)] - [I_A] - [G_{AB}][v_B(t)]$$

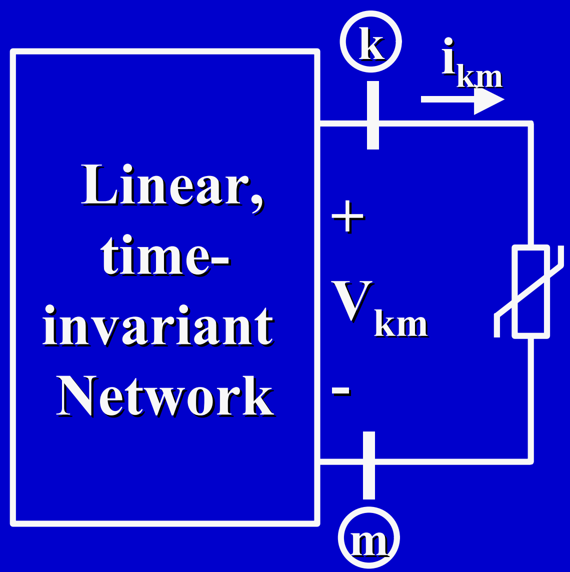
- The conductance matrix (G or G_{AA}) is symmetrical
  Triangular factorization is applied
- Limitation: Only linear systems
- Further improvements
  - Nonlinear components
  - Control system dynamics
  - Frequency dependent lines and cables
  - Rotating machines

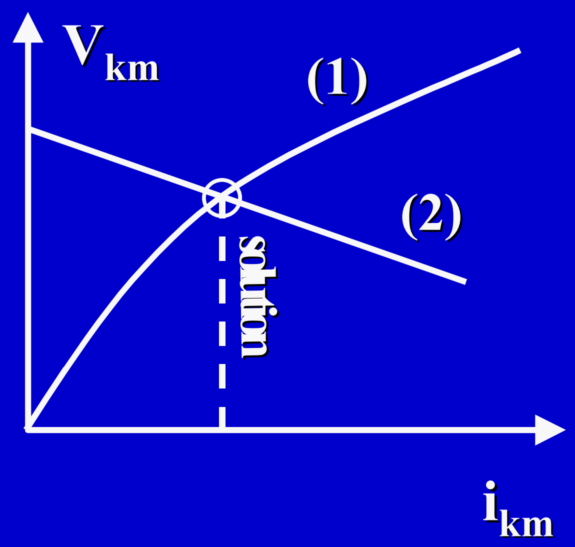
EMTP Solution Methods: Transient Solution

- Nonlinear networks: Compensation method

$$v_{km} = v_{km}(0) - r_{thev}\, i_{km}$$

$$v_{km} = f(i_{km},\ di_{km}/dt,\ t,\ \ldots)$$

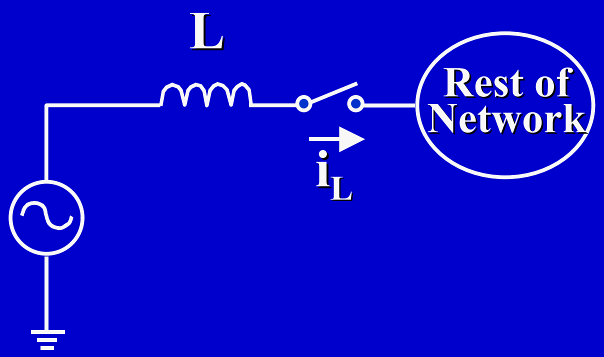


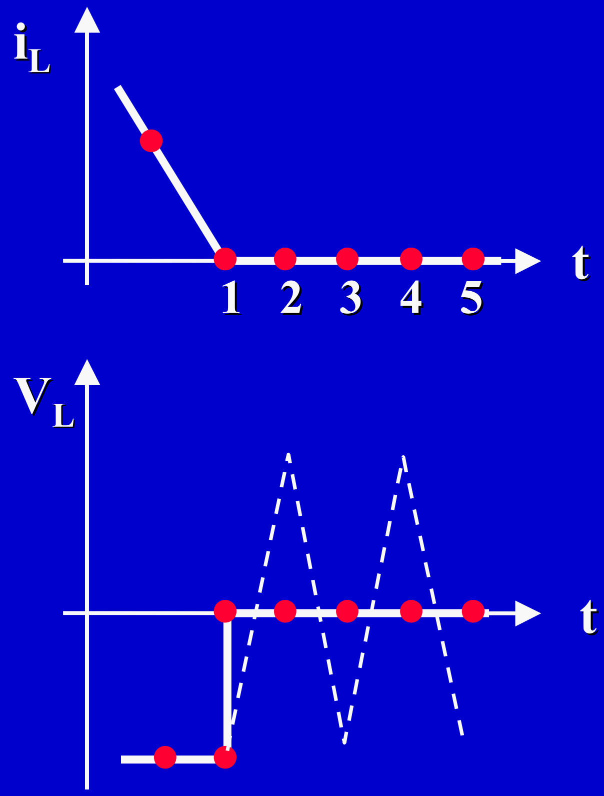


EMTP Solution Methods: Transient solution

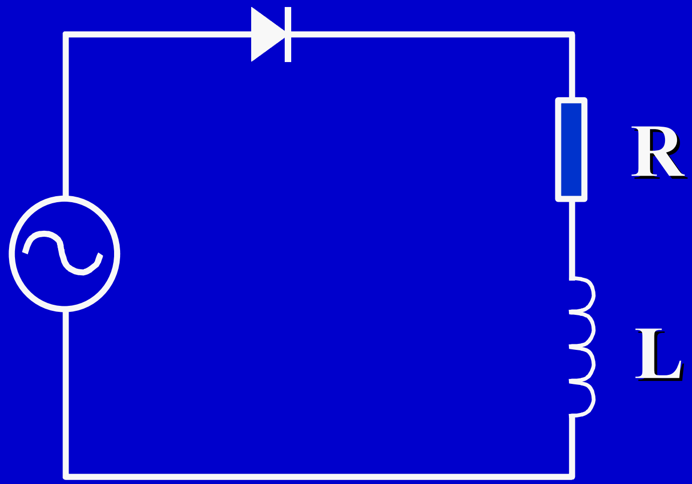
- Drawbacks of the trapezoidal rule
  - fixed time step size
  - numerical oscillations
- Techniques to reduce sustained oscillations
  - additional damping
  - snubber circuits
  - temporary modification of the solution method
    - Critical Damping Adjustment (CDA)
    - Interpolation

Numerical Oscillations

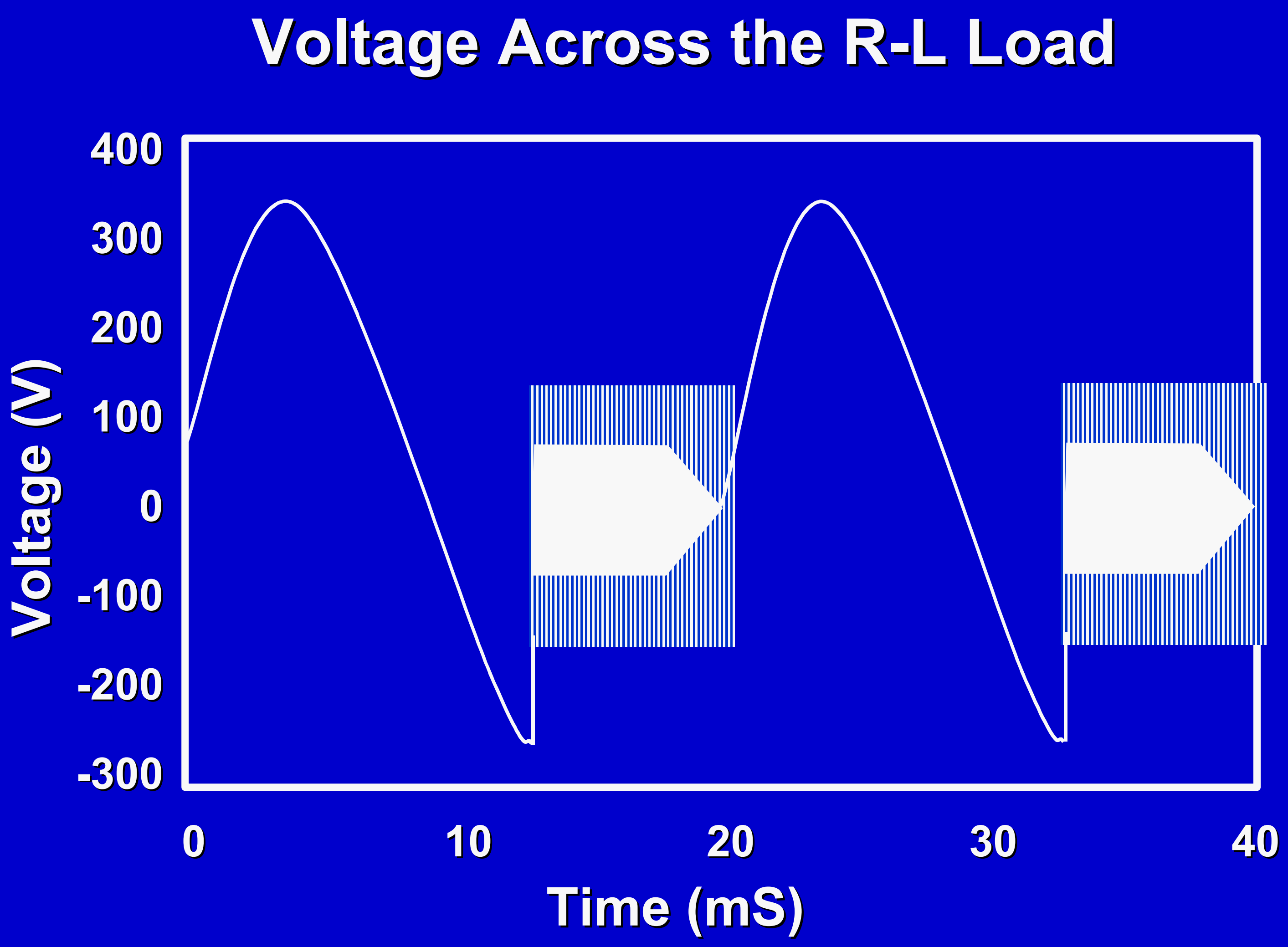




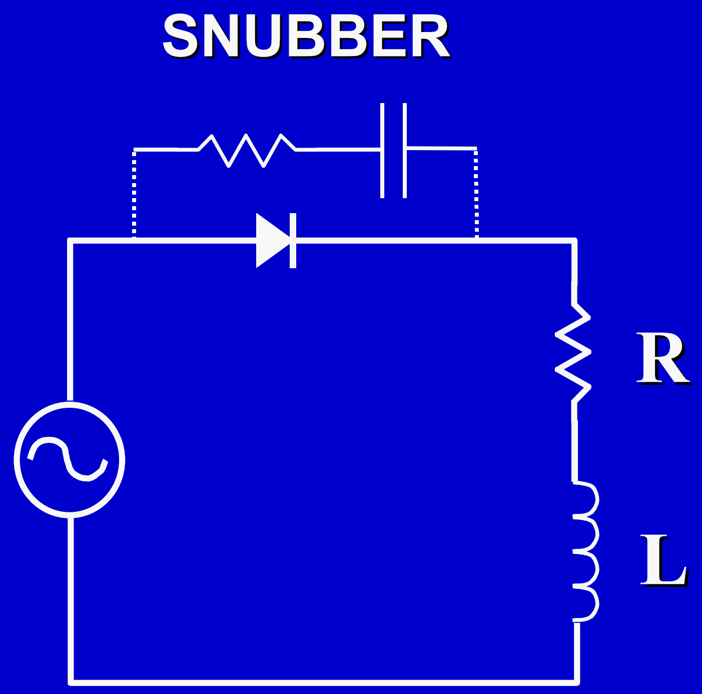
Numerical Oscillations



Numerical Oscillations

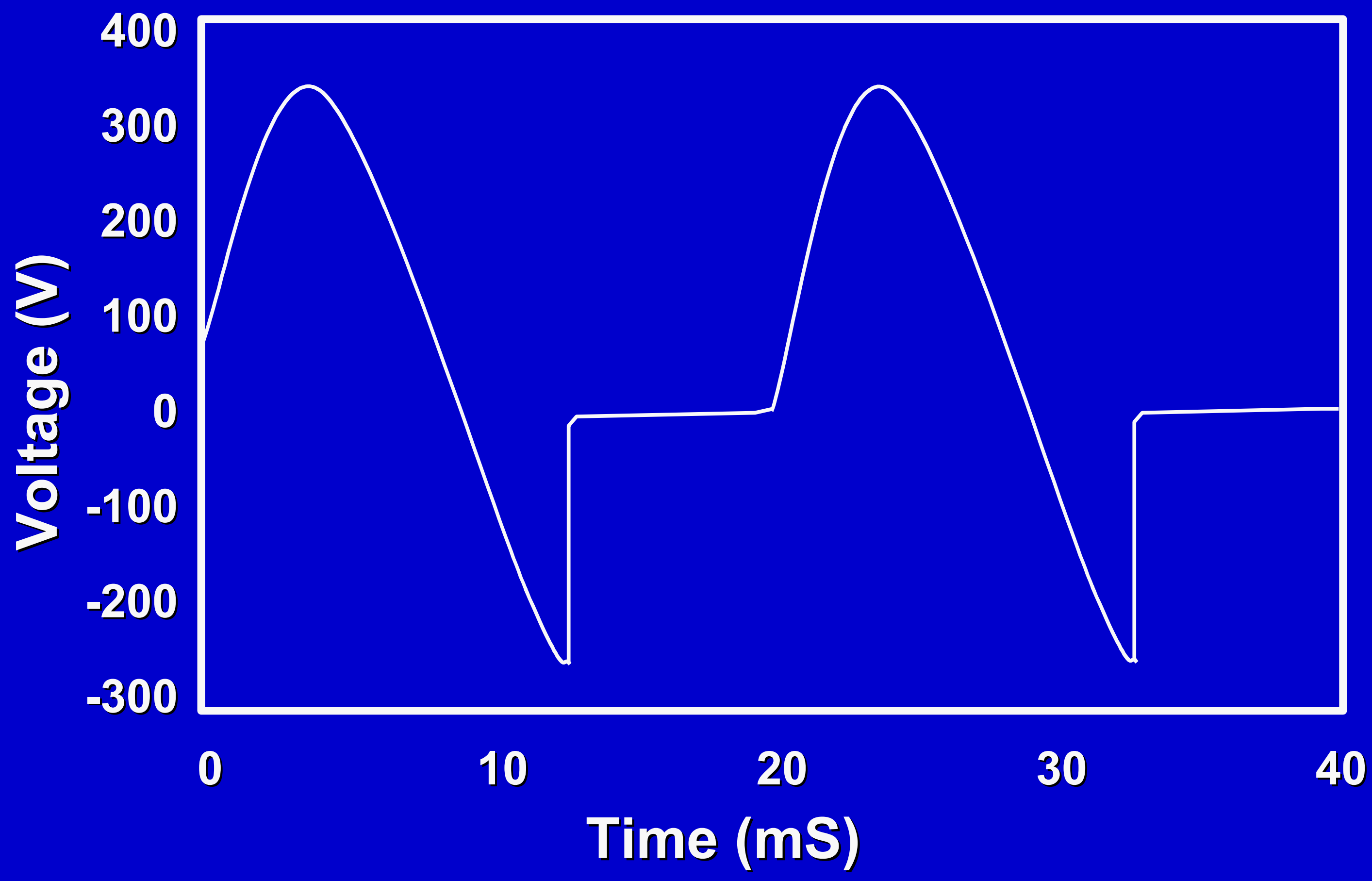


Numerical Oscillations



Numerical Oscillations

Voltage Across the R-L Load



EMTP Solution Methods: Initialization

- Importance of an initialization algorithm
- Steady state solution of linear networks

$$[Y]\ [V] = [I]$$

$$[Y_{AA}]\ [V_A] = [I_A] - [Y_{AB}] - [V_{AB}]$$

- Initial solution with harmonics
  - "Brute force" method
  - Start again/snapshot feature
- Initialization with harmonics (IwH)
- Load flow methods

EMTP Solution Methods: Control Systems

- Control systems represented by block diagrams

$$X(s) = G(s)\,U(s)$$

$$G(s) = K\,\frac{N_0 + N_1 s + \ldots + N_m s^m}{D_0 + D_1 s + \ldots + D_n s^n} \qquad m \leq n$$

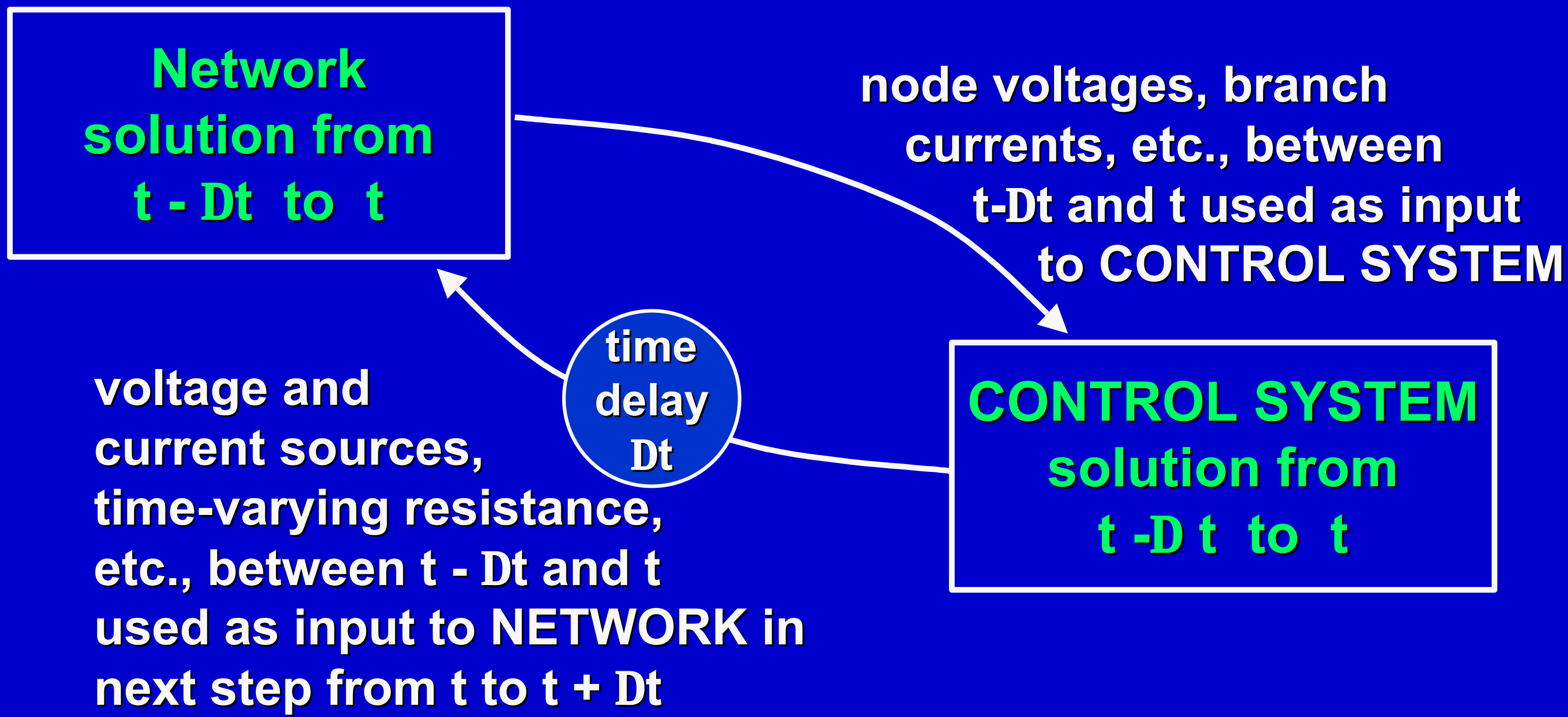
- Several types of control elements
- Solution method: Trapezoidal rule
  - Transfer function converted into an algebraic equation

$$[A_{xx}]\;[x] + [A_{xu}]\;[u] = [hist]$$

- Drawbacks of the solution method
  - Nonlinear blocks in a closed-loop
  - Unsymmetrical algebraic equations

EMTP Solution Methods: Control Systems

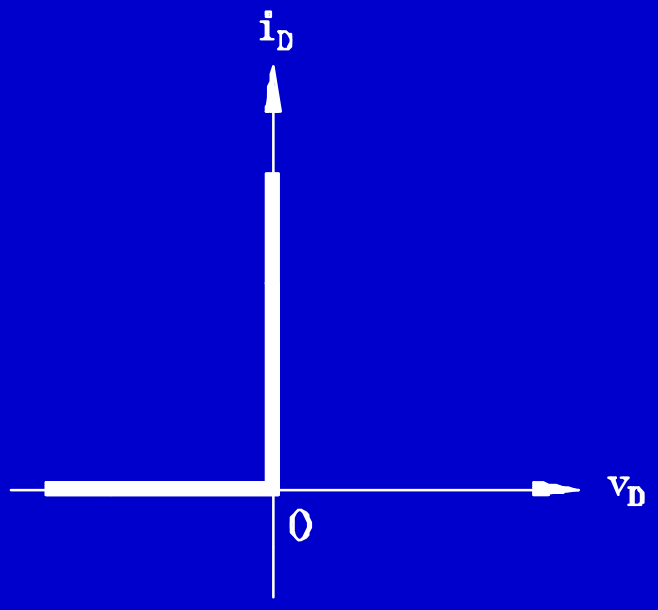
Interface Between a Network and a Control System



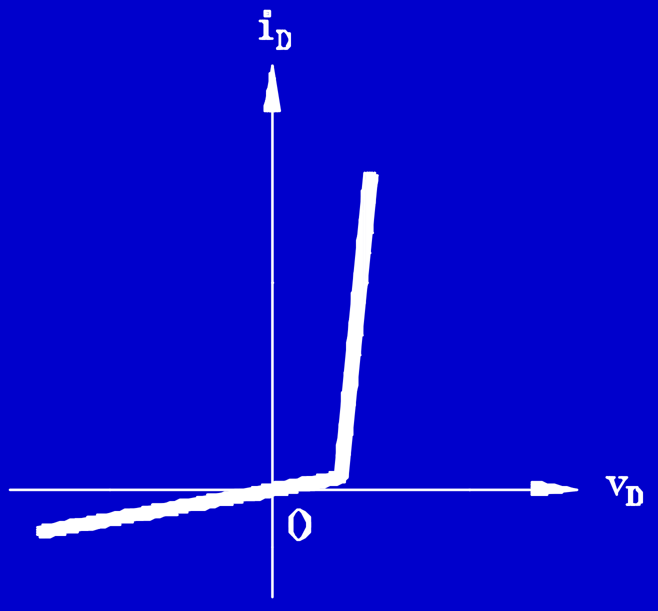
EMTP Built-in Models

- Basic components
  - Single- and multi-phase lumped parameter components
  - Single-phase distributed parameter components
  - Ideal and saturable transformers
  - Ideal switches
  - Ideal sources
- Overhead lines and insulated cables (frequency-dependent models)
- Power transformers
- Rotating machines
- Control systems

Semiconductor Models



Ideal switch



Piecewise linear resistance

Modelling Guidelines

- Important aspects
  - Network equivalents
  - Aggregated models
  - Frequency dependent models
- CIGRE Working Group 33-02 Brochure (1990)
  - Four frequency ranges
  - Guidelines for representing components for each frequency range
- IEEE Working Group on Modeling and Analysis of System Transients using Digital Programs
  - Low Frequency Transients, Switching Transients, Fast Front Transients, Very Fast Front Transients, Power Electronics, Protection and Control
  - Special Publication in 1999

Classification of Frequency Ranges

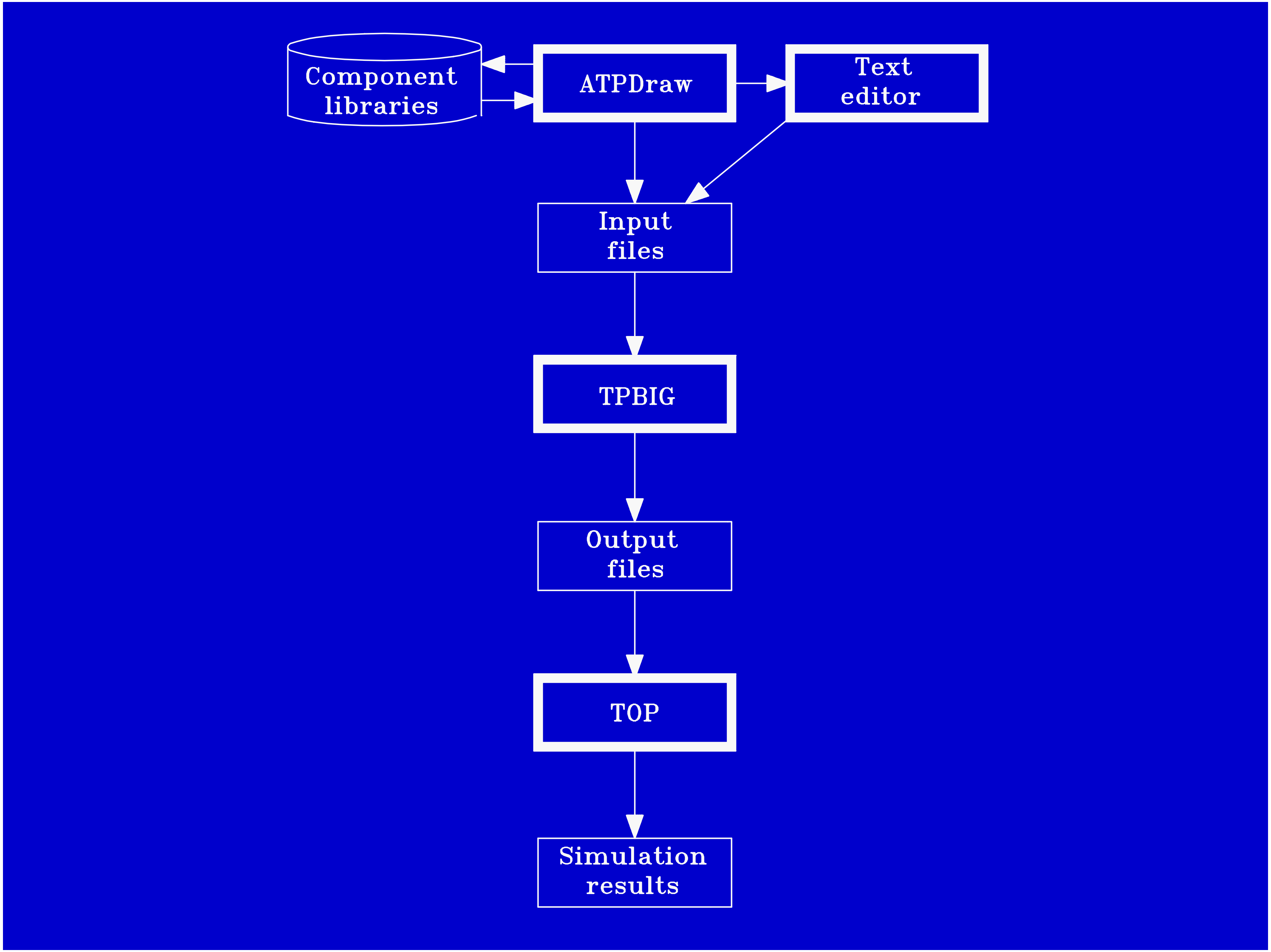
GROUP	FREQUENCY RANGE	SHAPE DESIGNATION	REPRESENTATION MAINLY FOR
I	0.1 Hz - 3 kHz	Low frequency oscillations	Temporary overvoltages
II	50 Hz - 20 kHz	Slow front surges	Switching overvoltages
III	10 kHz - 3 MHz	Fast front surges	Lightning overvoltages
IV	100 kHz - 50 MHz	Very fast front surges	Restrike overvoltages

Discussion

- Input data
  - Very often only approximated values
  - Specially for transients of Group III and IV
- Type of study
  - Maximum peak system transients
  - Representation of losses, inductances and capacitances
- System complexity
  - Very detailed representation, long simulation
  - The more components, the higher the probability of wrong modeling

Power Quality Studies Using Digital Simulation

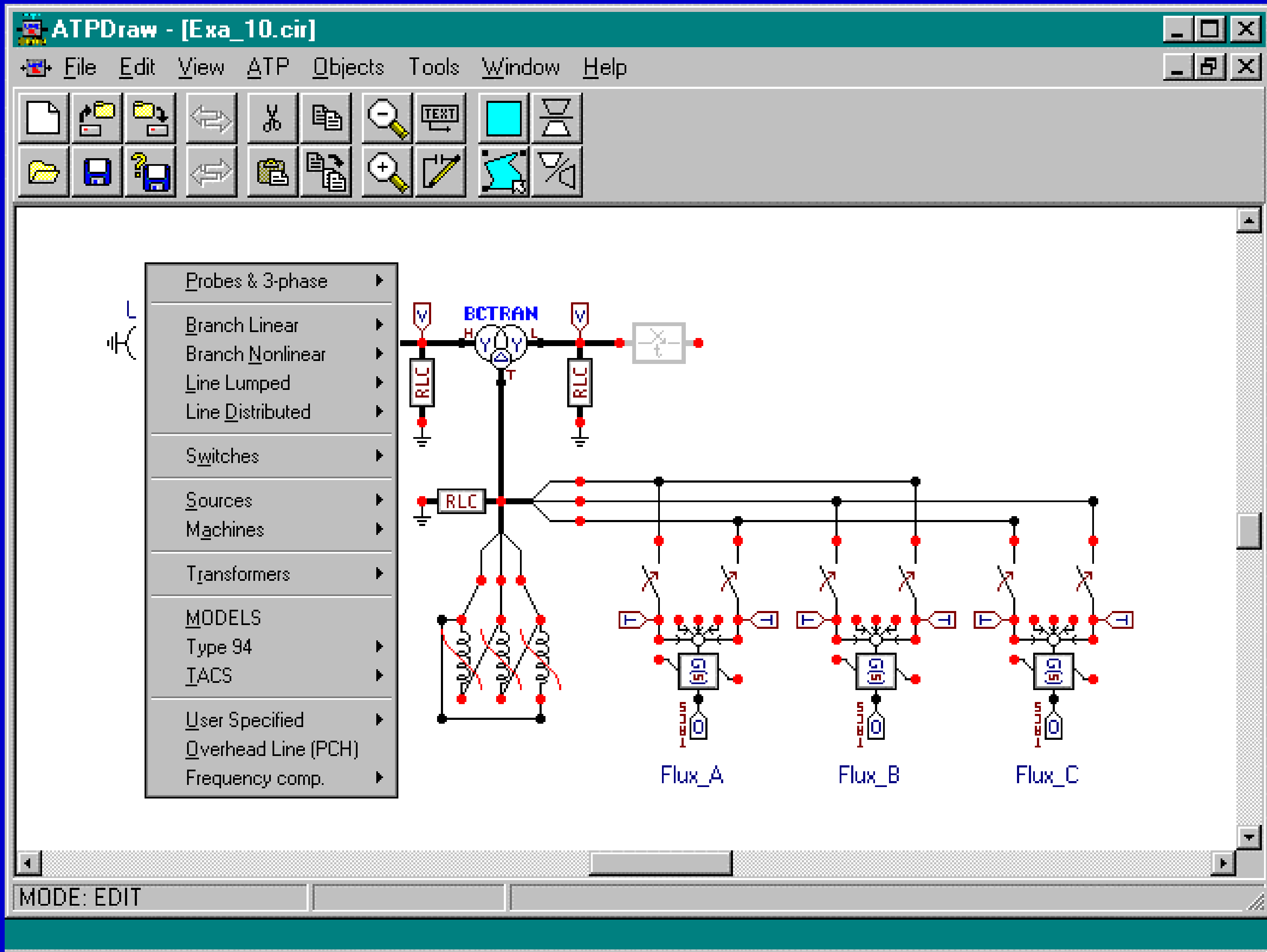
The ATP Package (Alternative Transients Program)


Component libraries
ATPDraw
Text editor
Input files
TPBIG
Output files
TOP
Simulation results

The ATP Package

- **ATPDraw** - Interactive graphical preprocessor
  - built-in editor for creating and correcting data files
  - support of Windows clipboard for metafile/bitmap
  - output of Windows metafile/bitmap file format or PS files
  - copy/paste, rotate, import/export, group/ungroup, undo,
  - print facilities
  - help on line
  - icon editor for user specified objects
  - multiple windows
- This tool can manipulate
  - circuit files in binary code, where the program stores the graphical picture of circuits
  - input files in ACSCII code, created as input for ATP simulations
  - support files for ATPDraw objects in binary code
  - files produced created by DATA BASE MODULE and called by user specified objects
  - MODELS files in ASCII code

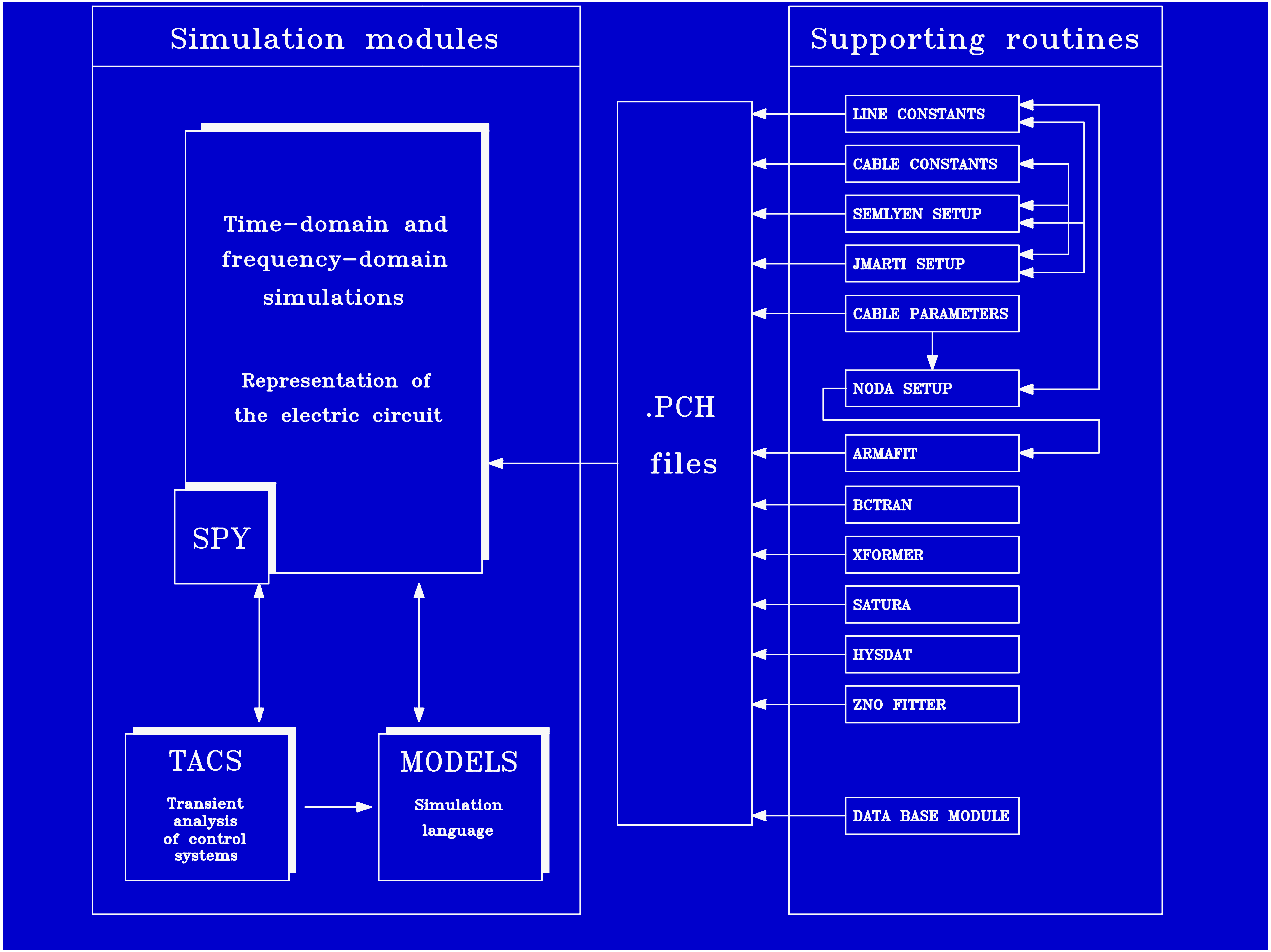
ATPDraw



ATPDraw - [Exa_10.cir]
File Edit View ATP Objects Tools Window Help
Probes & 3-phase
Branch Linear
Branch Nonlinear
Line Lumped
Line Distributed
Switches
Sources
Machines
Transformers
MODELS
Type 94
TACS
User Specified
Overhead Line (PCH)
Frequency comp.
BCTRAN
RLC
Flux_A
Flux_B
Flux_C
MODE: EDIT

The ATP Package

- **TPBIG : Tool for digital simulation of electromagnetic transients**
  - **Time- and frequency-domain techniques**
  - **Sensitivity and statistical studies**
  - **Two types of built-in capabilities**
    - **Simulation modules**
    - **Supporting routines**

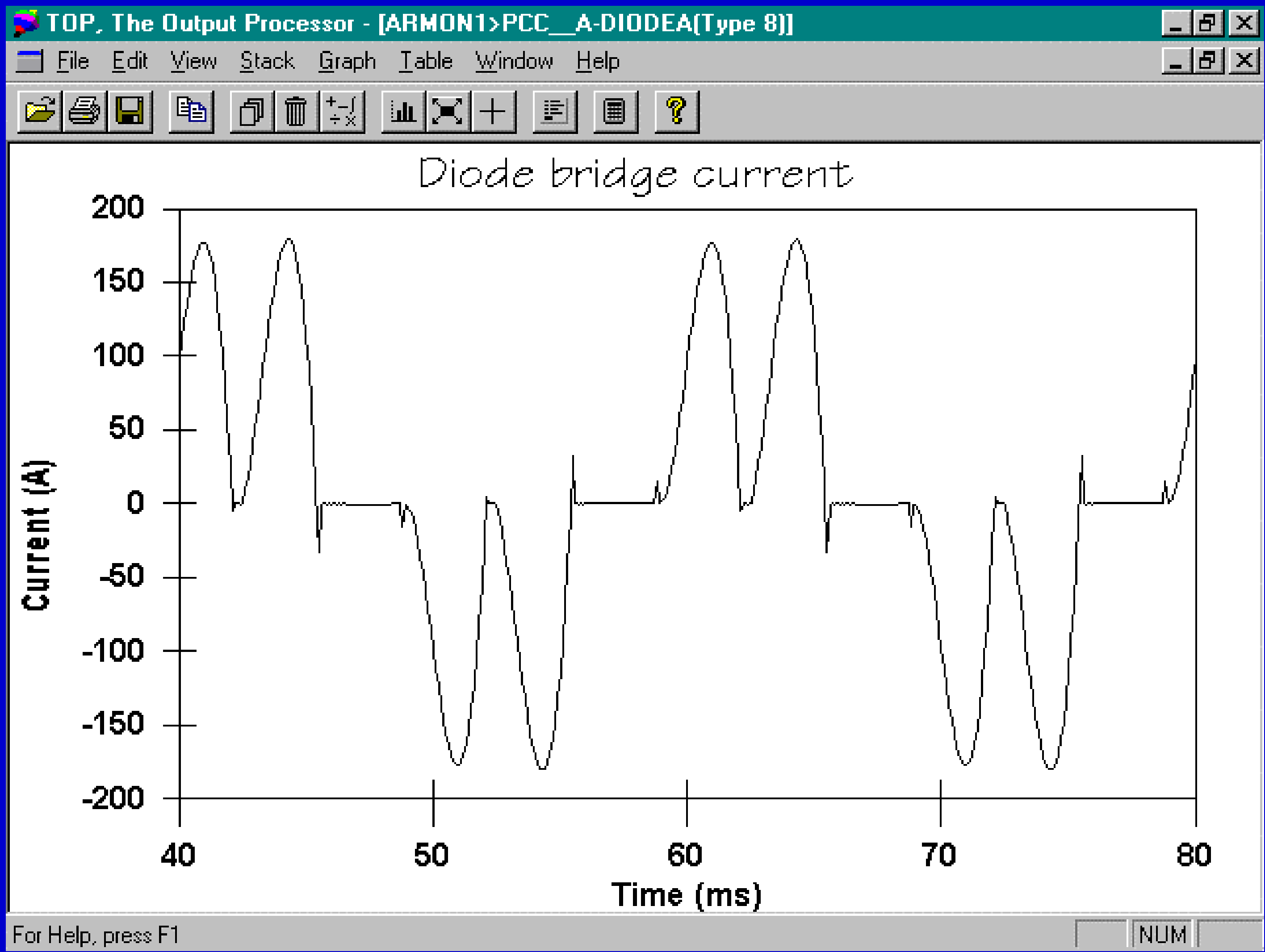


Simulation modules
Supporting routines
Time−domain and
frequency−domain
simulations
Representation of
the electric circuit
SPY
TACS
Transient
analysis
of control
systems
MODELS
Simulation
language
.PCH
files
LINE CONSTANTS
CABLE CONSTANTS
SEMLYEN SETUP
JMARTI SETUP
CABLE PARAMETERS
NODA SETUP
ARMAFIT
BCTRAN
XFORMER
SATURA
HYSDAT
ZNO FITTER
DATA BASE MODULE

The ATP Package

- **TOP : Interactive graphical postprocessor that allows users**
  - **to handle data from various sources**
  - **to visualize the data of interest in the form of tables and graphs**
  - **to view several plots simultaneously in multiple windows**
  - **to display selected data using *windows* and *frames***
  - **to perform mathematical operations on the various data objects**
  - **to format the data display based on user prefe-rences**
  - **to export the data being visualized**

TOP



TOP, The Output Processor - [ARMON1>PCC__A-DIODEA(Type 8)]
File Edit View Stack Graph Table Window Help
Diode bridge current
Current (A)
200
150
100
50
0
-50
-100
-150
-200
40
50
60
70
80
Time (ms)
For Help, press F1
NUM

Power Quality Studies Using ElectroMagnetic Transients Programs

EMTP Applications in Power Quality Studies

- Modelling of power system components and sources of power quality problems
- Simulation of the effects of power quality disturbances
- Analysis of mitigation techniques
- Postprocessing of results
- Development of custom-made simulation tools

Component representation

- Development of new models
  - There are many models not yet available in EMTP-type tools
- Development of custom-made modules
  - Integrated modules can simplify simulation tasks
- Network equivalents
  - Represent those parts of the system for which a detailed model is not needed, reduce the comple-xity and computation time, preserve the accuracy
- Aggregated models

Harmonic analysis

- **Goals**
  - investigate harmonic generation and propagation
  - quantify distortion in voltages and currents
  - determine resonant conditions
  - analyze reduction/compensation techniques
- **Representation of harmonic sources**
  - voltage/current source
  - "switching function"
  - detailed representation
- **Methods**
  - Load flow, Current injection analysis, Transformed methods, Probabilistic methods
- **Techniques**
  - Frequency domain $[Y_n][V_n]=[I_n]$
  - Time domain $[G][v(t)]=[i(t)]-[I]$
  - Hybrid techniques

Transient Analysis

- Overvoltage calculation and analysis of protection devices
- Capacitor switching
  - Voltage magnification, Nuisance tripping
- Voltage dips originated by faults and motor startup
  - Network equivalents, Aggregated models
- Voltage notching caused by normal commutation actions of controlled converters
- Voltage flicker associated to lighting effects
  - Cyclic : Arc furnaces
  - Noncyclic : Large motor startup
- Statistical calculations
  - Lightning and switching overvoltages
- Power quality problems due to improper grounding

Mitigation Techniques

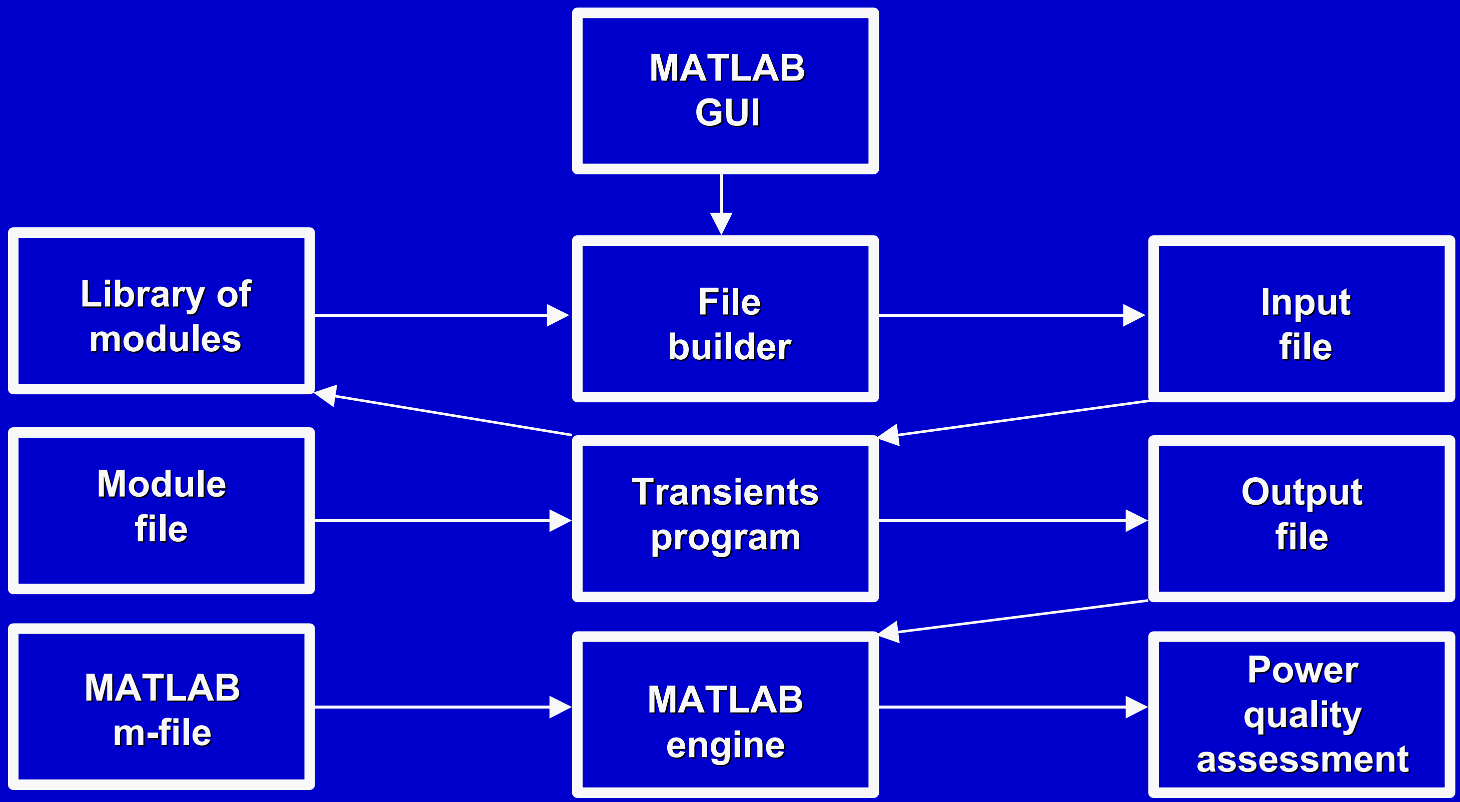
- Passive and active filters
- Uninterruptible power supply (UPS)
- Static VAr compensation (SVC)
- Superconducting magnetic energy storage (SMES)
- Custom Power devices
- Guidelines for modelling power electronics systems using EMTP-like tools
- Some EMTP applications
  - Simulation and design of passive filters, active filters, control strategies based on current wave-shaping
  - Performance analysis of micro-SMES systems for protection of customer facilities
  - Simulation and design of custom power devices

Postprocessing of results

- Analysis of simulation results to
  - calculate power quality indexes
  - test algorithms aimed at identifying disturbances
- Postprocessing possibilities
  - current tools (TPPLOT, GTPLOT, TOP)
  - POSTPROCESS PLOT FILE option
  - capabilities of a external software, i.e. MATLAB

Development of custom-made tools

- **Capabilities available in other packages can be used to develop custom-made simulation tools**
- **Example : A MATLAB-EMTP based tool that consists of the MATLAB-based GUI, an EMTP module library (based on EMTP Data Module), the EMTP main program, MATLAB processing and plotting capabilities**



Development of custom-made tools

- **EMTP is controlled from a master program, whose goal is to create and edit input files, and analyze simulation results, although these can also be analyzed by the EMTP**