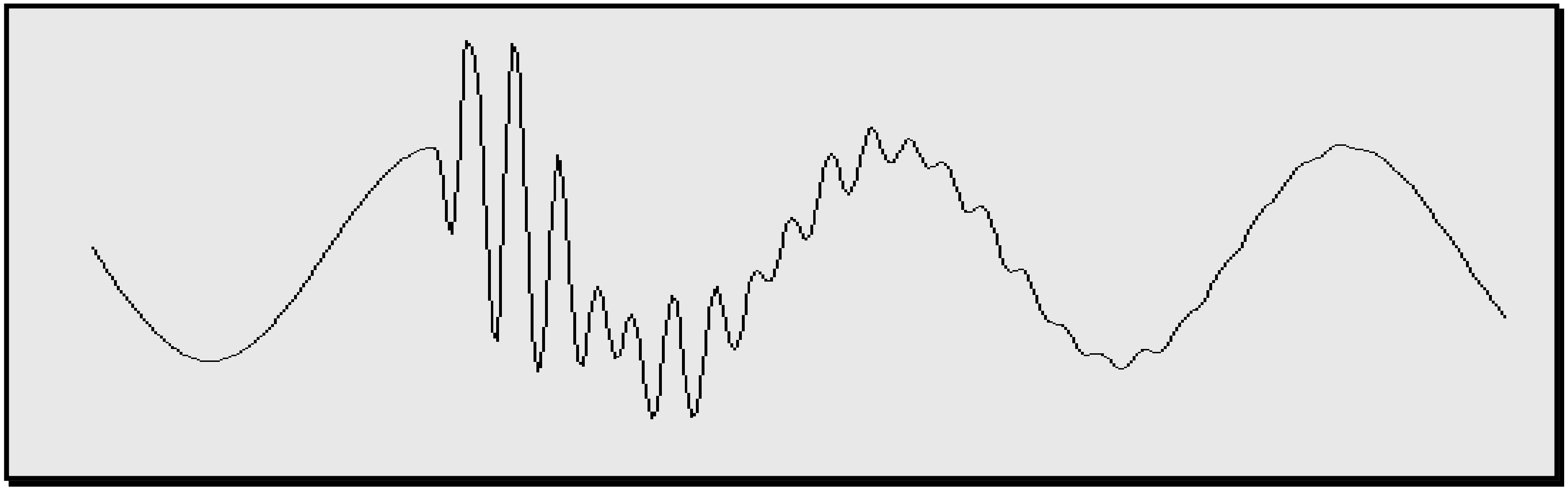
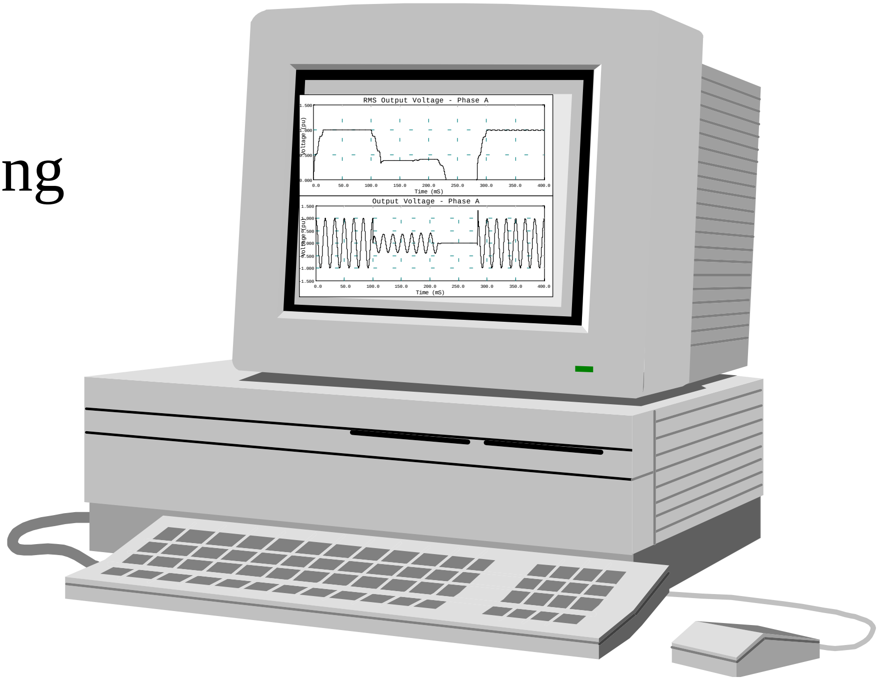
Power Systems Analysis Using the Electromagnetic Transients Program



EMTP Case Study Workbook
Custom Power Workshop
October, 1996

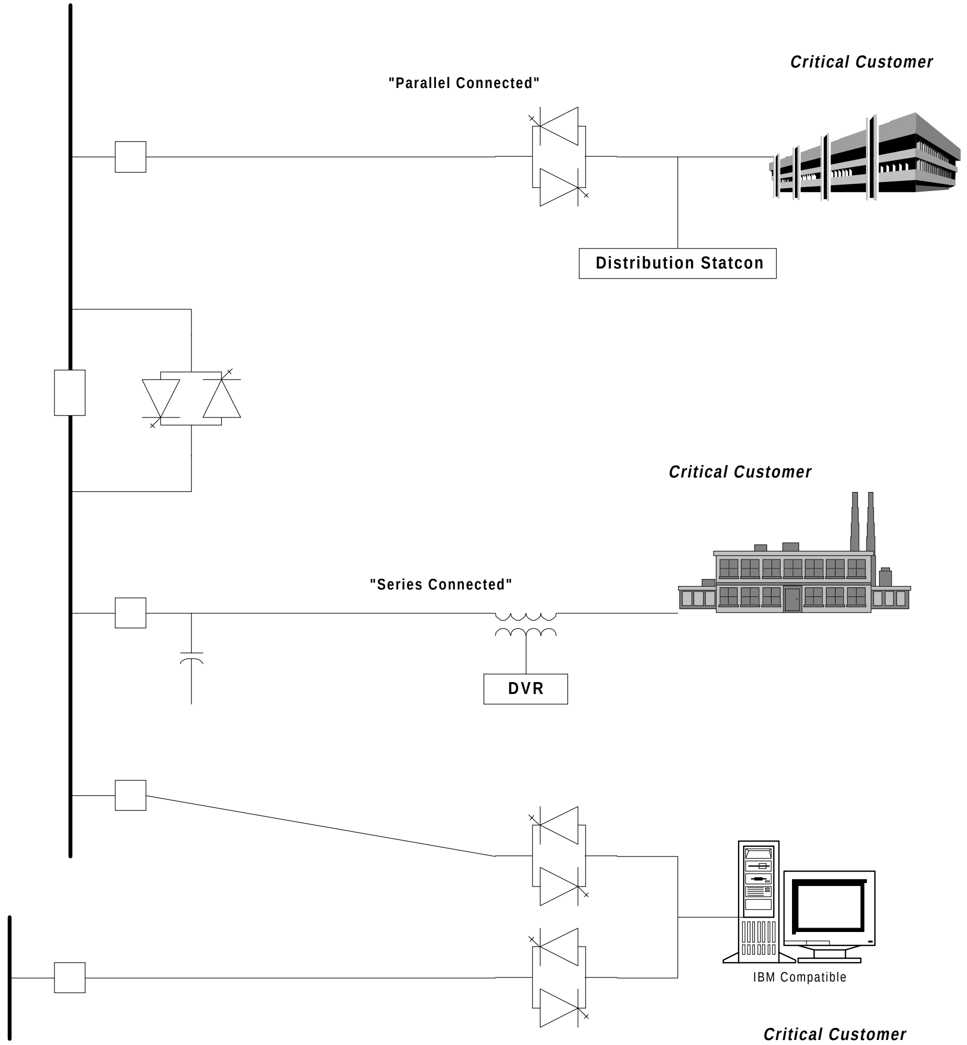
Introduction - Custom Power Workshop

- Introduction / Custom Power Applications / Devices
- Modeling Requirements and Guidelines
  - TACS
  - TACS Examples
- System Considerations
- Device / Component Modeling
  - Active Filter, Static Load Transfer Switch, DVR, STATCON
- Using Results in Other Simulations
- Case Studies



Custom Power Applications & Devices

- ❑ Silicon Load Transfer Switch (STS)
- ❑ Dynamic Voltage Regulator (DVR)
- ❑ Static Condensor (STATCON)
- ❑ Shunt Active Filter



Modeling Requirement & Guidelines

- ❑ Refresher - *Modeling Guidelines*
  - Suggested Study Procedure
  - Modeling Accuracy
  - System Simplification, Model Verification
  - EMTP Workstation Structure
  - Structure of an EMTP Datafile
- ❑ Refresher - *TACS - Transient Analysis of Control Systems*
- ❑ Refresher - *Power Electronic Modeling Using EMTP*
- ❑ **Control System Modeling using TACS**
  - Simple Examples - RMS Meter / Analog & Digital Filters
  - PWM Control (ASD Case Study)
- ❑ **TACS Lab Exercises**

Suggested Study Procedure

- ☑ Define Study Objectives
- ☑ Determine Outputs Required
- ☑ Determine Frequency Range of Phenomena to be Studied
- ☑ Determine Extent of System to be Modeled
- ☑ Draw Connection Diagram and Label Buses
- ☑ Collect Input Data for Component Models
- ☑ Run Steady-State Solution and Complete Verification
- ☑ Estimate Expected Simulation Results (Hand-Calcs)
- ☑ Run Cases Required to Complete Study

Modeling Accuracy

- High accuracy is required for:
  - Comparison with measured quantity
  - Failure analysis

- Conservative approach (reasonable results) is acceptable for:
  - Insulation coordination
  - Device duty evaluation
  - Parametric study for a general trend

- Accuracy is less important for:
  - Typical waveform generation
  - Phenomena illustration

System Simplification

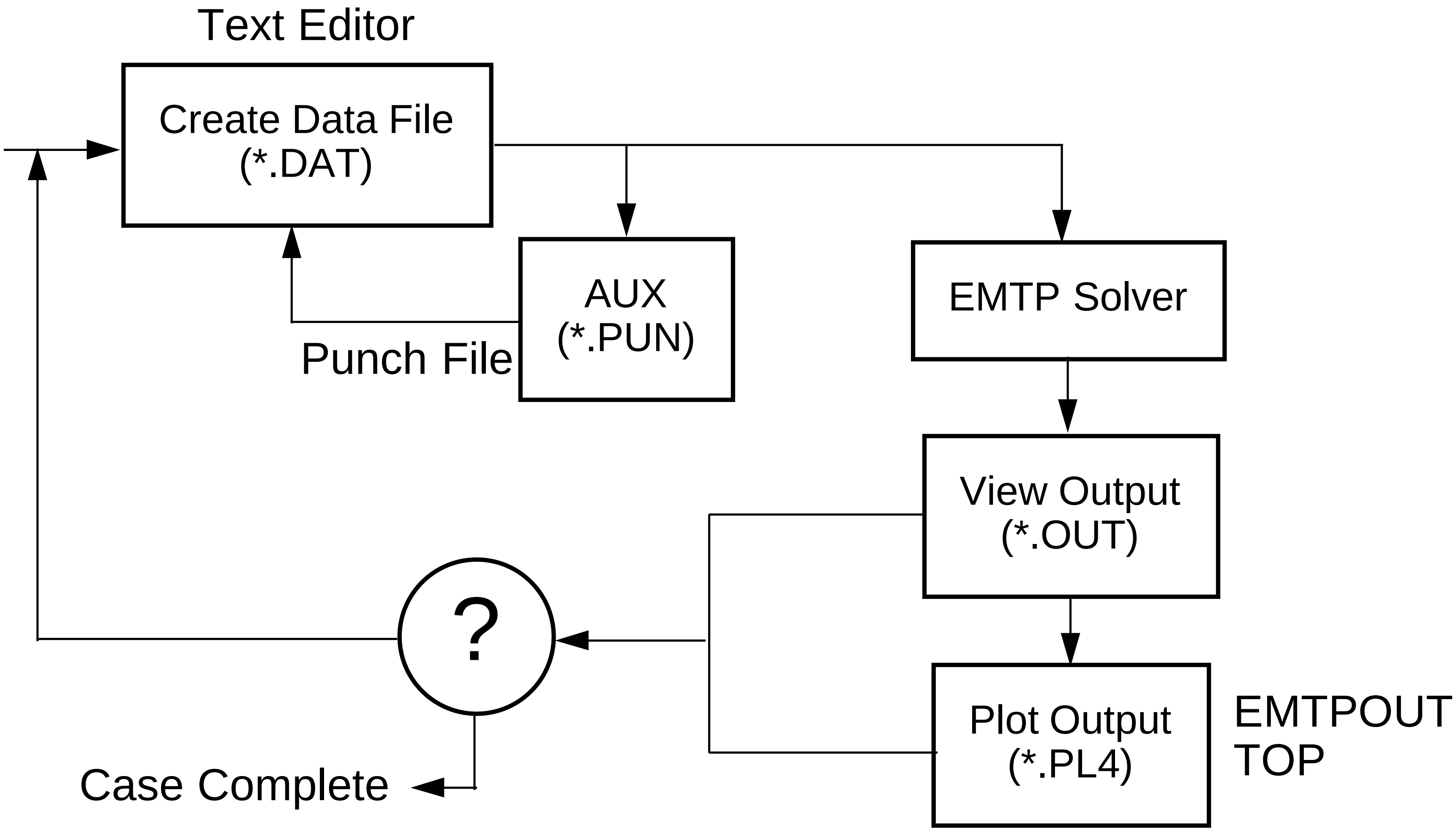
- Simplification is always required:
  - Model development and simulation time
  - Requirement of simulation program (i.e. # buses, etc.)

- Simplification without loss of accuracy:
  - Define the problem well
  - Start with a simple model
  - Use equivalents to represent less important portions of the system
  - Verify model after each step and increase size only when necessary

Model Verification

- The single most important tool that the user has for verifying the EMTP case results is a basic knowledge of power system transients. Field test results, technical papers, basic textbooks, and more experienced engineers can all help. Learning by doing can be very frustrating and applying the simulation results can be risky, when the user does not feel comfortable with the results of the study.
- When verifying the results of an EMTP case, the user should always check the input parameter interpretation and network connectivity table. The steady-state solution should be checked to verify known quantities, such as bus voltage, branch currents, etc.
- Pre-switching steady-state waveforms should be examined for characteristic harmonic content and the waveform should be allowed to reach a stable condition before any switching is done.

EMTP Workstation Structure



Structure of EMTP Input Data

- BEGIN NEW DATA CASE
  - Miscellaneous Data Cards
  - TACS (BLANK)
  - Linear / Nonlinear Branches (BLANK)
  - Switches (BLANK)
  - Sources (BLANK)
  - Initial Conditions
  - Node Voltage Output Requests (BLANK)
- BLANK END OF DATA CASE

- TACS / EMTP Options:
  - Network only (TACS not included)
  - TACS alone (“TACS STAND ALONE”)
  - TACS used in conjunction with network (“TACS HYBRID”)

Introduction to TACS

- ❑ Transient Analysis of Control System (TACS) was developed by L. Dube during 1976-1977. During 1983 and 1984, Ma Ren-ming made very extensive improvements to TACS modeling.

- ❑ TACS was originally designed to simulate HVDC converter operation. However, after TACS was developed, it has been used to simulate all types of dynamic systems.

- ❑ TACS consists mainly of:
  - Transfer function blocks
  - Signal sources
  - Special devices

Solution Methods for Network

- At each time step, the network configuration is examined by checking the switch table. According to the actual network connection, the Y matrix is updated and network nodal equations are formulated as

  [Y][V]=[I],

  where,

  [Y] is a symmetric nodal conductance matrix,

  [V] is vector of node voltages, and

  [I] is a dependent current vector known from a previous time step.

- The system of linear equations are solved for the nodal voltages.
- A dependent current vector is assembled for use of next time step.

Solution Methods for TACS

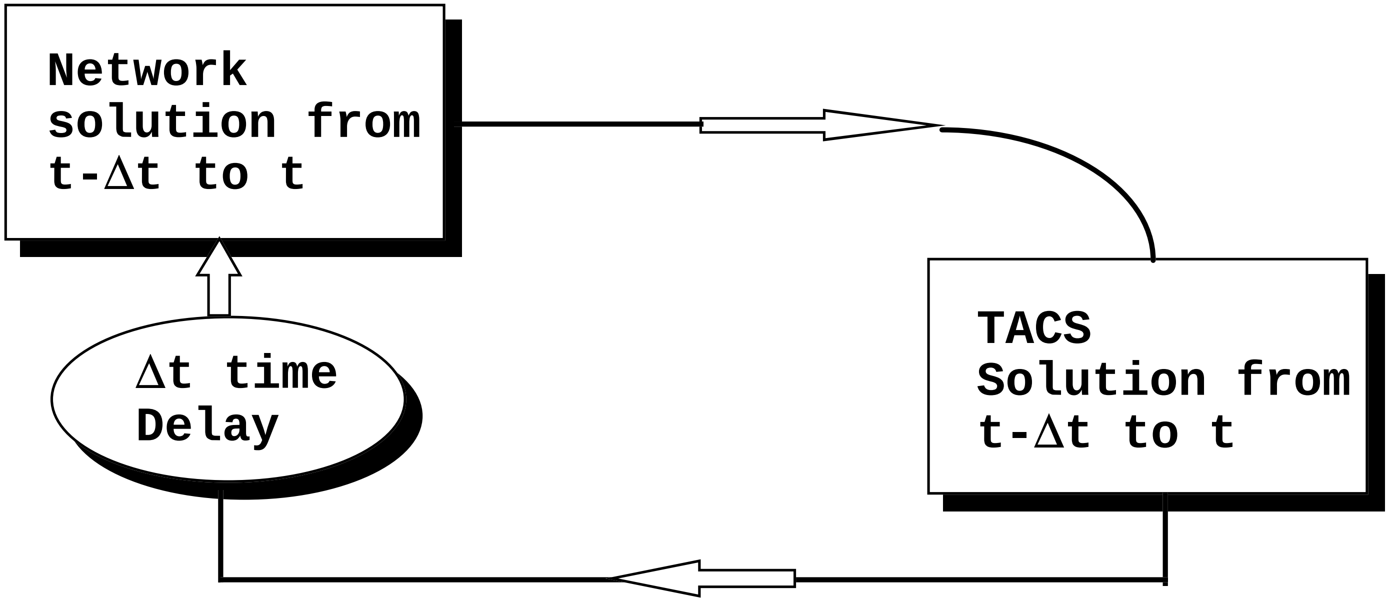
❑ Why is TACS System Solved Separately from Network ?

- To solve TACS equations simultaneously with the electric network is difficult.
- Equations for a control system are quite different from those for an electric network.
- Control model matrices are usually unsymmetric and cannot be represented as equivalent resistive networks.
- TACS models are solved separately and interface with the network solution at each time step.

Interface between TACS & Network

One Time Step Delay

- ☐ Network output can be used as TACS input over the same time step, however,
- ☐ TACS output can become network input only over the next time step.



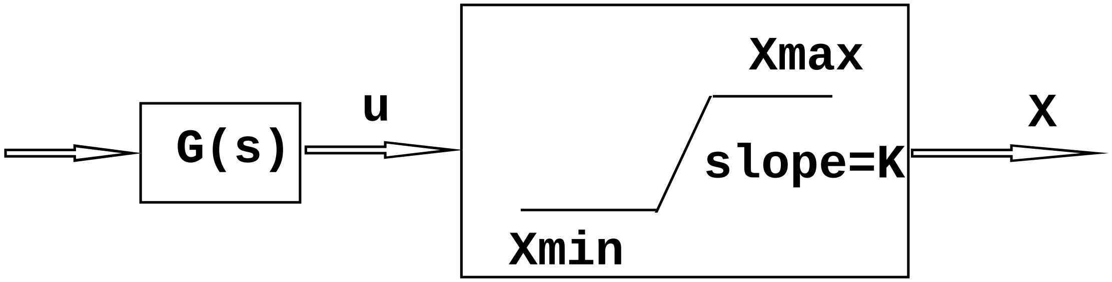
TACS Capability and Application Areas

- HVDC converter controls
- Excitation and voltage regulation control
- Arcing characteristics
- Circuit breaker restriking
- Current limiting gaps in surge arresters
- Variable load
- SVC, TCR
- Wind turbine dynamics
- Solid state switching, STATCON, FACTS & **Custom Power**
- SMES simulation
- PWM drive and motor controls

TACS Models: Limiters

Windup Limiter(Static Limiter):

The output of a transfer function block is just clipped, without affecting the dynamic behavior of the transfer function block on the input side itself.



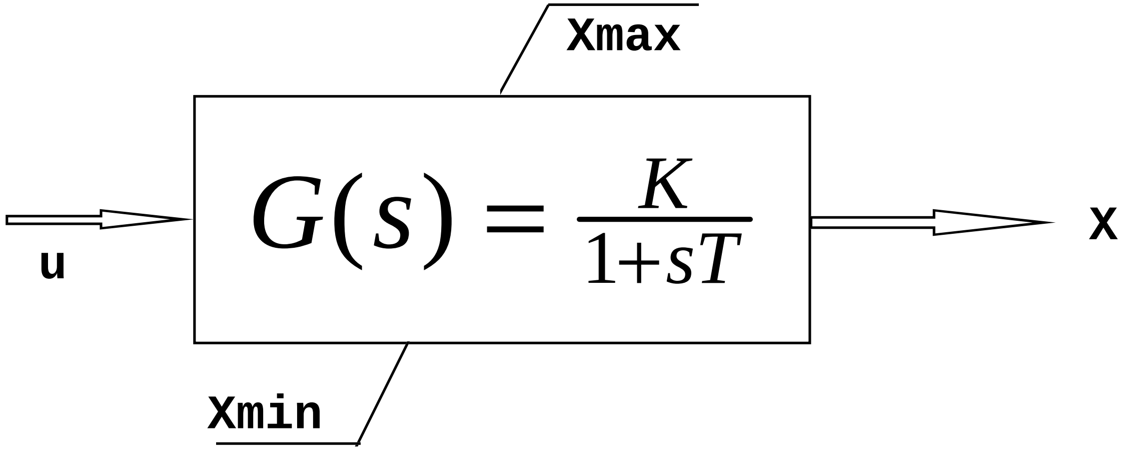
```
X=Ku,   if Xmin < Ku < Xmax,
X=Xmin, if Ku <Xmin,
X=Xmax, if Ku >Xmax.
```

These three equations are special case of Eq.6, with c=d=1, hist=0 inside the limits, and c=1, d=0, hist=(Xmax or Xmin) at the limit.

TACS Models: Limiters - cont

Non-windup Limiter(Dynamic Limiter):

The dynamic behavior of the transfer function block is changed by the limiting action. This type of limiter is allowed on first-order transfer functions with no zeros.



$$G(s) = \frac{K}{1+sT}$$

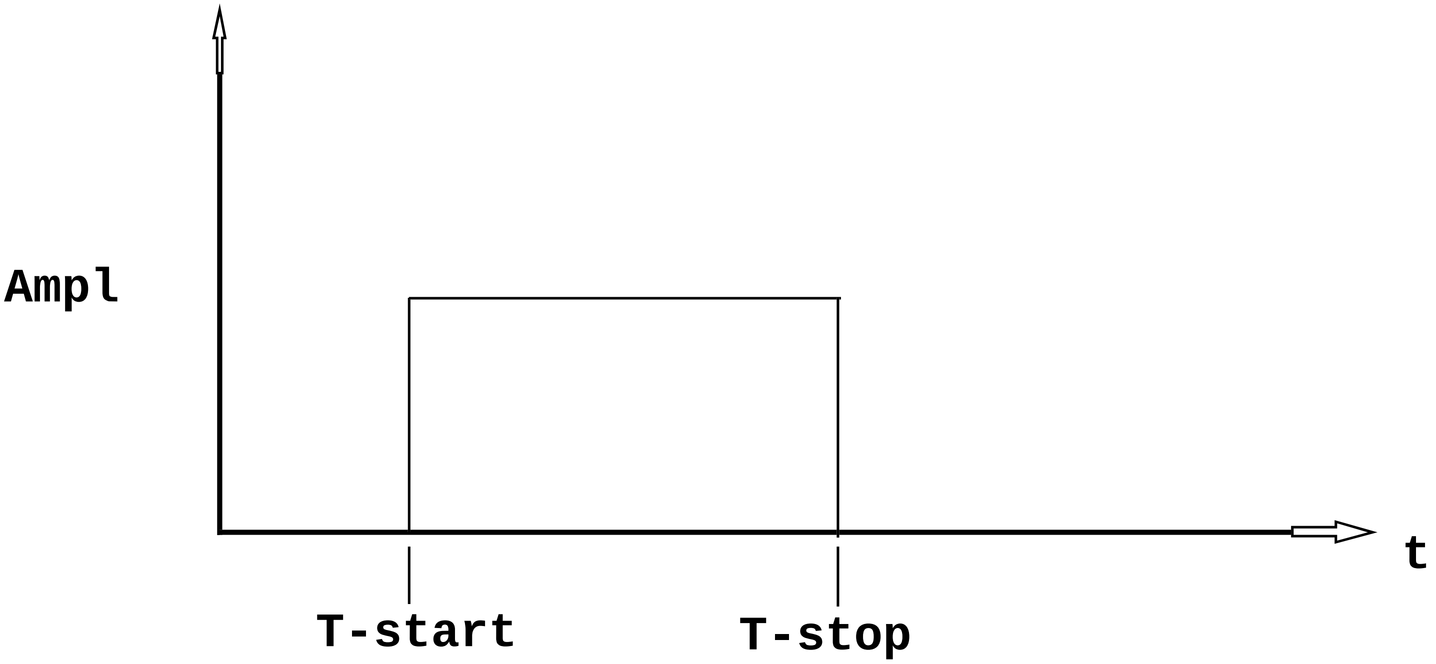
```
X+TdX/dt=Ku,   if Xmin < X < Xmax,
       X=Xmin, if X .LE. Xmin and (Ku-X) < 0,
       X=Xmax, if X .GE. Xmax and (Ku-X) > 0.
```

These equations are special cases of Eq.6, with d=K, c=1+2T/Δt, hist=Ku(t-Δt)-(1-2T/Δt)X(t-Δt).

TACS Models: Signal Sources

- ❑ Built-in Signal Sources: User needs to provide data specification for these signal sources.

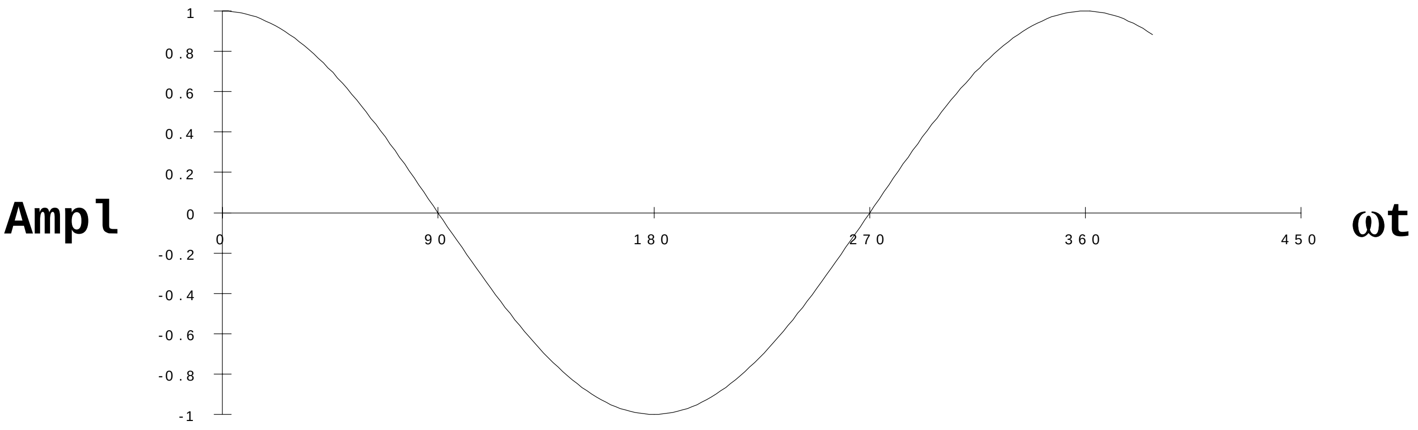
Single rectangular pulse (Level Signal): Type-11



TACS Models: Signal Sources - cont

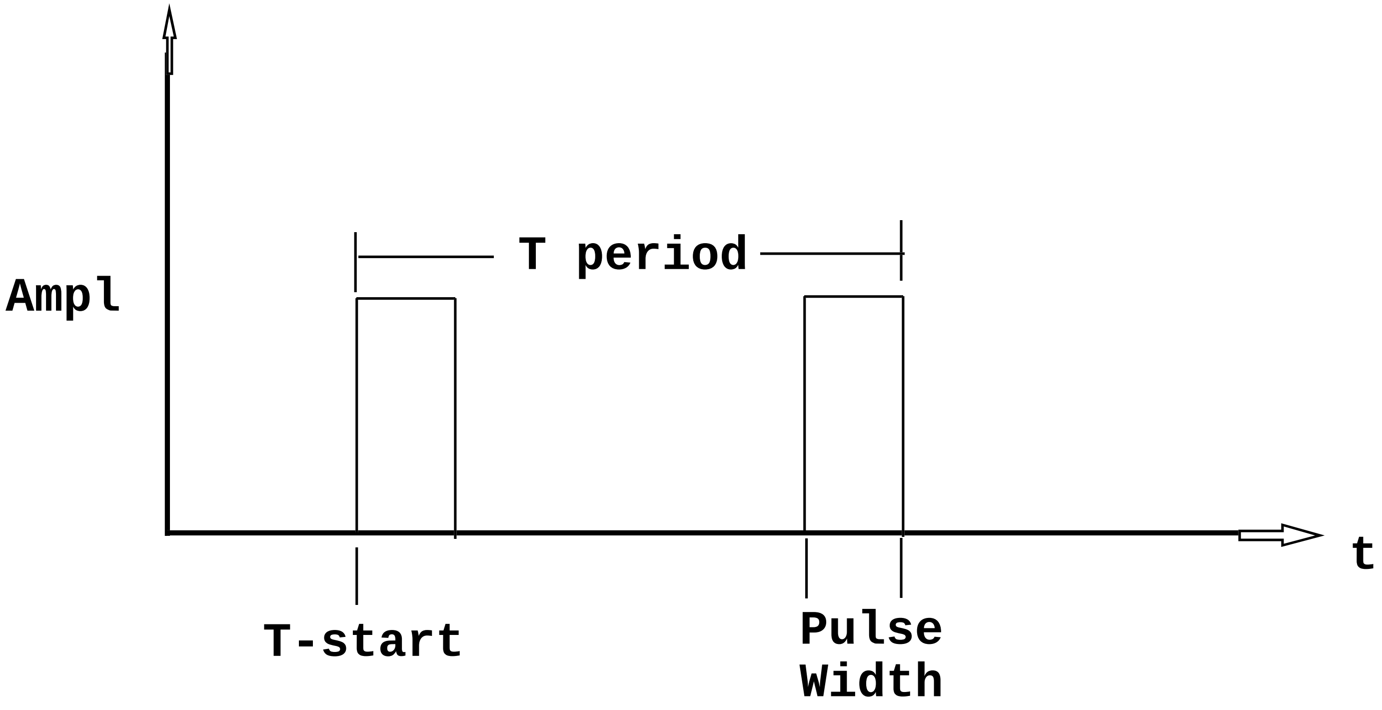
Sinusoidal function: Type-14

Output = Ampl*Cos(ωt + ϕ)



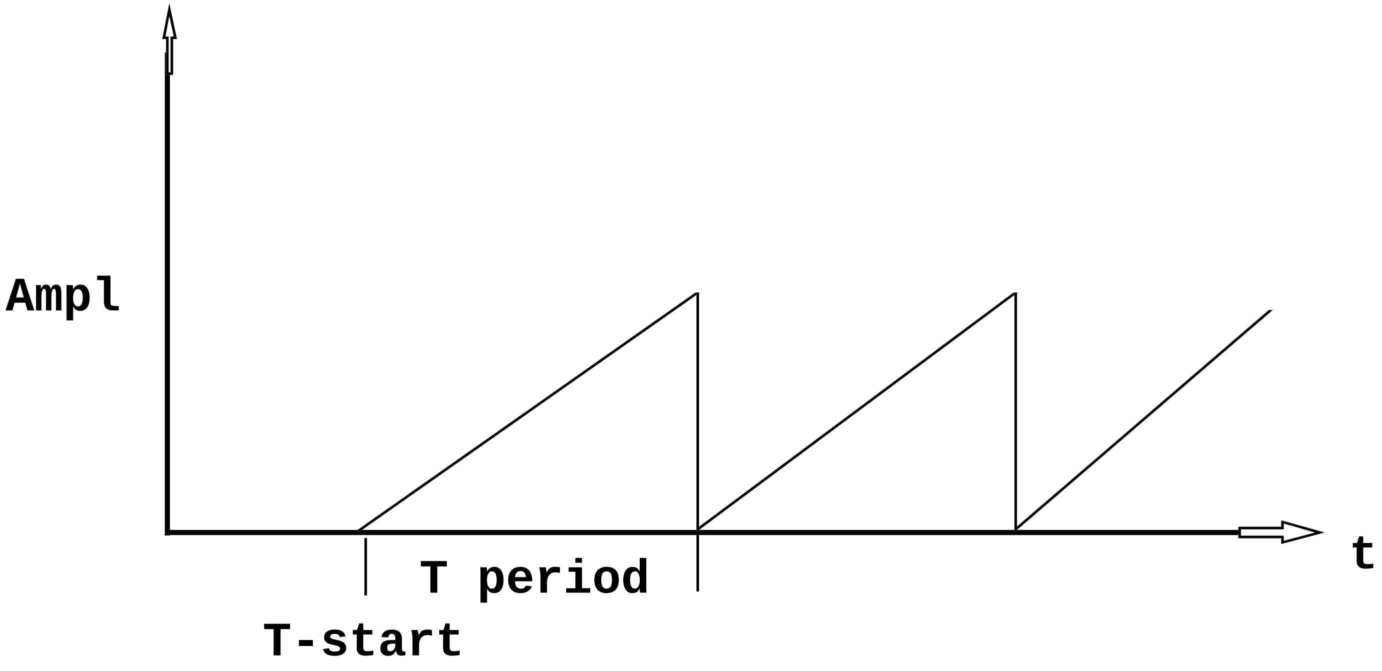
TACS Models: Signal Sources - cont

Repetitive Pulse: Type-23



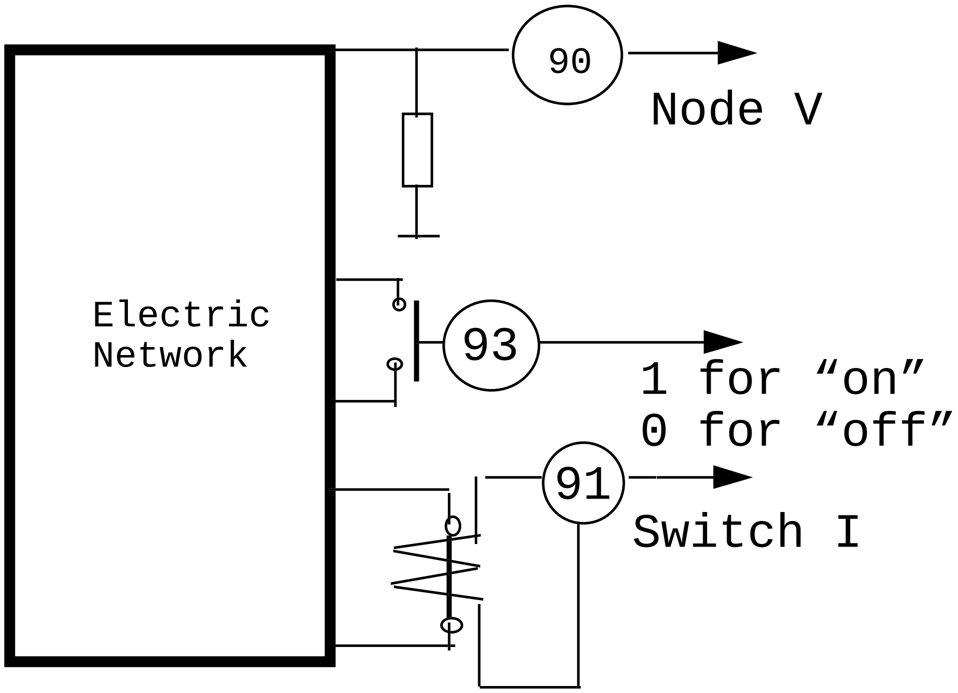
TACS Models: Signal Sources - cont

Repetitive Ramp: Type-24



TACS Models: Signal Sources - cont

Node Voltage Coupling: Type-90
Switch Current Coupling: Type-91
Special Network Variable : Type-92 (e.g., rotor q coupling)
Switch Status Monitor: Type-93



Any node voltage or switch current of the electric network can be coupled through type-90 and type-91 sources into the TACS models. These sources are often used to sample the network quantities for deriving adequate system control signals.

TACS Models: Special Devices

- ❑ FORTRAN-Defined (Rule-book, pg 14-20)
  - Operators:

Algebraic Operators:

+, -, *, /, **

Relation Operators:

.EQ. , .NE. , .LT. , .LE. , .GE. , GT.

Logical Operators:

.OR. , .AND. , .NOT.

TACS Models: Special Devices - cont

FORTRAN Functions:

SIN, COS, TAN, COTAN, SINH, COSH, TANH, (in rad)
ASIN, ACOS, ATAN, (in rad)
EXP, LOG, LOG10, SQRT, ABS

Special Functions:

RAD, DEG, SIGN, RAN, ...

Note: A FORTRAN assignment statement of the form

BUSVLT=BUSVLT + {Arithmetic Expression)

is not allowed.

No FORTRAN if statement in the current version.

TACS Models: Special Devices - cont

- Built-in Special Devices (Rule-book, pg 14-22)

  Seventeen built-in special devices are available. For the motor-drive simulation, the following devices are especially useful.

Frequency-sensor:	Code # 50,
Transport delay:	Code # 53,
Controlled integrator:	Code # 58,
Sample and track:	Code # 62,
Accumulator and counter:	Code # 65,
RMS value:	Code # 66.

TACS Template #1

```
C TRANSFER FUNCTION
C
C <- the order of the highest power of "s" is place in the first two columns
C    if greater than 0  two more lines follow for numerator and denominator
C
C  TRANSFER FUNCTION                                             LIMITS
C                                                            fixed     NAMED
C OUTPUT  +IN1--> +IN2--> +IN3--> +IN4--> +IN5--> <-gain<--low<-highLOW-->HIGH->

C .....^  ^.....^ ^.....^ ^.....^ ^.....^ ^.....^ ^.....^.....^.........^.....^
C
C<-N/D-0--<-N/D-1---<--N/D-2--<--N/D-3--<--N/D-4--<--N/D-5--<--N/D-6--<--N/D-7--

C ........^.........^.........^.........^.........^.........^.........^.........

C ........^.........^.........^.........^.........^.........^.........^.........


C FORTRAN EXPRESSION
C
C OUTPUT  = free-format Fortran expression.................................


88.....^  =
```

TACS Template #2

```
C TACS SOURCES
C
C   TYPE       A        B          C
C   11        AMPL     -----     -----     DC source
C   14        AMPL     FREQ      PHASE     AC source
C   23        AMPL     T(sec)    WIDTH     pulse
C   24        AMPL     T(sec)    -----     ramp
C   90        1.0 dc   FQ ac     -----     EMTP VOLTAGE
C   91        1.0 dc   FQ ac     -----     EMTP CURRENT
C   92                                     Special
C   93                                     SW State
C
C <TYPE code in the first two columns
C  SOURCE
C
C OUTPUT  <-----A---<----B----<----C----                    <-T-START-<-T-STOP--


C .....^  ^.........^.........^.........                    ^.........^.........

C TACS INITIAL CONDITIONS
C OUTPUT  <---------

77......
```

TACS Template #3

```
C DEVICES
C
C  CODE                            CODE
C   50  frequency-sensor            58  integrator
C   51  relay switch                59  derivative
C   52  level switch                60  input IF
C   53  transport delay             61  signal selector
C   54  pulse delay                 62  sample and track
C   55  digitizer                   63  min/max function
C   56  point-by-point function     64  min/max tracking
C   57  time-sequenced switch       65  counter
C
C    use 88 in the first two columns
C       ||<CODE                                        see rule book
C DEVICE||
C       ||
C OUTPUTvv+IN1--> +IN2--> +IN3--> +IN4--> +IN5--> <--A--<--B--<--C--<--D--<--E--


88.....>^^+.....^ +.....^ +.....^                 ^.....^.....^.....^.....^.....

C TACS outputs to plot file
C ----->----->----->----->----->----->----->----->----->----->----->----->-----

33
```

Problems Associated with TACS

- ☐ One Step Time Delay Problem

  One step time delay does not cause problem in most studies where the involved frequency is relatively low and the phenomenon is non-repetitive in nature. Under such circumstance, the error introduced by one step time delay is usually negligible if the time step used in the simulation is selected small enough. When the phenomenon is high frequency and repetitive in nature, the error caused by one step time delay can be accumulated and cause numerical instability.

- ☐ TACS Initialization Problem

  The automatic initialization of TACS variables is complicated and not available in the current version because of difficulties introduced by a variety of TACS initial conditions. User must supply initial conditions in complicated cases and for most special devices. This, in many cases, becomes impractical.

Power Electronic Modeling using EMTP

- ❑ Available switching devices
  - Diode, SCR, GTO, IGBT, MCT

- ❑ Characteristics of PE device
  - Turn-on control, Turn-off control
  - Forward drop, On-status loss

- ❑ Fundamental Components of a PE System
  - Switching Devices and Application Topologies
  - Tracking and Sampling
  - Operation Control System
  - Firing Circuit

PE Applications

- ❑ Transmission Levels:
  - HVDC: ac/dc conversion
  - FACTS (SVC, STATCON, UPFC, SMES)

- ❑ Subtransmission and Distribution Levels
  - SVC, Static switching load transfer, DVR, etc.
  - Fault current limiting switching, Active filters

- ❑ Customer Levels:
  - ASDs
  - Power supplies
  - UPS, SSD

Simulation Goals & Methods

- ❑ What needs to be studied ?
  - – Performance Characteristics
    - – Harmonic generation, Dynamic response
    - – Transient response, System interaction
- ❑ Why simulate ?
  - – Complicated system, Non-linearity
  - – Existing problems, New devices and new applications
- ❑ Simulation technologies:
  - – TNA, Numerical, Hybrid
- ❑ Types of simulation:
  - – Frequency domain, Time domain, Real time

Simulation Tools & EMTP

- ❑ Common Tools for Numerical Simulation:
  - Saber
  - Spice
  - NETOMAC (Siemens)
  - EMTP/ATP/EMTPDC

- ❑ Why EMTP ?
  - Application oriented.
  - Suitable for doing steady-state, dynamic and transient studies.
  - Easy interface between PE system, utility or industrial circuit and related mechanical system. (TACS features).
  - **Not** for detailed device or PE system level study.

TACS for Power Electronics

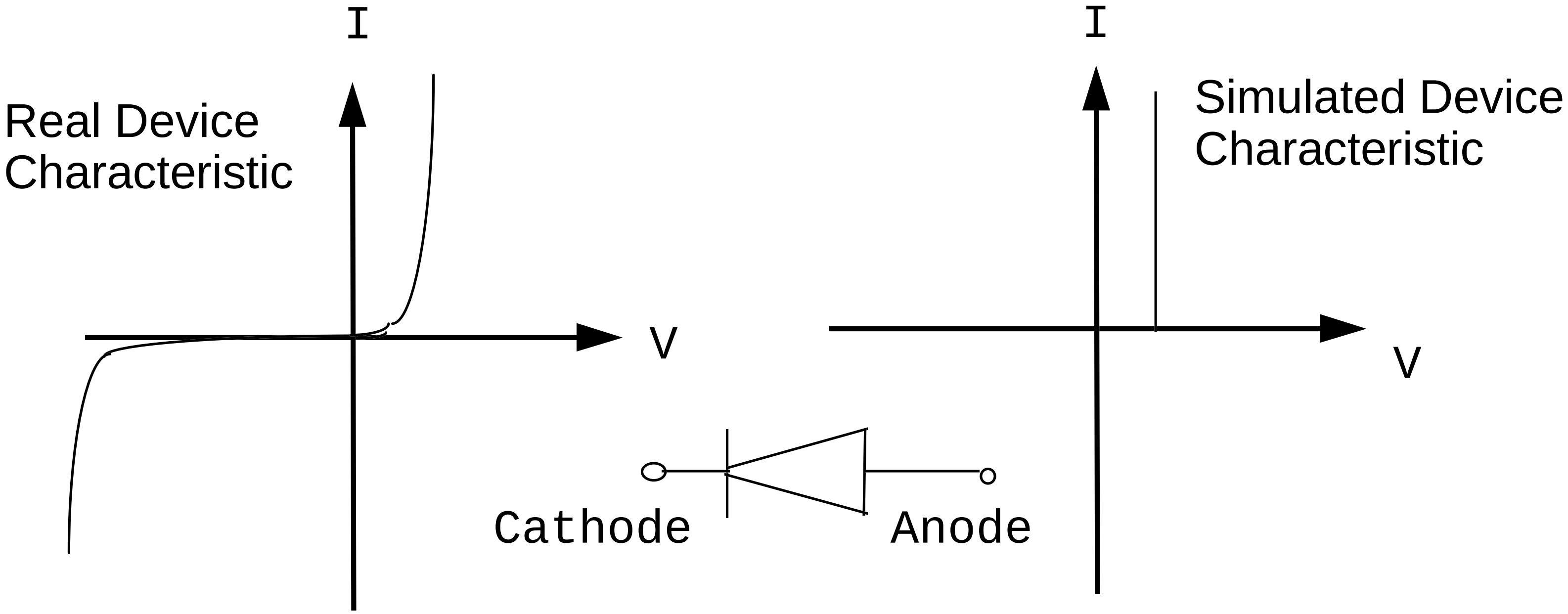
- ❑ Power Electronics Switching Devices and Snubber Requirement
  - Diode
  - Thyristor (SCR)
  - GTO (Gate-turn-off thyristor)

- ❑ Switching Device Firing Signal Generation
  - Square pulse
  - PWM scheme

- ❑ System Interface
  - Control logical
  - Synchronization

Power Electronic Switching Devices

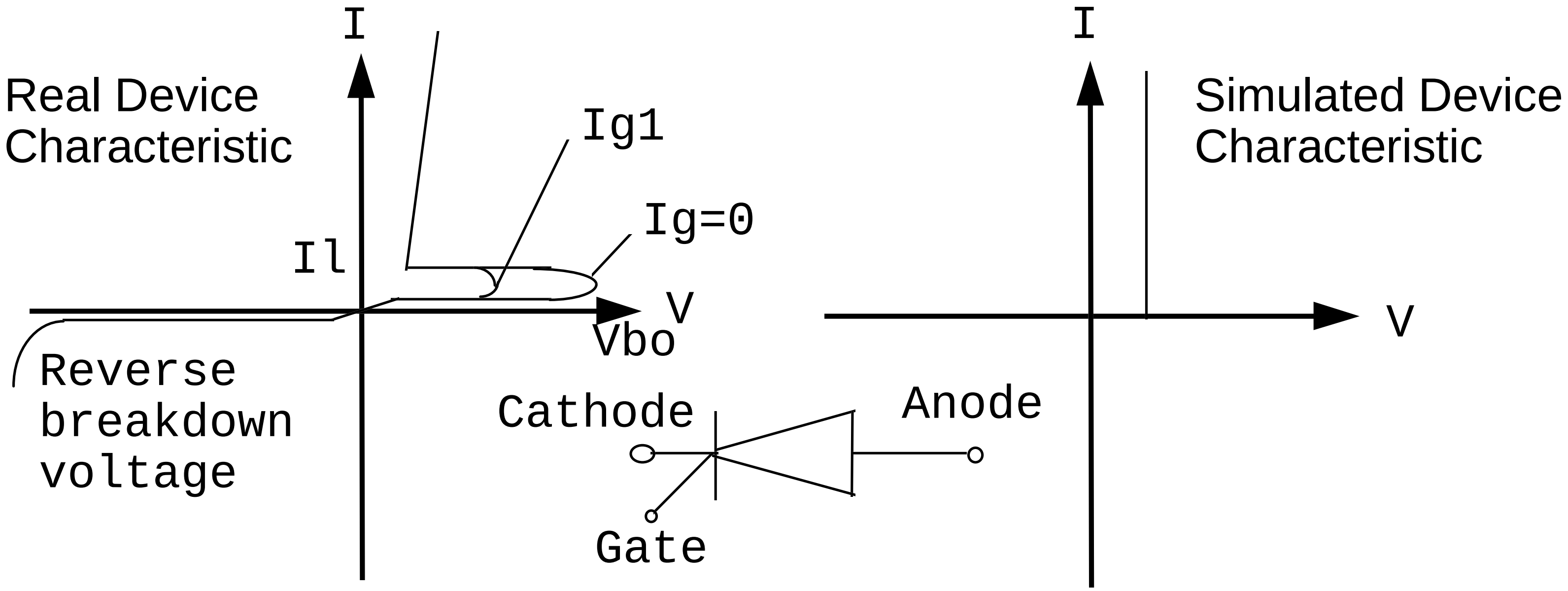
- Diode: type-11 switch without any control



The diode starts conducting when the forward voltage becomes greater than the minimum ignition voltage and ceases conducting when the forward current becomes smaller than the minimum holding current.

Power Electronic Switching Devices - cont

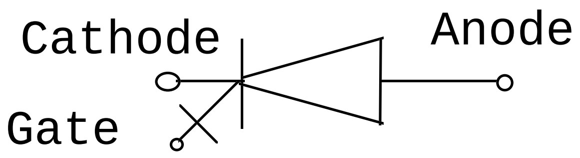
- Thyristor(SCR): type-11 switch with the grid control

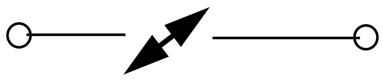


Working with rules of diode except that the conducting will not take place until the grid signal becomes greater than zero.

Power Electronic Switching Devices - cont

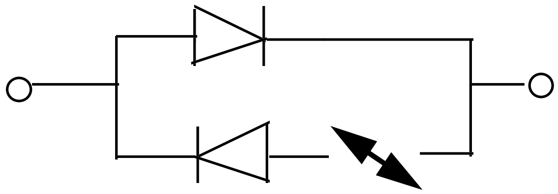
- GTO: Device is idealized without implementation of detailed turn-on/turn of characteristics. Different modeling representation can be used





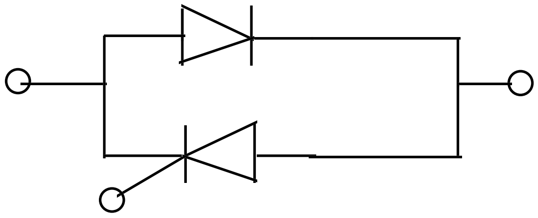
(1)

Type-13 TACS controlled switch only



(2)

Type-13 Combined with uncontrolled type-11 switches



(3)

Controlled Type-11 combined with uncontrolled Type-11

Power Electronic Switching Devices - cont

- GTO Model (1):
- Use type-13, TACS controlled switch with open/close control,
  - Bi-directional current flows are allowed,
  - Allow to stay on for entire period,
  - No need for added diode,
  - Use least number of switch component, and
  - With dual sources, the dc link initial condition is incorrect.

Power Electronic Switching Devices - cont

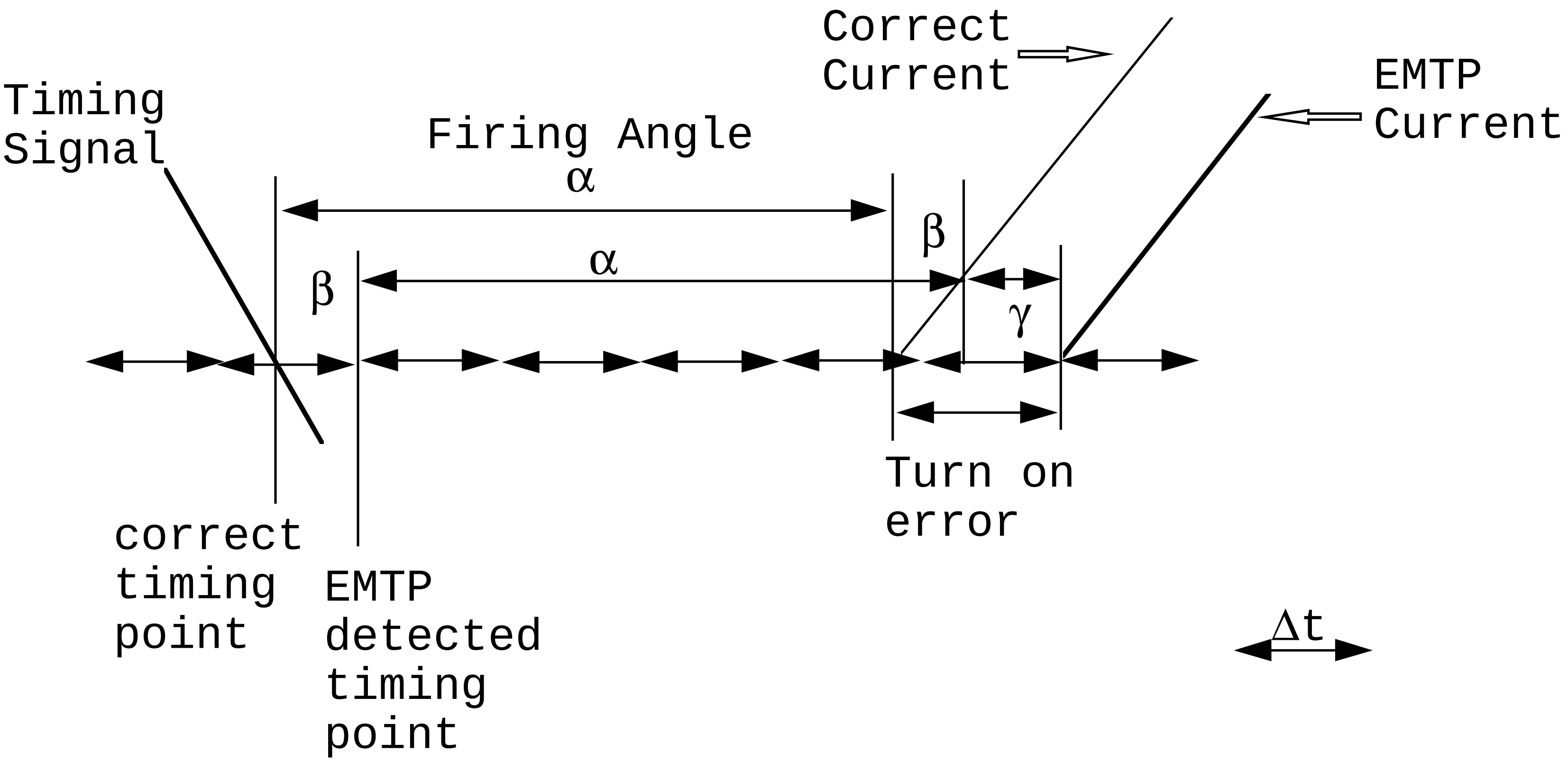
- GTO Model (2):
- Use type-13, TACS controlled switch with open/close control,
  - Series diode connection prevents bi-direction current flowing,
  - Must have anti-parallel diodes to form an inductive current loop,
  - Requires turn-off snubbers for diode,
  - Use most switching elements, and
  - No initial condition problem.

Power Electronic Switching Devices - cont

- ❑ GTO Model (3):
- ❑ Use type-11, TACS controlled switch with open/close control,
  - Short grid signal to turn on,
  - Open/close set to 0 while switch on ,
  - Open/close set to negative to turn off GTO at end of cycle,
  - Must add anti-parallel diodes for inductive current loop,
  - Requires turn-off snubbers for diode,
  - No initial condition problem.

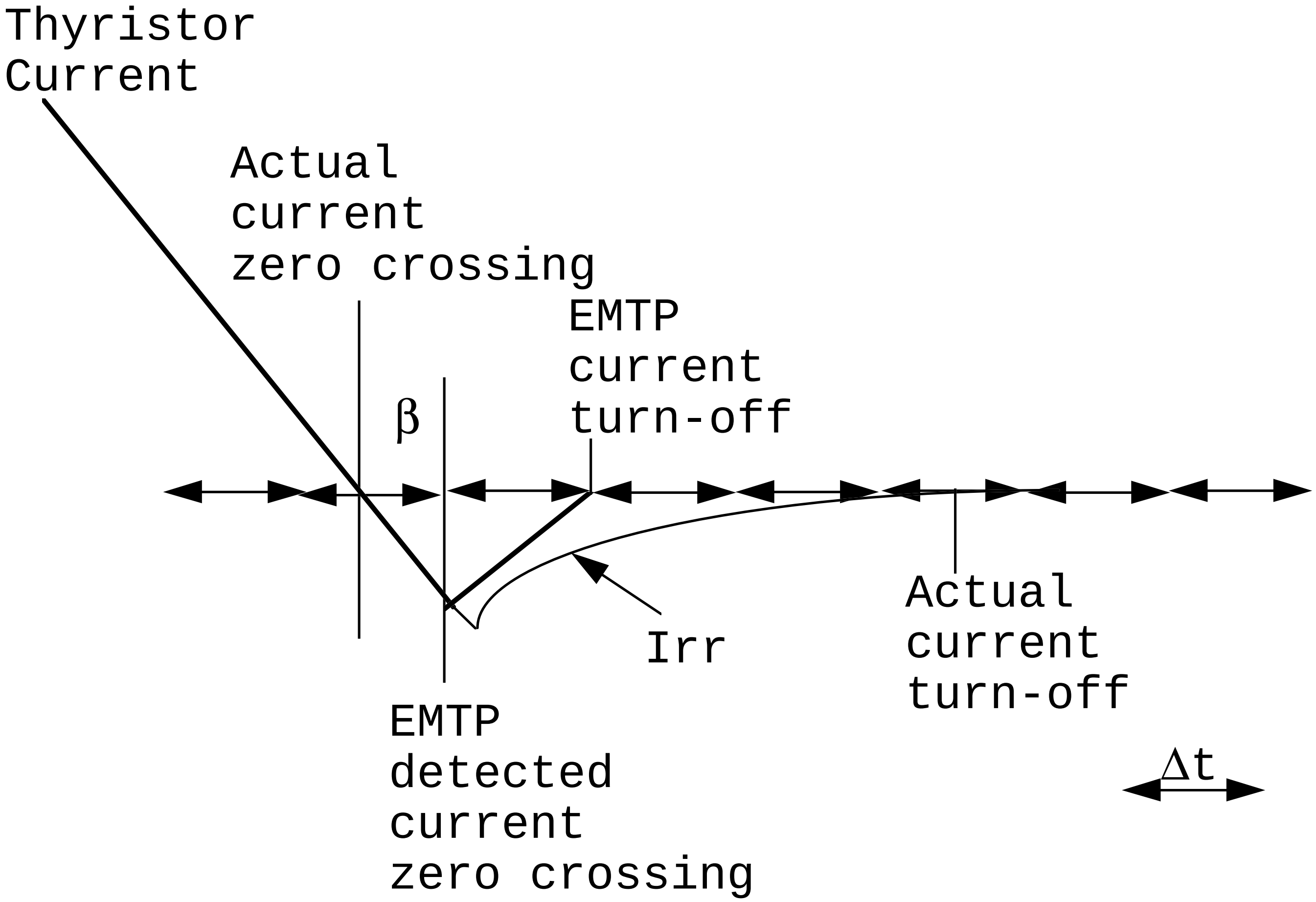
Switching Errors Due to Time Step Size

- ❑ Turn on errors: SCR turn-on errors can introduce fake harmonics, but do not cause numerical problems.



Switching Errors Due to Time Step Size

- EMTP turn-off error.

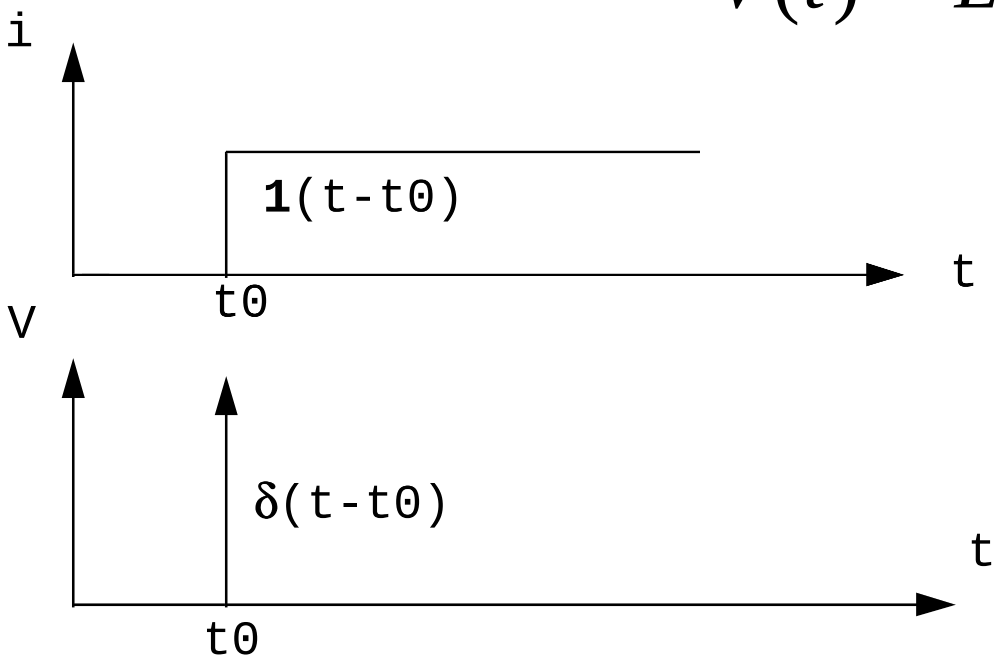


Numerical Oscillations

- The turn-off error can cause a numerical oscillation problem when a high di/dt inductance current is switched.

`Theoretically,`

$$V(t) = L\frac{di}{dt}$$



```
A step current
change at the t0.
```

```
A delta function
at the t0, and
zero elsewhere.
```

Numerical Oscillations - cont

In EMTP:

$$V(t) = -V(t-\Delta t) + \frac{2L}{\Delta t} i(t) - \frac{2L}{\Delta t} i(t-\Delta t)$$

If i(t-Δt)=0, i(t)=1.0, assuming V(t-Δt)=0, then, at time=t:

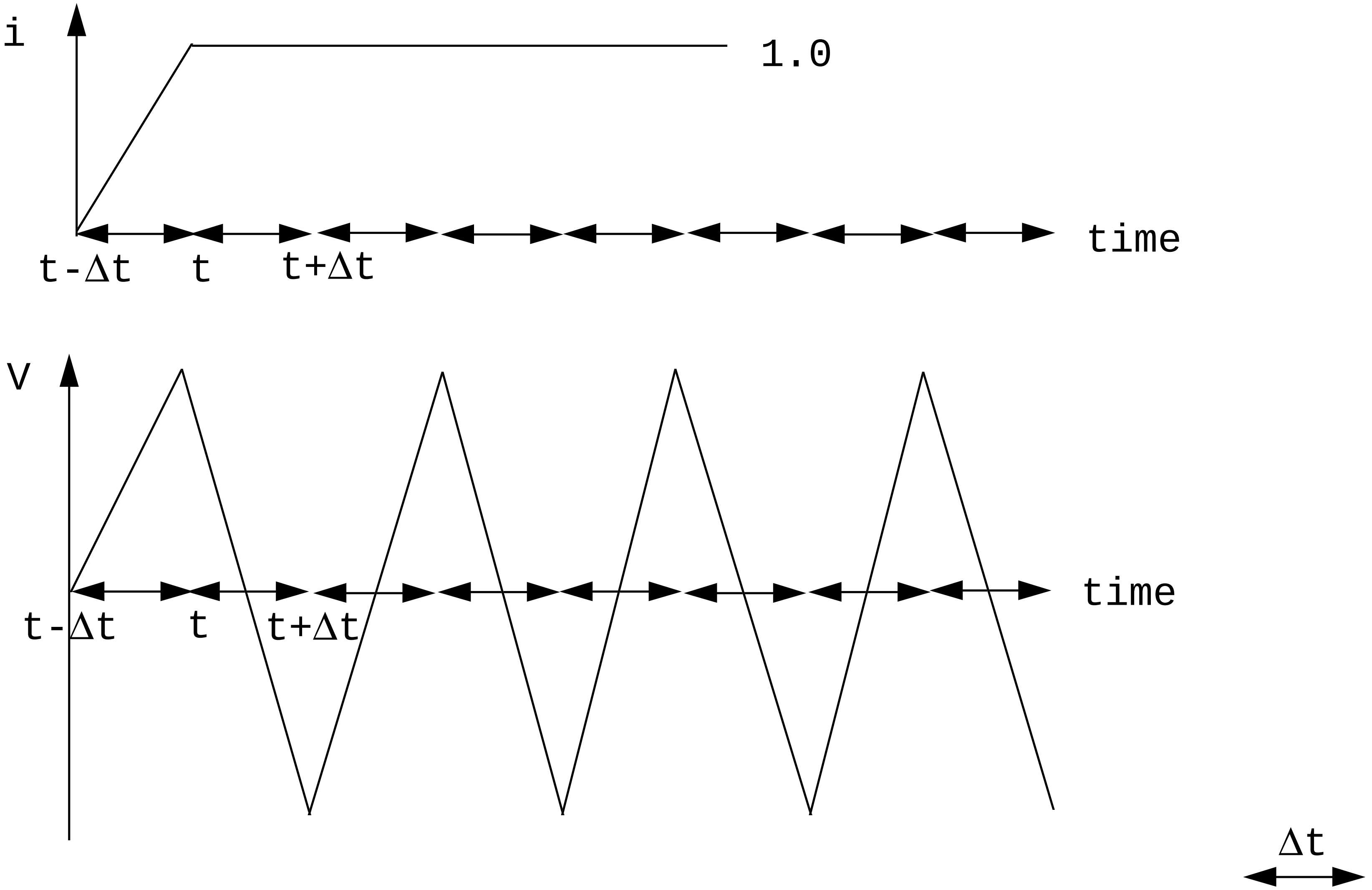
$$V(t) = \frac{2L}{\Delta t} \quad ,$$

At time=t+Δt,

$$V(t+\Delta t) = -V(t) + \frac{2L}{\Delta t} i(t+\Delta t) - \frac{2L}{\Delta t} i(t)$$

$$= -V(t)$$

Numerical Oscillations - cont



Numerical Oscillations - cont

- For slow changing current, the problem will not occur.

`If the current takes two Dt to reach the peak, then,`

$$V(t) = -V(t-\Delta t) + \frac{2L}{\Delta t} i(t) - \frac{2L}{\Delta t} i(t-\Delta t)$$

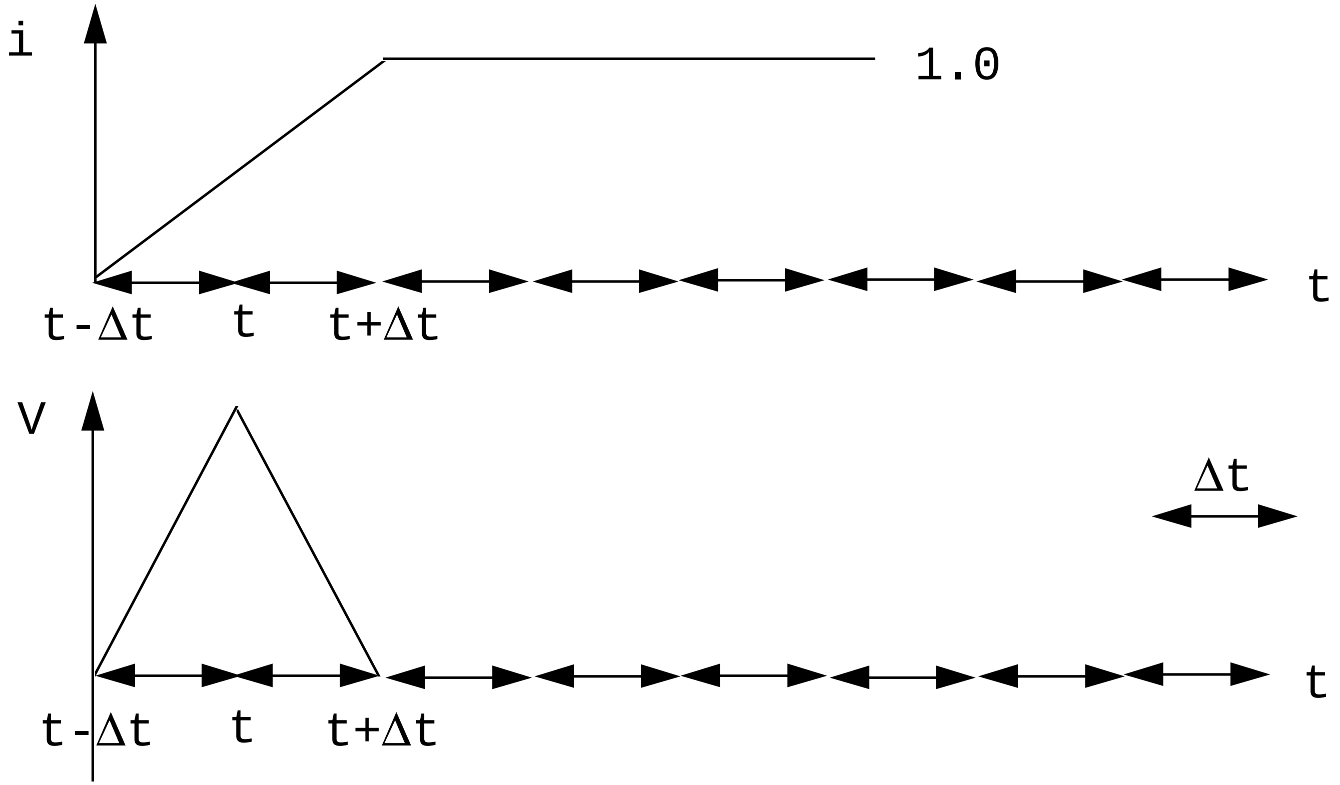
$$= \frac{2L}{\Delta t} \times \frac{1}{2} = \frac{L}{\Delta t} \ ,$$

`At time=t+Δt,`

$$V(t+\Delta t) = -V(t) + \frac{2L}{\Delta t} i(t+\Delta t) - \frac{2L}{\Delta t} i(t)$$

$$= -V(t) + \frac{2L}{\Delta t} \times 1 - \frac{2L}{\Delta t} \times \frac{1}{2} = 0$$

Numerical Oscillations - cont

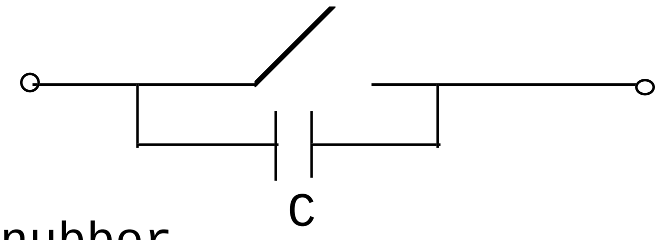


Snubber Requirement

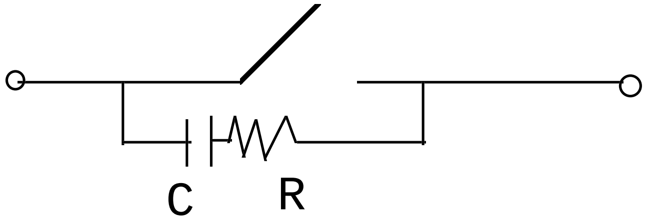
- Practical power electronic circuits need the turn-off snubbers to protect the device from high high dv/dt because of Irr.
- EMTP simulated power electronic circuits need the turn-off snubbers to prevent the numerical isolation problems even though Irr is not actually characterized in the device model.
- Snubber parameters designed for pratical P.E. applications may or may not work for EMTP simulation
- In the EMTP study, the artificial snubbers should be carefully selected so the errors introduced by the snubbers are controlled to an acceptable level.

Solutions to Numerical Oscillations

1. Include a stray capacitor between the switch contacts.

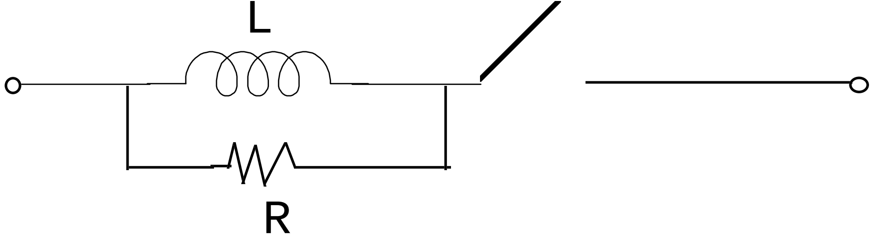


2. Using a snubber



The minimum RC time constant should be greater than $3\Delta T$

3. Using a damping resistor across the switched inductor



$R=L/(\beta\Delta t)$

$\beta=0.15$ - 0.3 is recommended for P.E. applications

TACS Modeling

- A Quick Introduction - RMS Meter
  - Definition of RMS:

$$V_{RMS} = \sqrt{\frac{1}{T}\int_0^T i^2 dt}$$

  - Common 60Hz RMS Shortcut:

$$V_{RMS} \frac{V_{Max}}{\sqrt{2}}$$

  - EMTP RMS Computation Options:
    - TACS RMS meter (Device 66)
    - Apply analog or digital filter
    - Use external program (EMTPOUT, TOP, MatLab, etc.)

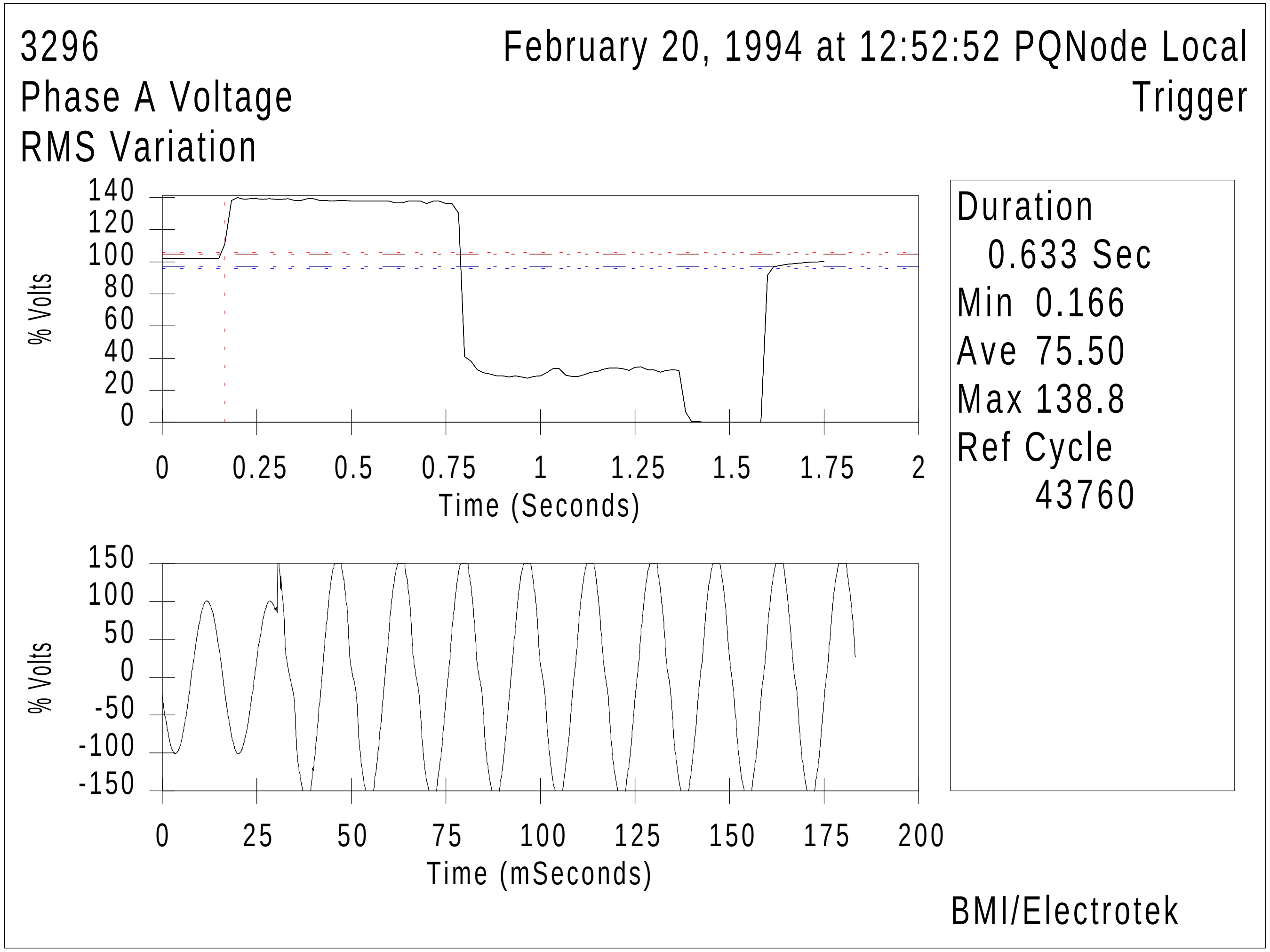
RMS Meter Using “Built-in” Device

```
TACS HYBRID
C
/TACS
C
90XFMRHA                  60.0
90XFMRHB                  60.0
90XFMRHC                  60.0
C .....^XX.........^.........^.........^XXXXXXXXXXXXXXXXXXXX.........^.........^
C
88 VARMS66+XFMRHA                                    60.0
88 VBRMS66+XFMRHB                                    60.0
88 VCRMS66+XFMRHC                                    60.0
C .....^.^^.....^X^......^X......^X^.....^X^.....^X.....^.....^.....^.....^.....^
C
C <-Bus1<-Bus2<-Bus3
33 VARMS VBRMS VCRMS
C .....^.....^.....^
C
/SWITCH
C <-------- Fault Switch
C
C BUS-->BUS--><---TCLOSE<----TOPEN<-------IE<----FLASH<--REQUEST<-----TARGET<--O
  XFMRHA  FLTA  99.99E-3 233.33E-3                                             1
  XFMRHB  FLTB 166.66E-3 233.33E-3                                             1
C XFMRHC  FLTC  99.99E-3 166.67E-3                                             1
C .....^.....^.........^.........^.........^.........^.........^...........^...^
```

Node Voltage Input: Type 90

Integrator: Device 66

Measurement Results - Typical Event



3296
Phase A Voltage
RMS Variation

February 20, 1994 at 12:52:52 PQNode Local
Trigger

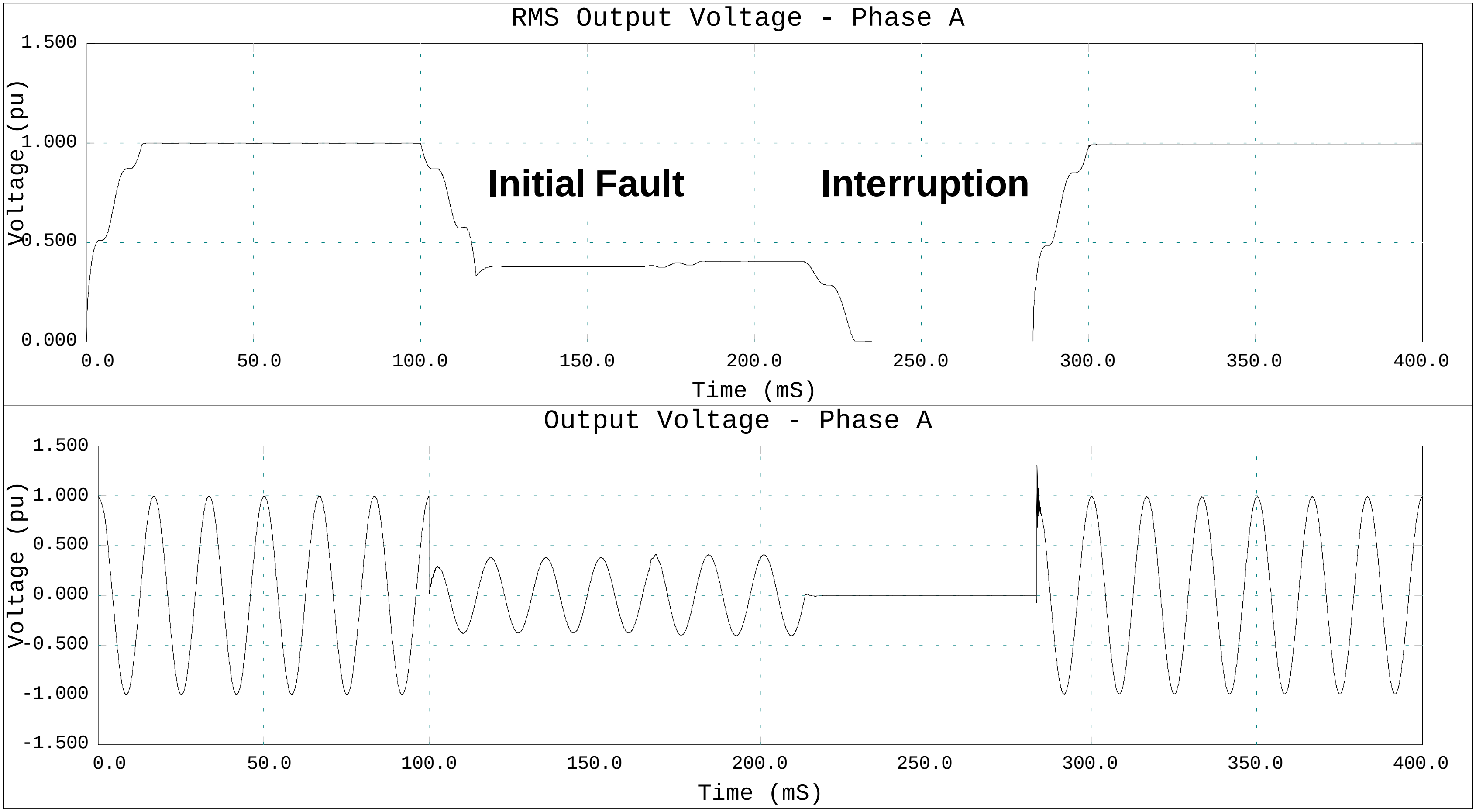
Duration
0.633 Sec
Min 0.166
Ave 75.50
Max 138.8
Ref Cycle
43760

BMI/Electrotek

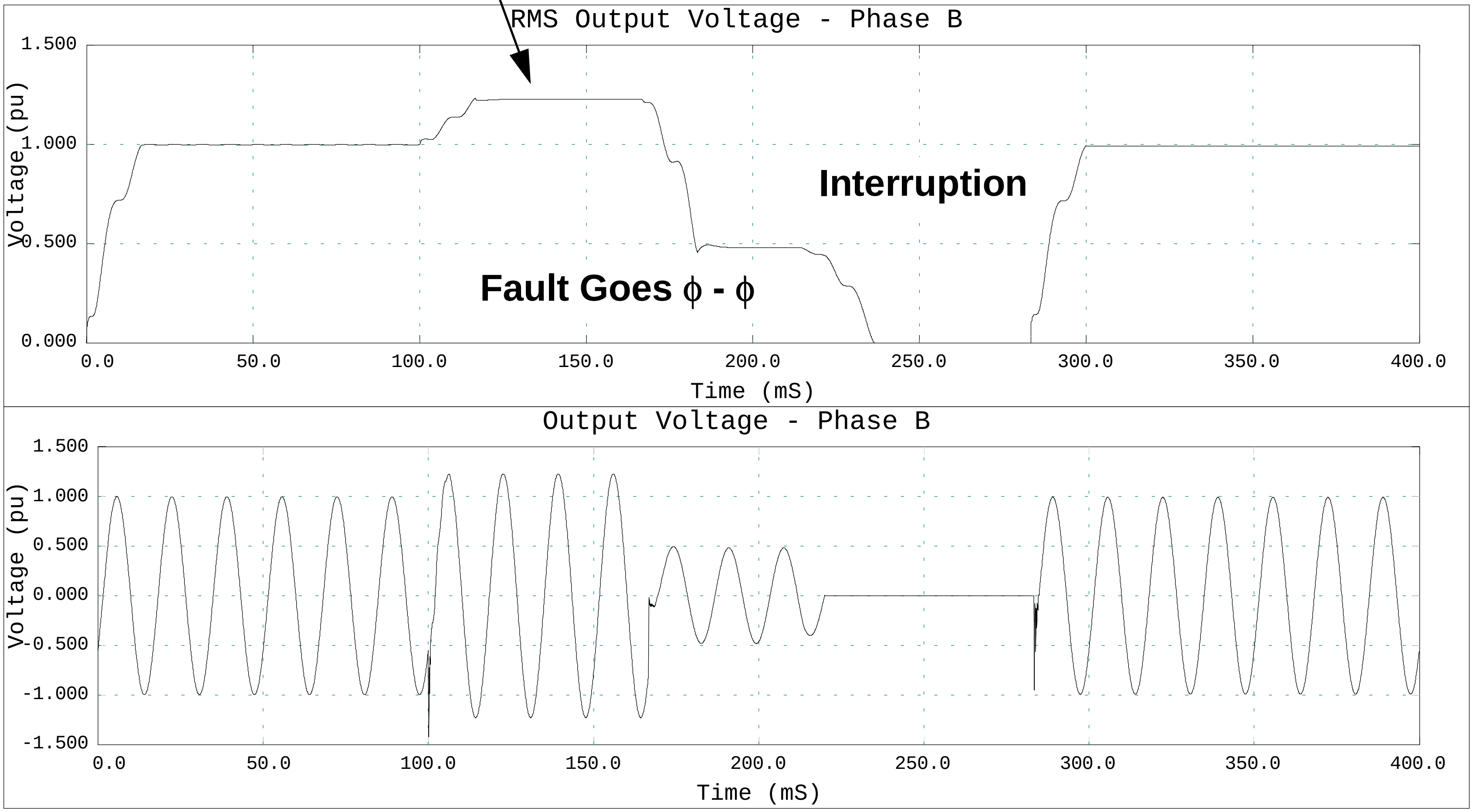
Fault Sequence

```
C <-------- Fault Switch
C
C BUS-->BUS--><---TCLOSE<----TOPEN<-------IE<----FLASH<--REQUEST<-----TARGET<--O
  XFMRHA  FLTA  99.99E-3 233.33E-3                                             1
  XFMRHB  FLTB 166.66E-3 233.33E-3                                             1
C XFMRHC  FLTC  99.99E-3 166.67E-3                                             1
C .....^.....^.........^.........^.........^.........^.........^...........^...^
C
C <-------- Fault Impedance
C <---Nodes--><---Refer--><-ohms<---mH<---uF<--------------------------------Out
C <-Bus1<-Bus2<-Bus3<-Bus4<----R<----L<----C                                   V
    FLTA                     4.0
    FLTB                     4.0
    FLTC                     4.0
C .....^.....^.....^.....^.....^.....^.....^...................................^
C
C <-------- Feeder Breaker
C BUS-->BUS--><---TCLOSE<----TOPEN<-------IE<----FLASH<--REQUEST<-----TARGET<--O
   LINEA  CKTA -99.00E-3 213.33E-3
   LINEB  CKTB -99.00E-3 213.33E-3
   LINEC  CKTC -99.00E-3 213.33E-3
C .....^.....^.........^.........^.........^.........^.........^...........^...^
   LINEA  CKTA 283.33E-3   9999.99
   LINEB  CKTB 283.33E-3   9999.99
   LINEC  CKTC 283.33E-3   9999.99
C .....^.....^.........^.........^.........^.........^.........^...........^...^
```

Simulation Results - Fault Phase (A)



Simulation Results - Healthy Phase (B)



Phase A Fault - Swell

Interruption

Fault Goes ϕ - ϕ

TACS Examples - cont

- A Second Example - RMS Meter
- Constant Current Source Injection

-1 -> current source

```
/SOURCE
C
C <-------- 200 HP Adjustable-Speed Drive (dc Drive, three-phase)
C
C  Harmonic Current Source for 200 HP DC Drive
C  IFL = 240 Amps  I5 = 33.6%, I7 = 1.6%,  I11 = 8.7%,  I13 = 1.2%
C
C <--Bus<I<-----Ampl<-----Freq<----Phase<-------A1<------T1><---Tstart<----Tstop
14200HPA-1     339.4      60.0     -75.0                      50.0E-06     9999.
14200HPA-1       4.1     180.0      28.0                      50.0E-06     9999.
14200HPA-1     114.0     300.0     156.0                      50.0E-06     9999.
14200HPA-1       5.4     420.0      29.0                      50.0E-06     9999.
14200HPA-1      29.5     660.0      49.0                      50.0E-06     9999.
14200HPA-1       4.1     780.0      54.0                      50.0E-06     9999.
14200HPA-1      15.3    1020.0     -57.0                      50.0E-06     9999.
14200HPA-1       4.4    1140.0     -46.0                      50.0E-06     9999.
C .....^.^.........^.........^.........^.........^.........^.........^.........^
C
C [repeated for phases B & C]
```

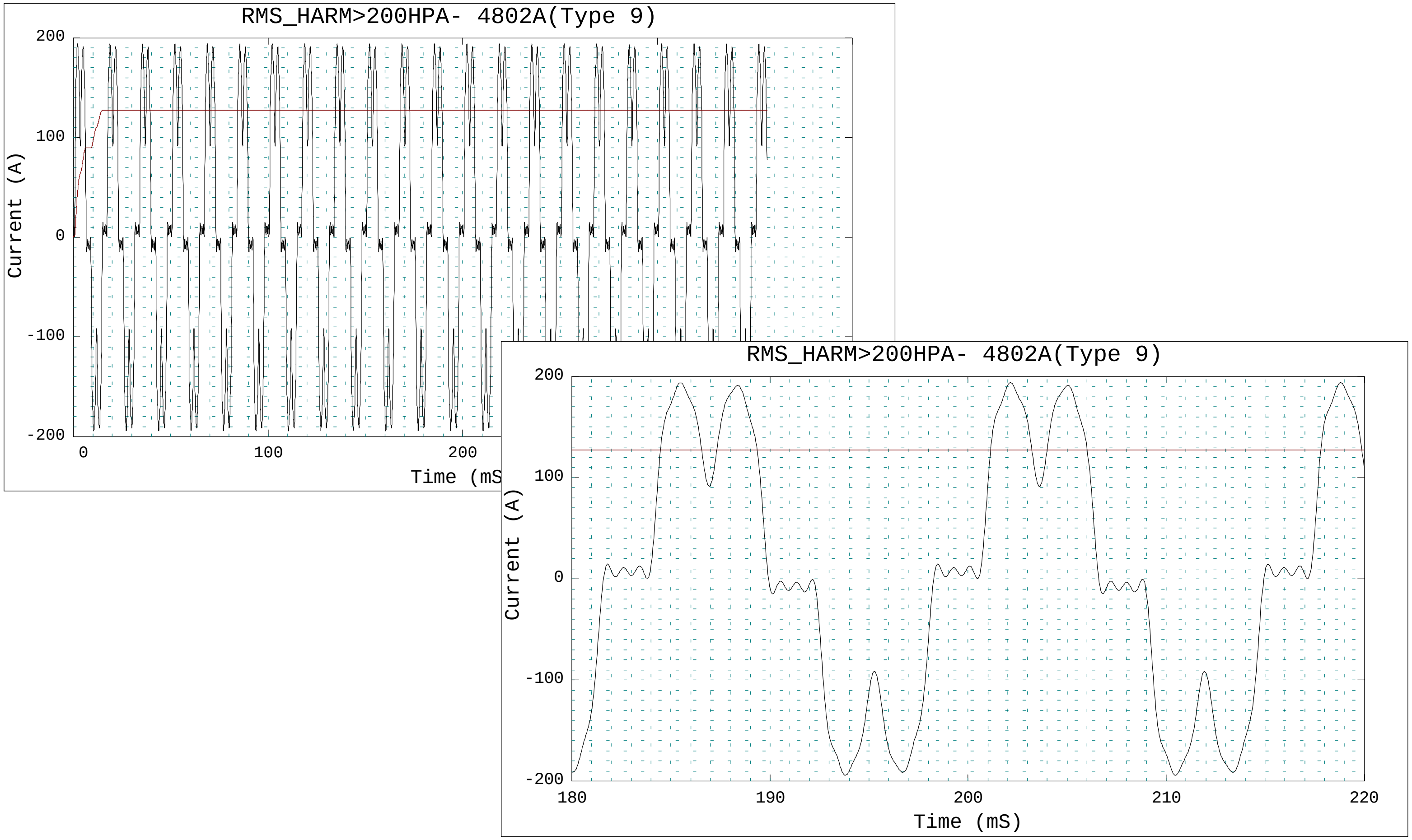
non zero start time

TACS “Built-In” RMS Meter

```
TACS HYBRID
C
C
C <-------- TACS "Built-in" RMS Meter
C
/TACS
C
C [current Source from EMTP portion of case]
C
91200HPA                  60.0
91200HPB                  60.0
91200HPC                  60.0
C .....^XX.........^.........^.........^XXXXXXXXXXXXXXXXXXXX.........^.........^
C
C [full waveform - phases A, B, & C]
C
88 IARMS66+200HPA                                    60.0
88 IBRMS66+200HPB                                    60.0
88 ICRMS66+200HPC                                    60.0
C .....^.^^.....^X^......^X......^X^.....^X^.....^X.....^.....^.....^.....^.....^
C
C
```

Simulation Results

- ❑ Plot of Drive Current and TACS RMS Quantity:



Analog Filter Method

- Four Point Analog Fourier Filter
  - Sample waveform four times per cycle
  - Create “SAL” and “CAL” functions (sin & cos)
  - Define samples as:

$$S_0 = F\sin(\omega t + \phi)$$

$$S_1 = F\sin(\omega t + \phi + 90^\circ)$$

$$S_2 = F\sin(\omega t + \phi + 180^\circ)$$

$$S3 = F\sin(\omega t + \phi + 270^\circ)$$

$$SAL = S_0 - S_1 - S_2 + S_4 = 2\sqrt{2}F\sin(\omega t + \phi + 45^\circ)$$

$$CAL = S_0 + S_1 - S_2 - S_4 = 2\sqrt{2}F\cos(\omega t + \phi + 45^\circ)$$

$$F_{RMS} = \frac{\sqrt{\left(SAL^2 + CAL^2\right)}}{4}$$

Analog Filter Data

```
C <-------- Perform analog filtering on current.
C           Uses a Point Walsh Function Calculation, which only removes
C           dc component and even harmonics.
C
C           Phase shifting of current measurements.
C
C OUTPUTvv+IN1--> +IN2--> +IN3--> +IN4--> +IN5--> <--A--<--B--<--C--<--D--<--E--
C
C [full waveform - phase A]
C
88IAZ1H 53+200HPA                                       .00209
88IAZ2H 53+200HPA                                       .00417
88IAZ3H 53+200HPA                                       .00626
88IAZ4H 53+200HPA                                       .00833
88IAZ5H 53+200HPA                                       .01043
88IAZ6H 53+200HPA                                       .01250
88IAZ7H 53+200HPA                                       .01460
C .....^.^^.....^X^......^X......^X^.....^X^.....^X.....^.....^.....^.....^.....^
```

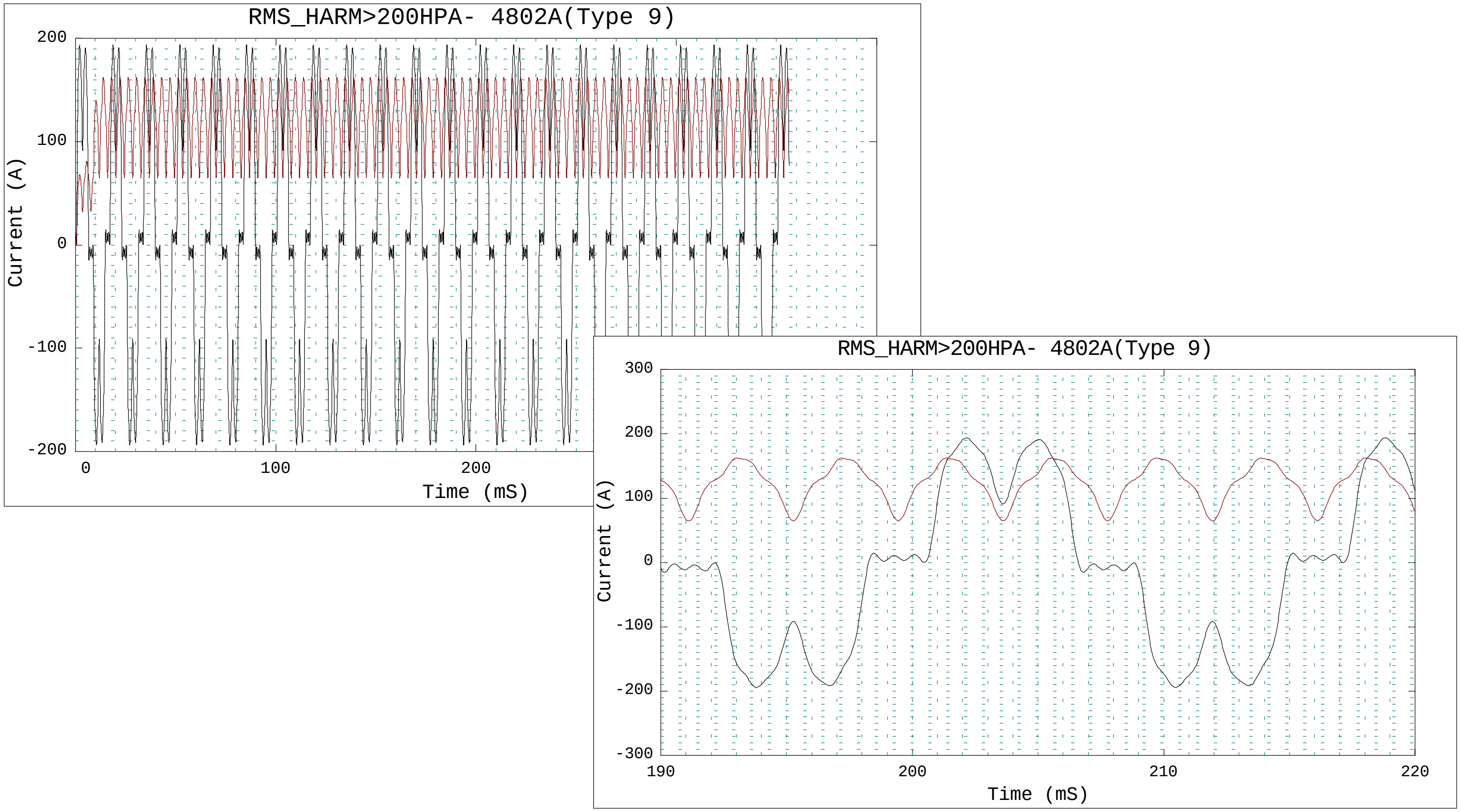
adding & subtracting phase shifter components cancels dc terms, also cancels even harmonics

Analog Filter Data - cont

```
C
C <-------- Walsh function calculations
C
C OUTPUT  +IN1--> +IN2--> +IN3--> +IN4--> +IN5--> <-gain<--low<-highLOW-->HIGH->
C
C [full waveform - phase a]
C
  ICALH   +200HPA +IAZ2H  -IAZ4H  -IAZ6H              1.
  ISALH   +200HPA -IAZ2H  -IAZ4H  +IAZ6H              1.
C .....^  ^.....^ ^.....^ ^.....^ ^.....^ ^.....^ ^.....^.....^..........^.....^
C
C <-------- Compute RMS magnitude
C
C [full waveform - phase A]
C
88AFRMSA  =SQRT(ISALH*ISALH+ICALH*ICALH)/4
C .....^..^
```

Simulation Results

- ❑ Plot of Drive Current and TACS Analog Filter RMS Quantity:



Digital Filter Method

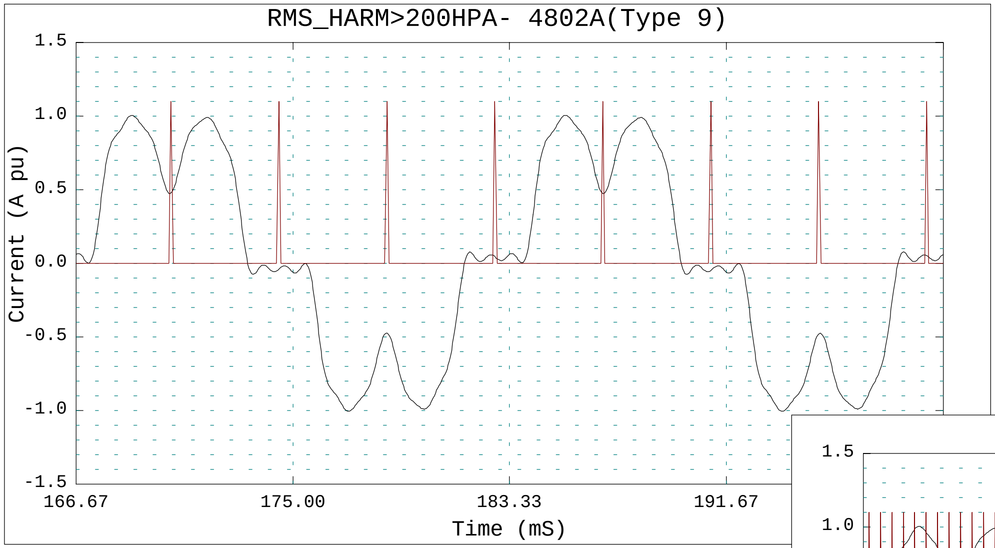
- Four Point Digital Fourier Filter
  - Basic concept same as analog filter
  - Use sample and hold rather than continuous sampling
  - Face aliasing problem...
    - *Nyquist criterion: to avoid aliasing problem, frequencies above one half of the sampling rate should be removed.*
  - Requires 38 samples per cycle for 19th harmonic
  - EMTP is already a form of digital filter
  - Sample periods must be integral multiples of the timestep

Digital Filter Data

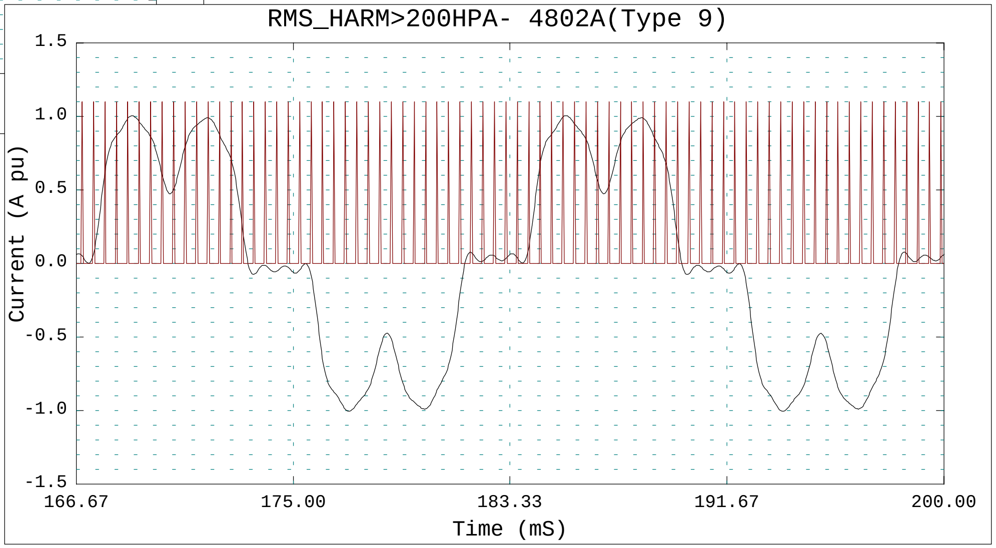
```
C
C <-------- Implement analog to digital converter - 38 samples per 60 Hz cycle
C           Also shows importance of synchronizing sampling with simulation
C           time step. The timestep acts to digitally filter signals too.
C
C [sample generator for A to D converter]
C             ampl     t(sec)  width(sec)
C OUTPUT  <-----A---<----B----<----C----                    <-T-START-<-T-STOP--
23DSAMPL         1.1    .00044    .00003                          -1.0    999.9
C .....^  ^.........^.........^.........                    ^.........^.........
C
C [generate A to D converter samples]
C OUTPUTvv+IN1--> +IN2--> +IN3--> +IN4--> +IN5--><--A--<--B--<--C--<--D--<--E--
88HADZ0 62+200HPA                                                        DSAMPL
C .....^.^^.....^X^......^X......^X^.....^X^.....^.....^.....^.....^.....^.....^
C
C [sample and hold delayed samples - needs to be multiples of dt]
C OUTPUTvv+IN1--> +IN2--> +IN3--> +IN4--> +IN5--> <--A--<--B--<--C--<--D--<--E--
88HADZ1 53+HADZ0                                        .00415
88HADZ2 53+HADZ0                                        .00830
88HADZ3 53+HADZ0                                        .01245
C .....^.^^.....^X^......^X......^X^.....^X^.....^X.....^.....^.....^.....^.....^
```

Digital Sampling

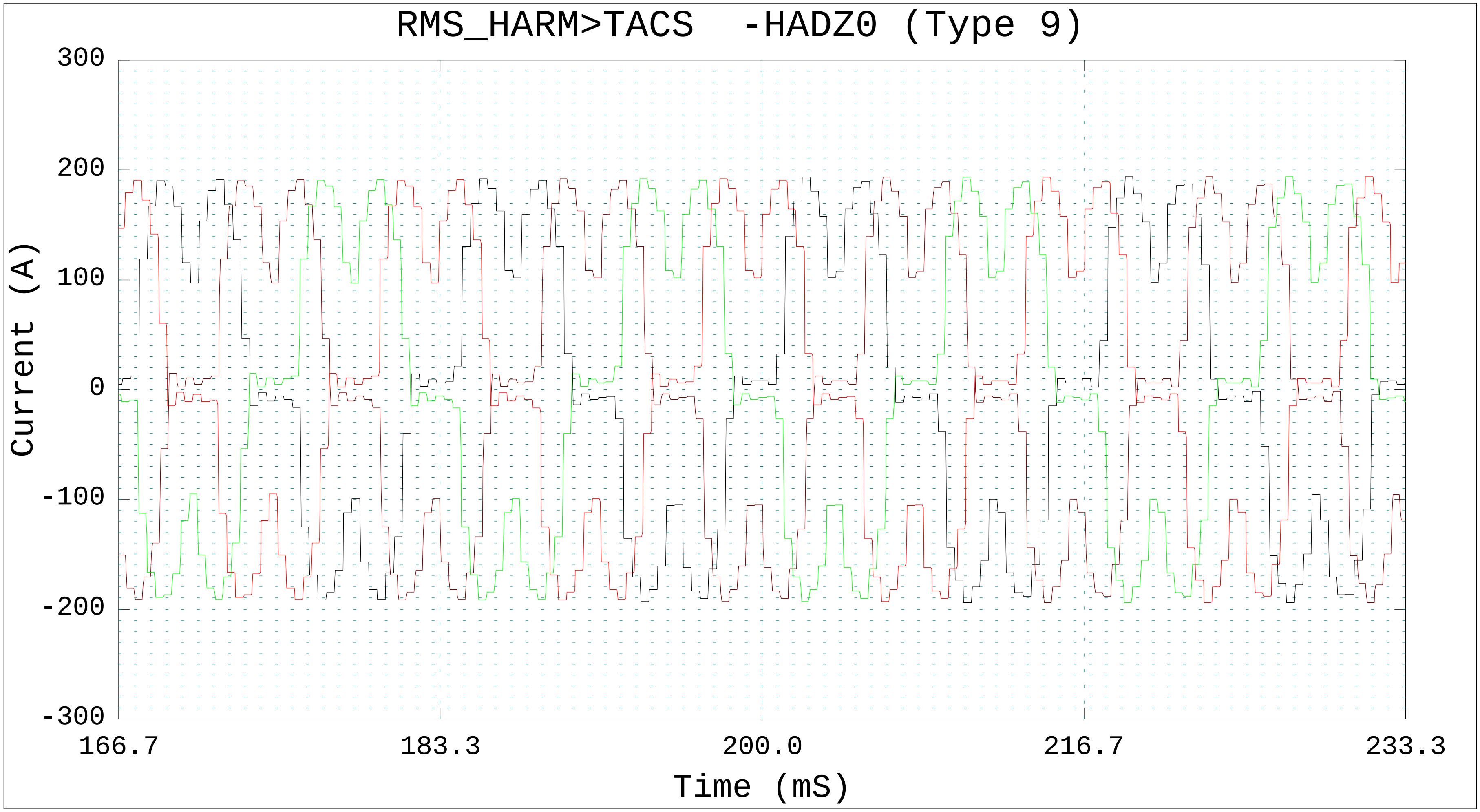
4 samples / 60 Hz cycle



38 samples / 60 Hz cycle



Phase Shifting

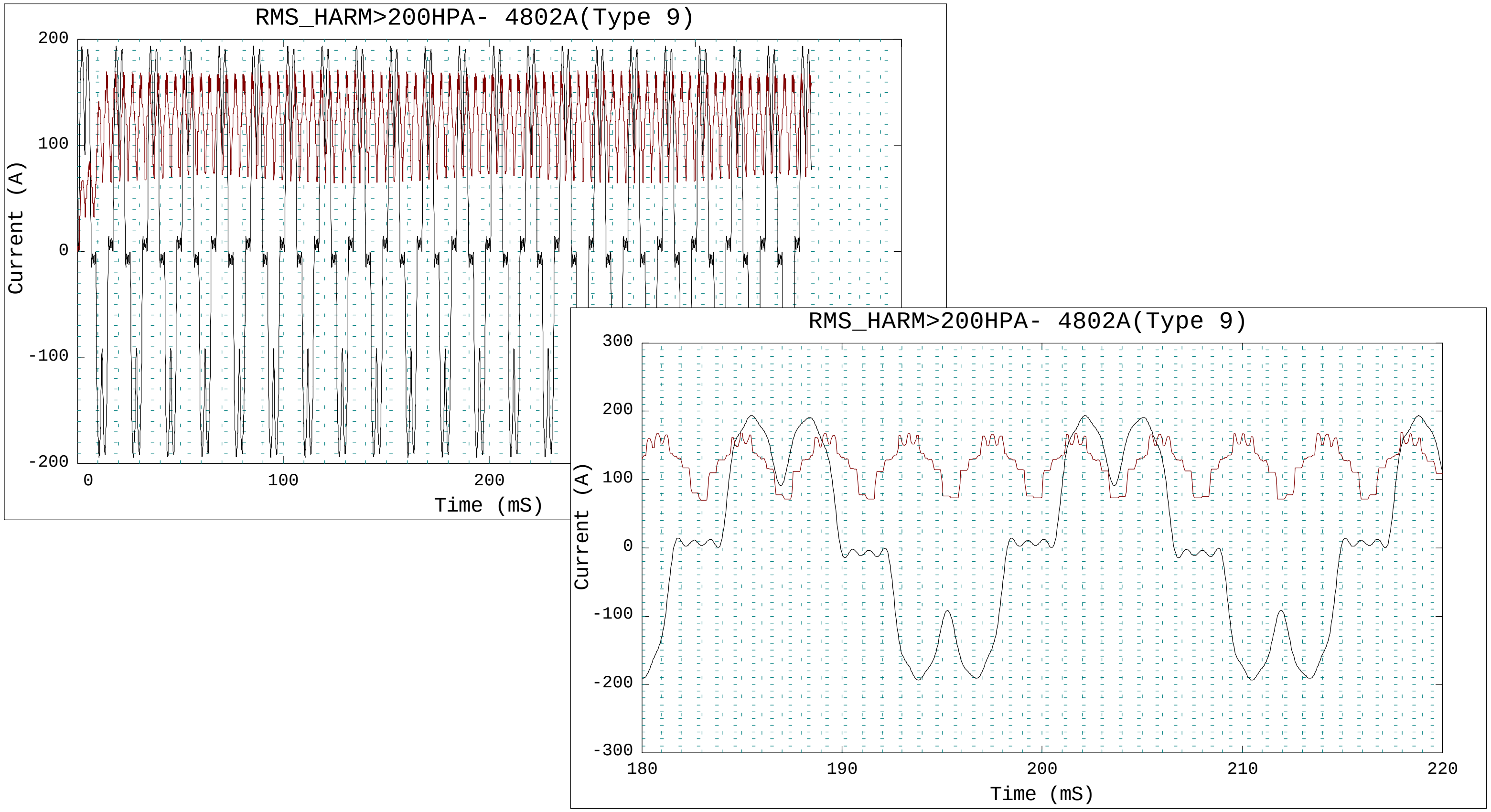


Digital Filter Data

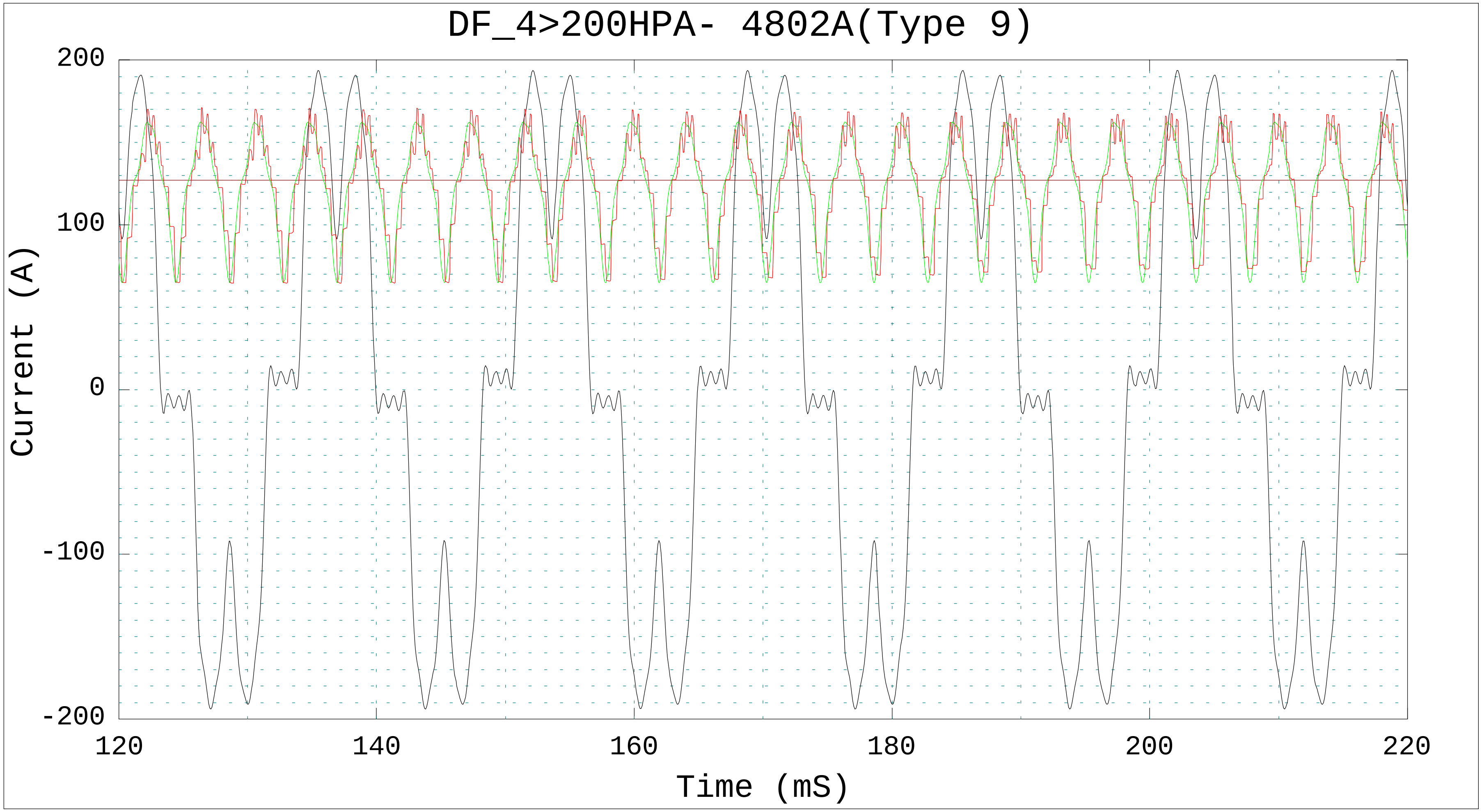
```
C [Walsh function calculations]
C OUTPUT  +IN1--> +IN2--> +IN3--> +IN4--> +IN5--> <-gain<--low<-highLOW-->HIGH->
  HZSAL   +HADZ0  +HADZ1  -HADZ2  -HADZ3              1.
  HZCAL   +HADZ0  -HADZ1  -HADZ2  +HADZ3              1.
C .....^  ^.....^ ^.....^ ^.....^ ^.....^ ^.....^ ^.....^.....^..........^.....^
C
C [compute RMS magnitude and phase for current]
C
C [full waveform - phase A]
C
88HZPHS   =ATAN(HZSAL/HZCAL)*3960/7
88DFRMSA  =SQRT(HZSAL*HZSAL+HZCAL*HZCAL)/4
C .....^..^
C
C <-------- TACS Output Request
C
C <Name1<Name2<Name3<Name4<Name5<Name6<Name7<Name8
33 IARMSAFRMSADFRMSADSAMPLHADZ0 HADZ1 HADZ2 HADZ3
C .....^.....^.....^.....^.....^.....^.....^.....^
```

Simulation Results

- Plot of Drive Current and TACS Digital Filter RMS Quantity:

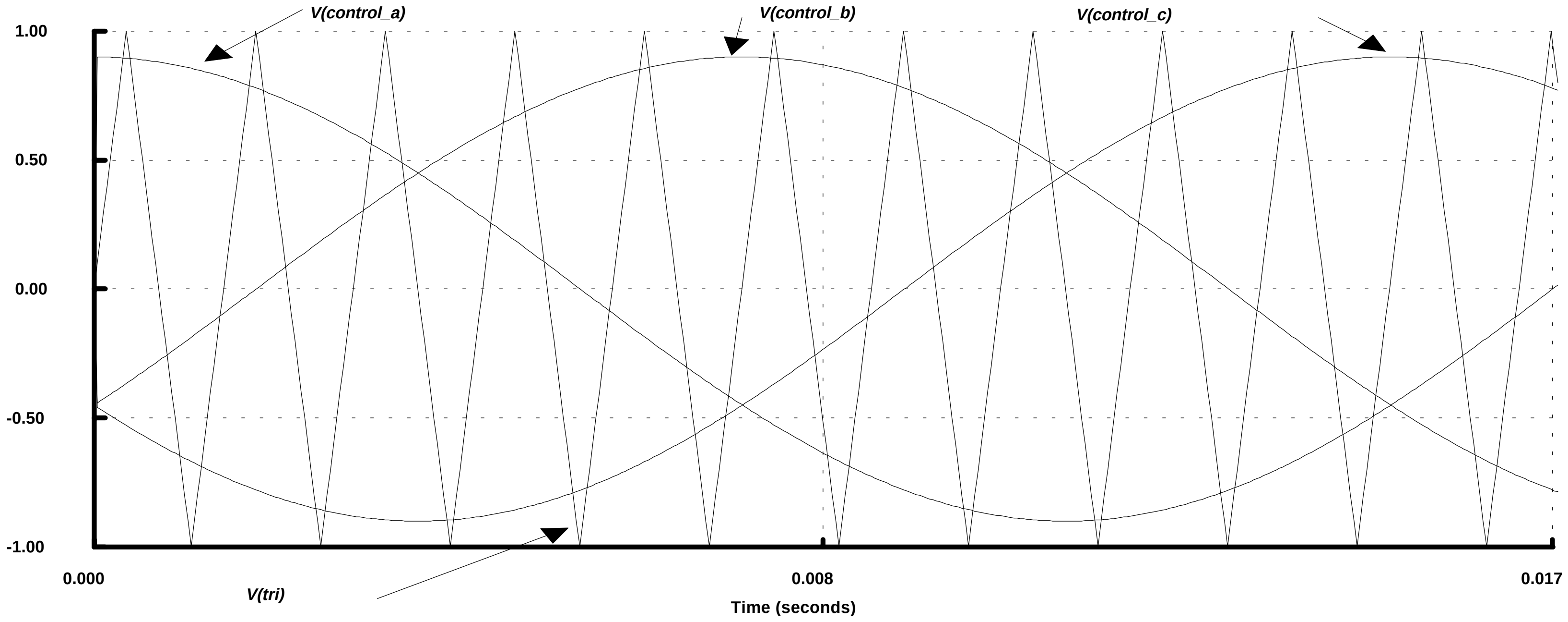


Comparing Simulation Results



PWM Control - TACS

- Drive to Run @ 45 Hz
  - want to have a frequency modulation ratio (m_f)= 15
  - switching frequency (f_s) = 45*15=675



EMTP Data - PWM Switching

```
/TACS
C
C <-------- Triangular voltage "VTRI" (next 5 cards)
C
C Name->xx<-----Ampl<---T(sec)<-Wid(sec)<------------------><---Tstart<----Tstop
23PULS           2.0  1.481E-3 0.7407E-3                      372.0E-6
C .....^xx.........^.........^.........^xxxxxxxxxxxxxxxxxxxx.........^.........^
C
C Name->xx=<---------Fortran Expression--------------------------
98AMPL    =  4.0 * FS
98SQPUL   =  AMPL * (UNITY - PULS)
98VDELTA  =  SQPUL * DELTAT
C .....^xx=............................
C
C Name->co+<--In1x+<--In2x+<--In3x+<--In4x+<--In5
98VTRI  65+VDELTA
C .....^^^^.....^x^.....^x^.....^x^.....^x^.....^
```

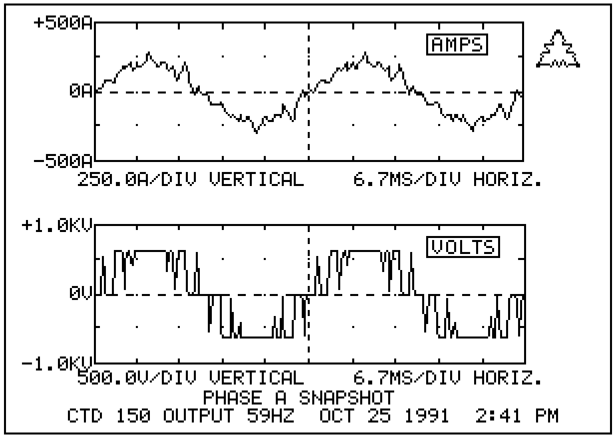
Switching frequency - fs = 675 Hz

Motor frequency - f1 = 45 Hz

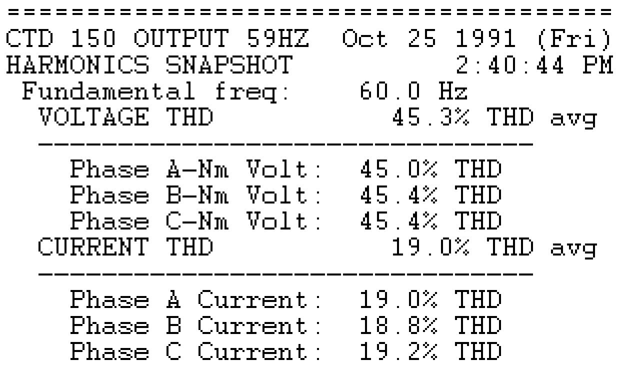
Modulation frequency - Mf

= fs/f1 = 15

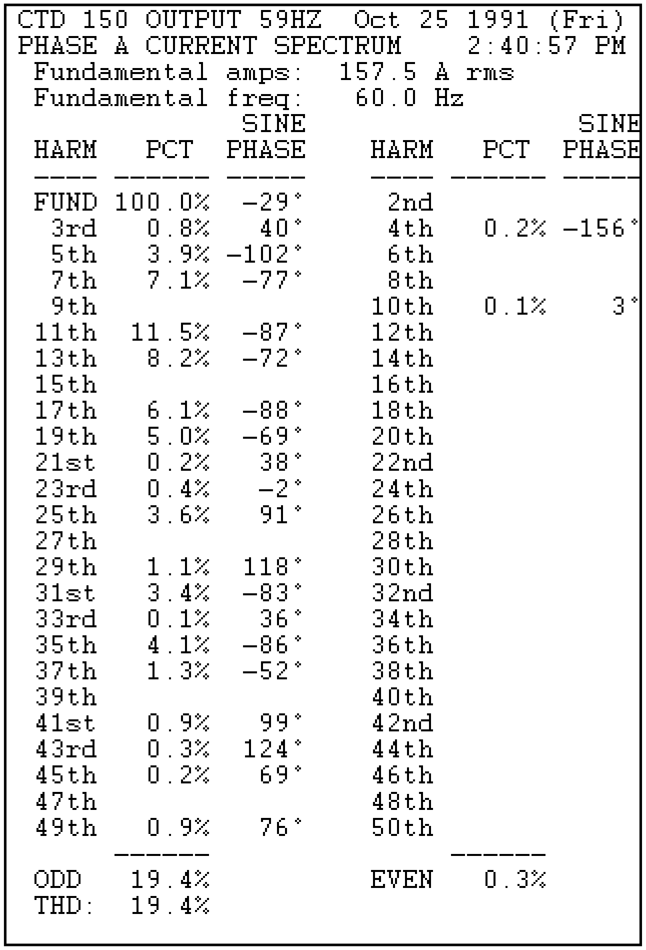
PWM Drive - Snapshot #3



PHASE A SNAPSHOT
CTD 150 OUTPUT 59HZ OCT 25 1991   2:41 PM

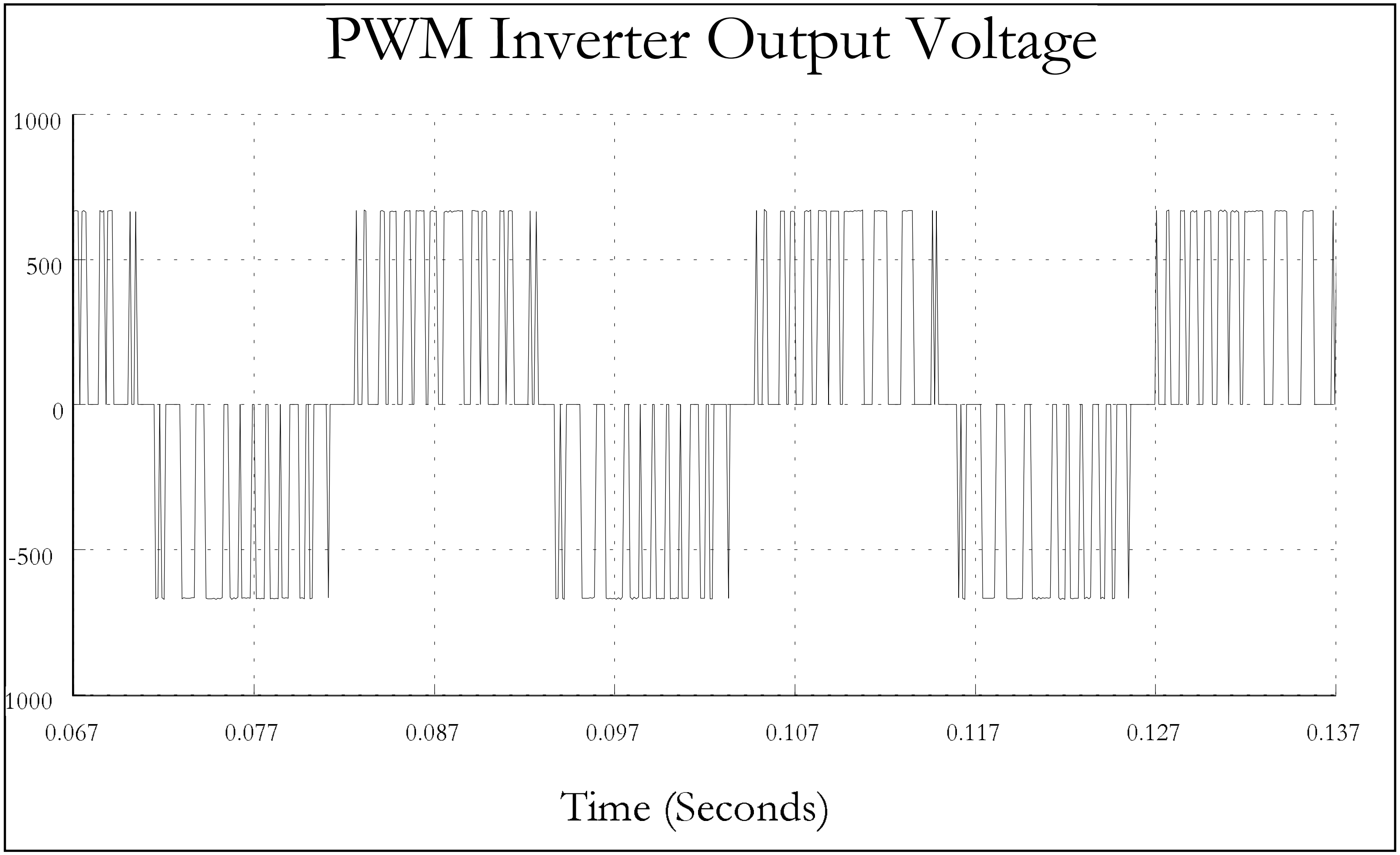


```
=====================================
CTD 150 OUTPUT 59HZ  Oct 25 1991 (Fri)
HARMONICS SNAPSHOT          2:40:44 PM
 Fundamental freq:    60.0 Hz
  VOLTAGE THD           45.3% THD avg
  -------------------------------
    Phase A-Nm Volt:  45.0% THD
    Phase B-Nm Volt:  45.4% THD
    Phase C-Nm Volt:  45.4% THD
  CURRENT THD           19.0% THD avg
  -------------------------------
    Phase A Current:  19.0% THD
    Phase B Current:  18.8% THD
    Phase C Current:  19.2% THD
```

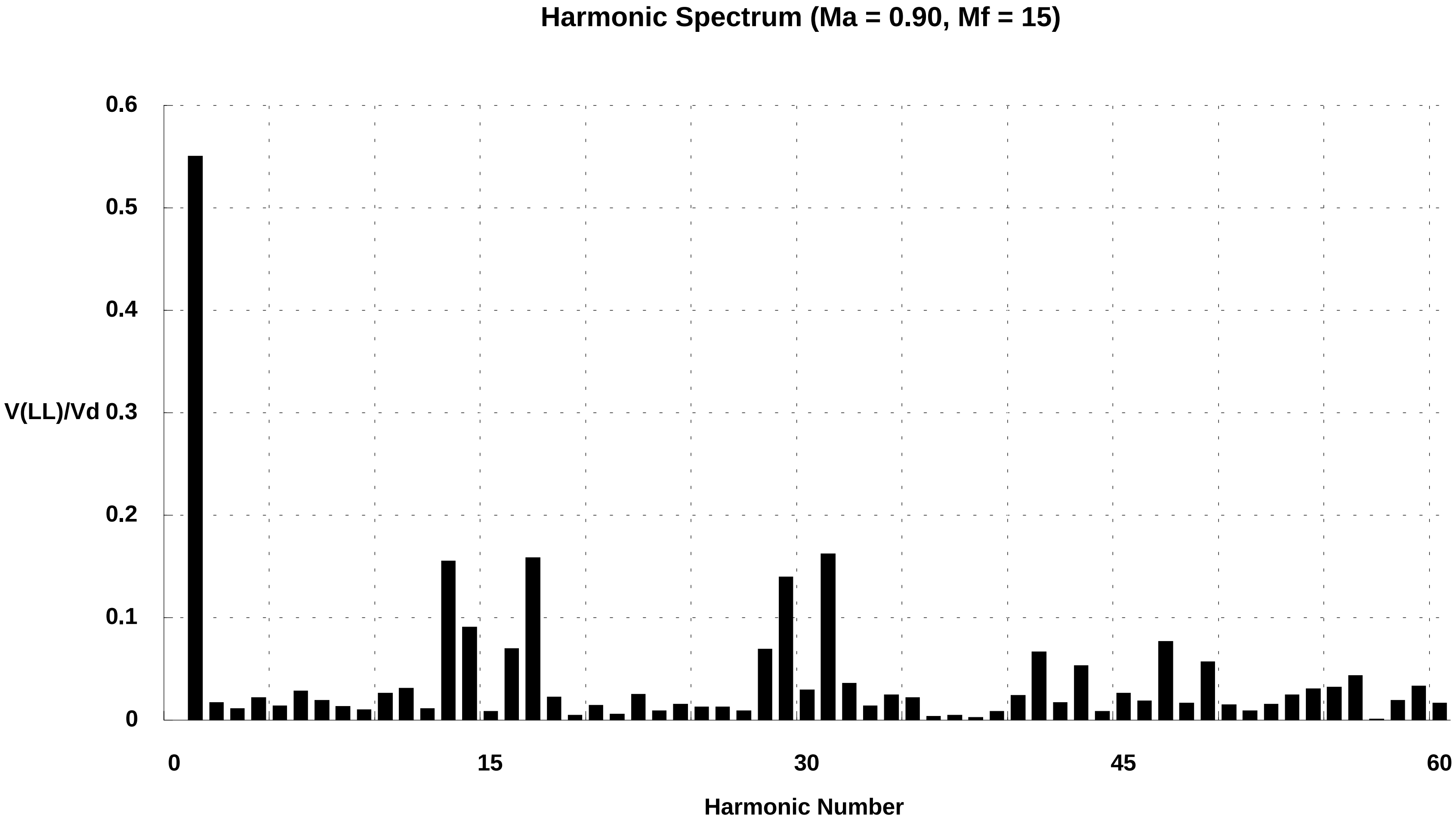


```
CTD 150 OUTPUT 59HZ  Oct 25 1991 (Fri)
PHASE A CURRENT SPECTRUM    2:40:57 PM
 Fundamental amps:  157.5 A rms
 Fundamental freq:   60.0 Hz
                 SINE                   SINE
 HARM   PCT   PHASE     HARM   PCT   PHASE
 ---- ------ -----      ---- ------ -----
 FUND 100.0%  -29°       2nd
  3rd   0.8%   40°       4th   0.2% -156°
  5th   3.9% -102°       6th
  7th   7.1%  -77°       8th
  9th                   10th   0.1%     3°
 11th  11.5%  -87°      12th
 13th   8.2%  -72°      14th
 15th                   16th
 17th   6.1%  -88°      18th
 19th   5.0%  -69°      20th
 21st   0.2%   38°      22nd
 23rd   0.4%   -2°      24th
 25th   3.6%   91°      26th
 27th                   28th
 29th   1.1%  118°      30th
 31st   3.4%  -83°      32nd
 33rd   0.1%   36°      34th
 35th   4.1%  -86°      36th
 37th   1.3%  -52°      38th
 39th                   40th
 41st   0.9%   99°      42nd
 43rd   0.3%  124°      44th
 45th   0.2%   69°      46th
 47th                   48th
 49th   0.9%   76°      50th
      ------                 ------
 ODD   19.4%            EVEN   0.3%
 THD:  19.4%
```

PWM Inverter Output Voltage - Waveform

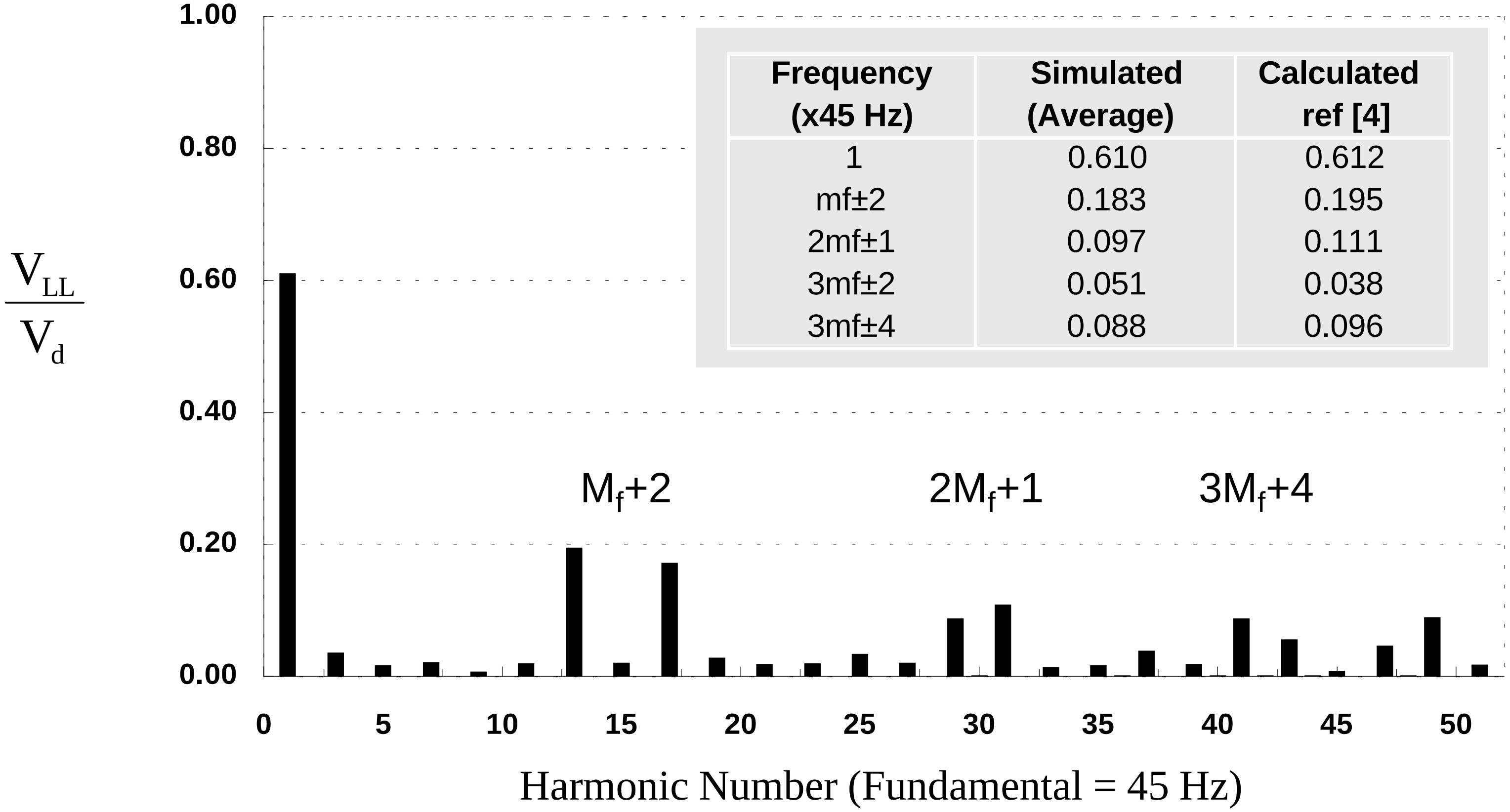


PWM Inverter Output Voltage - Spectrum



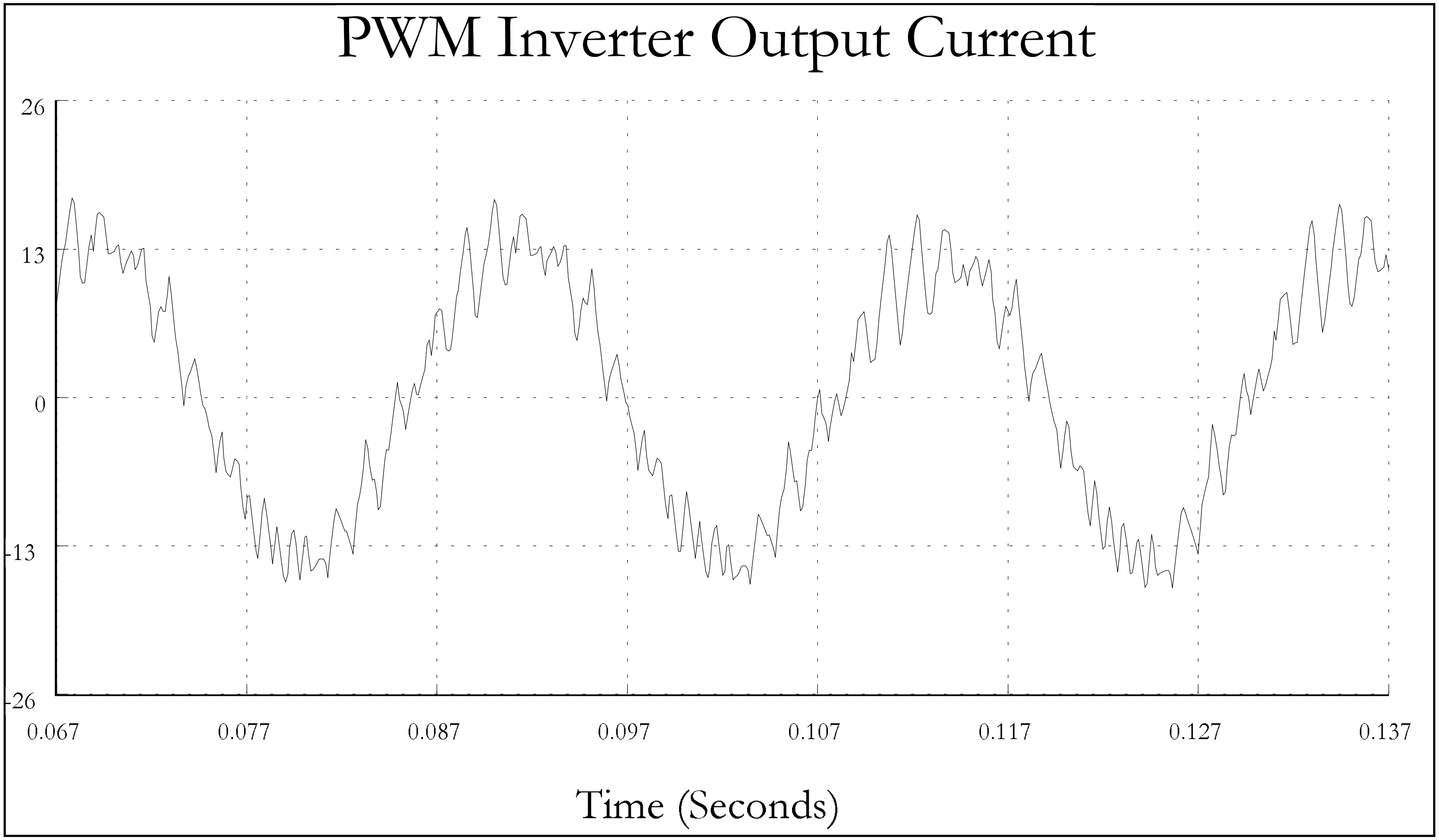
PWM ASD EMTP Model - Verification

Comparison of Simulated and Calculated Harmonic Voltage Spectrums:

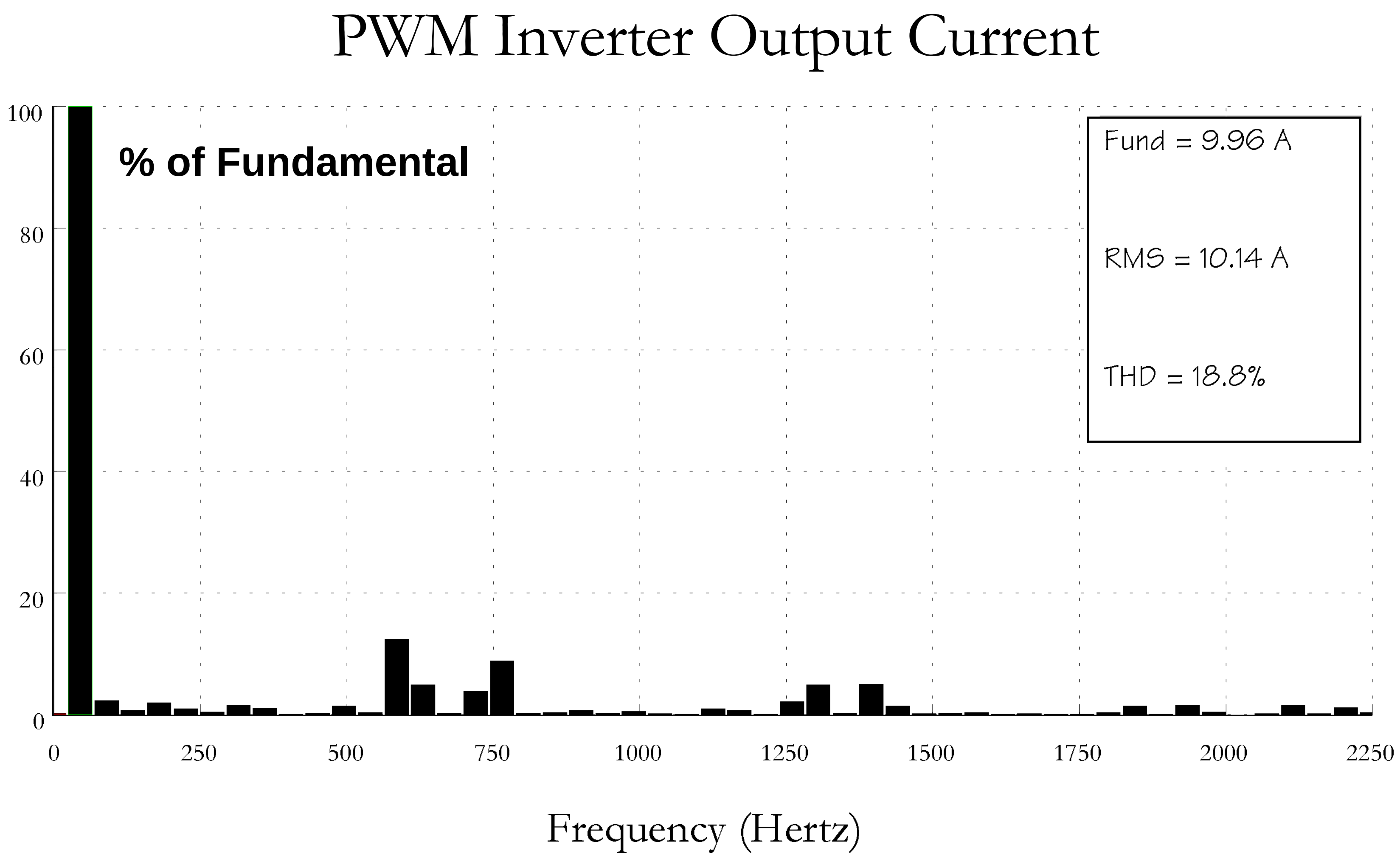


Frequency (x45 Hz)	Simulated (Average)	Calculated ref [4]
1	0.610	0.612
mf±2	0.183	0.195
2mf±1	0.097	0.111
3mf±2	0.051	0.038
3mf±4	0.088	0.096

PWM Inverter Output Current - Waveform

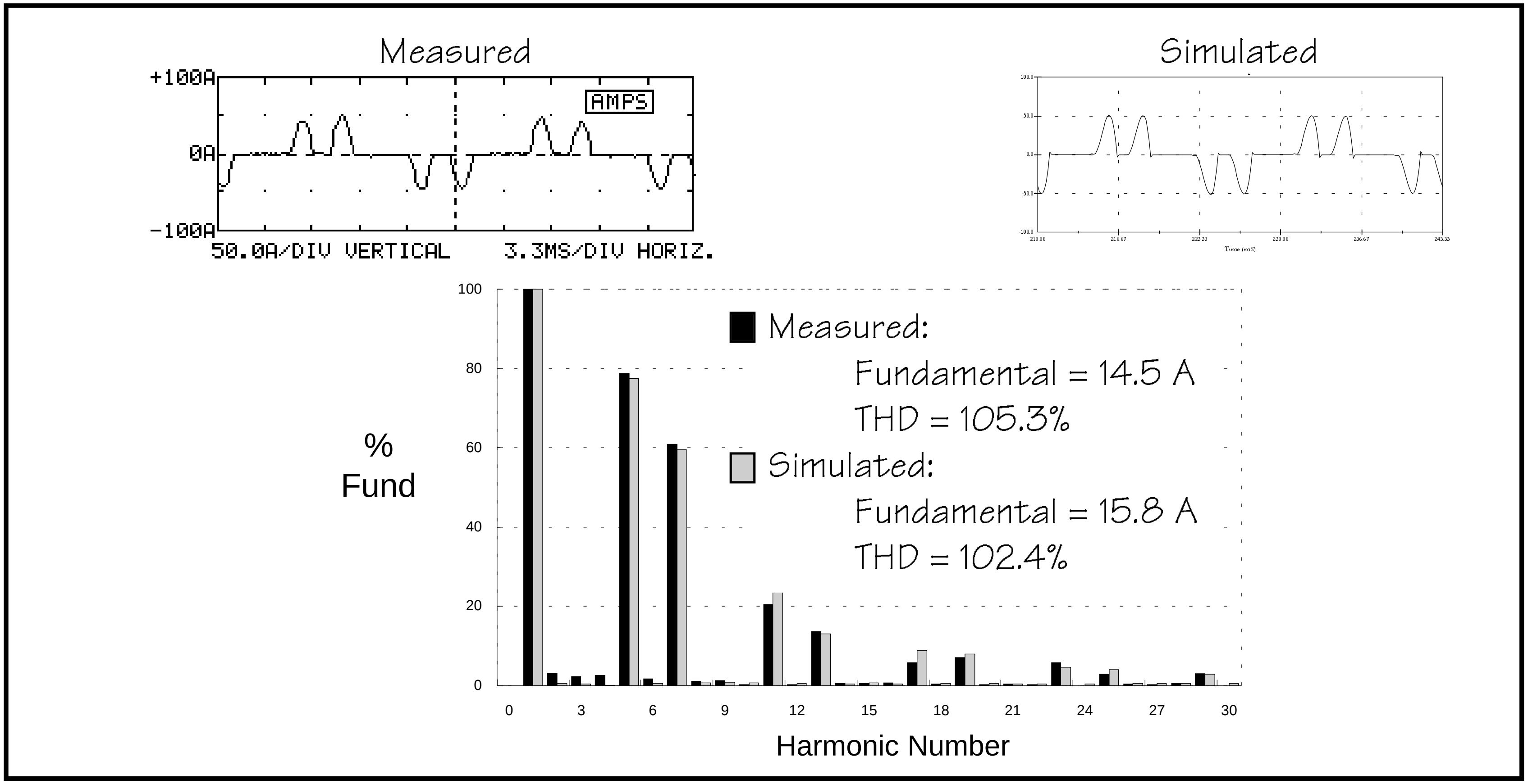


PWM Inverter Output Current - Spectrum



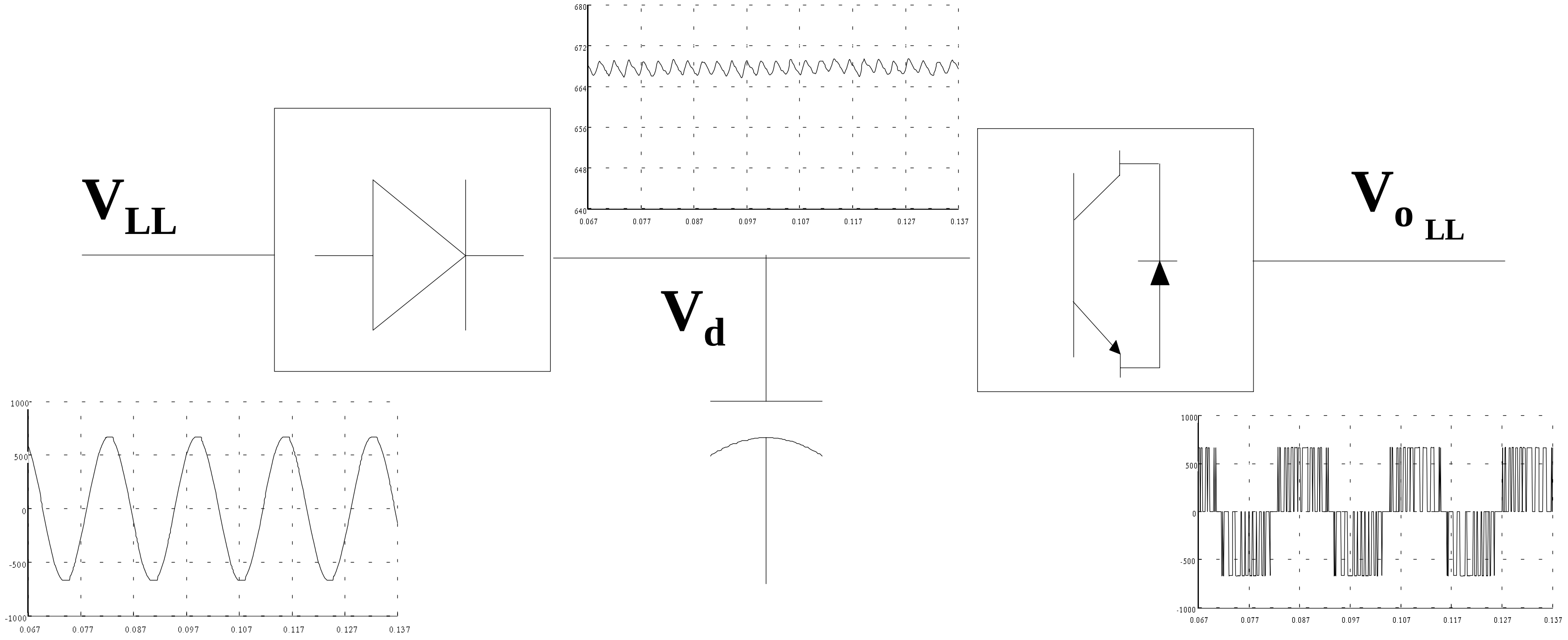
PWM ASD EMTP Model - Verification

Comparison of Simulated and Measured Harmonic Current Spectrums:



PWM ASD - Voltage Waveforms

$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL} \approx 1.35\, V_{LL} = 1.35 * 480 = 648\text{ V}$$



$$V_{o_{LL}} = \frac{\sqrt{3}}{2\sqrt{2}} * m_a * V_d \approx 0.612 * m_a * V_d = 0.612 * 0.90 * 648 = 357\text{ V}$$

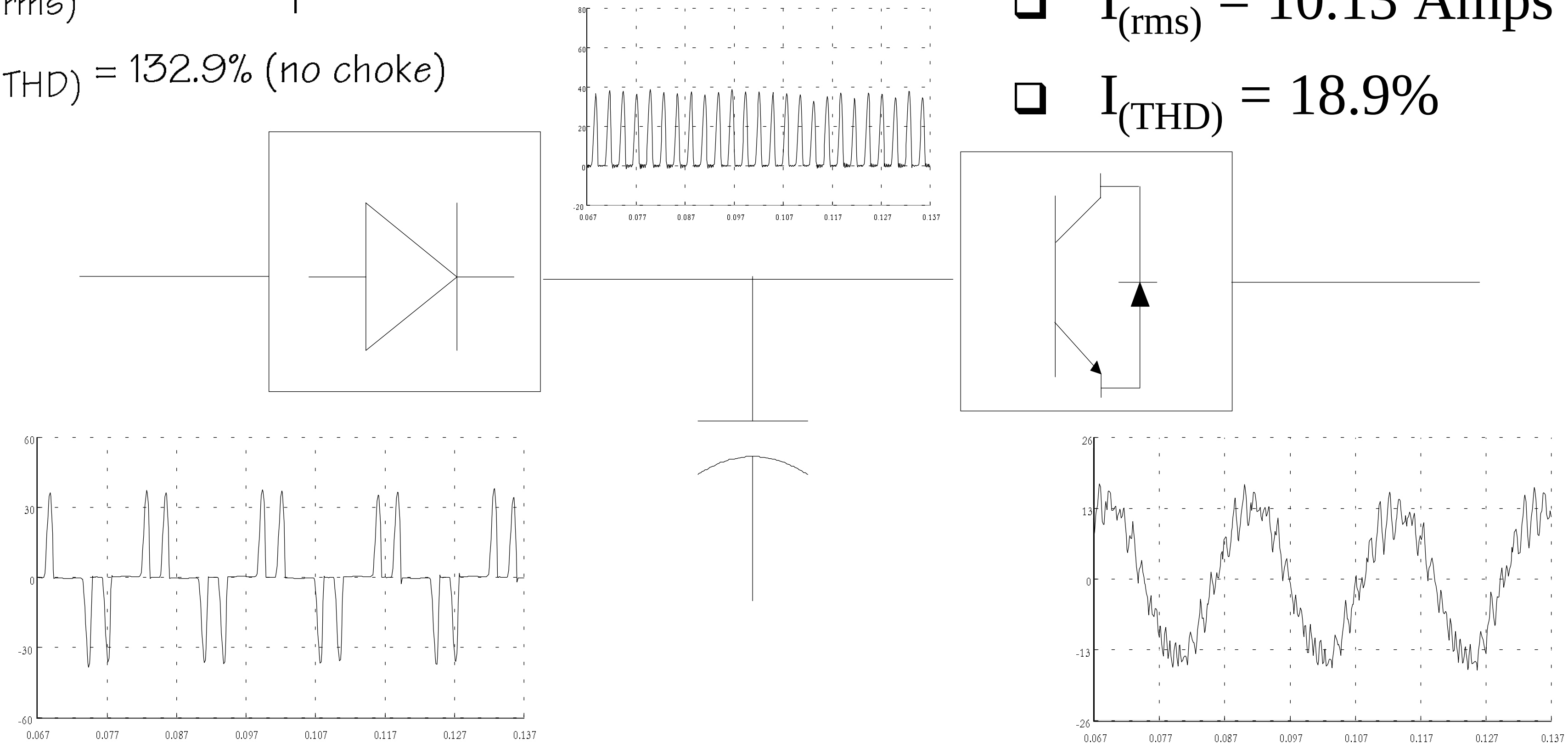
PWM ASD - Current Waveforms

$I_{(fund\text{-}60)}$ = 8.34 Amps

$I_{(rms)}$ = 13.87 Amps

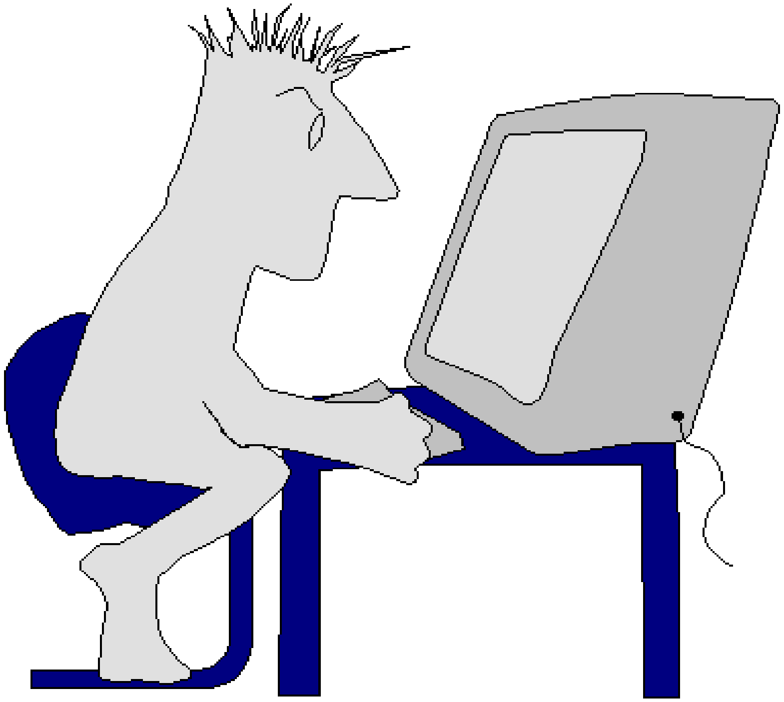
$I_{(THD)}$ = 132.9% (no choke)

- ❑ $I_{(fund\text{-}45)}$ = 9.98 Amps
- ❑ $I_{(rms)}$ = 10.13 Amps
- ❑ $I_{(THD)}$ = 18.9%



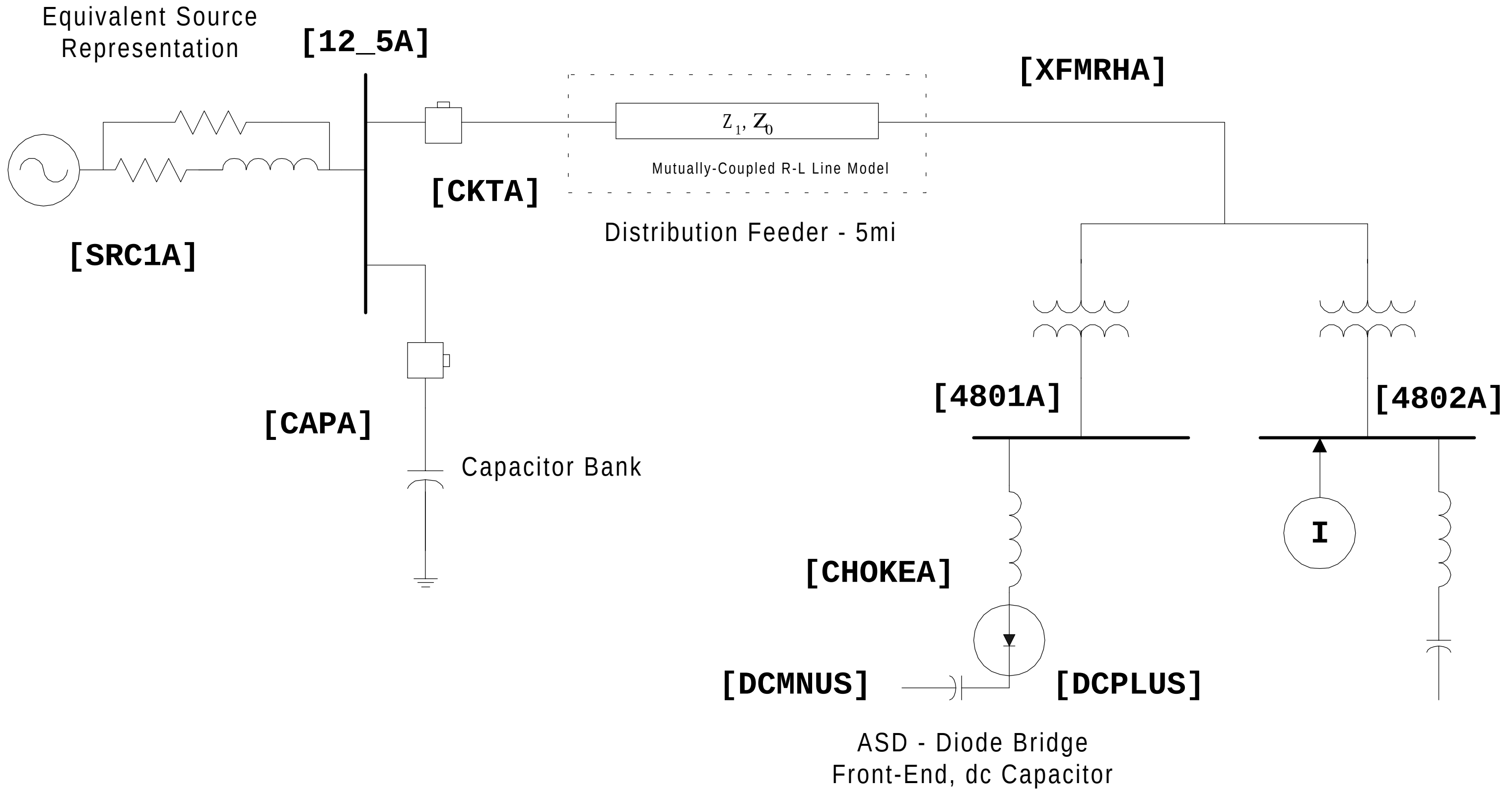
TACS Lab Exercises

- ☐ Voltage Sag - RMS Meter
- ☐ Harmonic Injection:
  - RMS Meter
  - Analog Filter Method
  - Digital Filter Method
- ☐ PWM ASD Control



RMS Meter Example #1

- ❑ Oneline Diagram:



RMS_SAG.DAT

RMS Meter Example #1

- Cases:
  - Run basecase and plot results
  - Evaluate impact of fault impedance, duration, and type
  - Evaluate impact of fault on dc bus voltage (simple drive model)
  - Increase dc capacitor size and determine impact

RMS Meter Example #2

❑ Cases:

  - Run basecase and plot results
  - Add dc component to waveform
  - Add even harmonics to waveform
  - Evaluate impact of sample rate

RMS_HARM.DAT

PWM ASD Control

- ❑ Cases:
  - Run basecase and plot results

    Harmonic spectrum (FFT for drive current)
  - Evaluate impact of ac choke
  - Evaluate impact of various dc capacitor sizes

That’s All Folks