# GUIDELINES FOR MODELING POWER ELECTRONICS IN ELECTRIC POWER ENGINEERING APPLICATIONS

A.M.Gole, Albert Keri, C. Nwankpa, E.W.Gunther, H.W. Dommel, I.Hassan, J.R. Marti, J.A.Martinez
K.G.Fehrle, L.Tang (Chairman), M.F. McGranaghan, O.B.Nayak, P.F.Ribeiro, R.Iravani, R. Lasseter
Power Electronics Modeling Task Force & Digital Simulation Working Group

**ABSTRACT** -This paper presents a summary of guidelines for modeling power electronics in various power engineering applications. This document is designed for use by power engineers who need to simulate power electronic devices and sub-systems with digital computer programs. The guideline emphasizes the basic issues that are critical for successfully modeling power electronics devices and the interface between power electronics and the utility or industrial system. The modeling considerations addressed in this guideline are generic for all power electronics modeling independent of the computational tool. However, for the purposes of illustration, the simulation examples presented are based on the EMTP or EMTP type of programs. The procedures used to implement power electronics models in these examples are valuable for using other digital simulation tools.

## 1. INTRODUCTION

As a consequence of the advances in power electronics technologies over the last two decades, power electronics applications have quickly spread to all voltage levels, from EHV transmission to low voltage circuits in end user facilities.

Commonly observed power electronics applications include HVDC terminals, various static var compensation (SVC) systems, high power ac to dc converter for dc arc furnaces, static phase shifter, isolation switch, load transfer switch, converter/inverter based drive technologies, active line conditioning, energy storage and instantaneous backup power systems, renewable energy integration, and numerous others covered under subjects of Flexible AC Transmission Systems (FACTS) and Custom Power Systems (CPS). The need for power electronics modeling and simulation is driven by both existing and new applications.

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A comprehensive review of various benefits, technical issues, capabilities of digital time-domain simulation packages, and existing difficulties associated with digital time-domain simulation of power electronic switches and circuits is given in [1].

Objectives of the simulation include:

- verify an application design
- predict the performance of a system
- identify potential problems
- evaluate possible problem solutions

The simulation is specially important for a concept validation and design iteration during a new product development.

Power electronics applications are relatively new to many power system engineers. This guideline provides general procedures to help these engineers to make their own simulation cases as needed. The theories of power electronics are not in discussion. Attention is focused on the simulation of the interaction between the power electronic sub-system and the connected power system. Thus, a model for a power electronic switching device can be greatly simplified. More details about the device representation is presented in the later section of this paper. In the last section of the paper, the references related to various power electronics simulations are listed.

## 2. GENERAL CONSIDERATIONS OF POWER ELECTRONICS MODELING

### 2.1 Types of Problems

Power electronics modeling can be divided into two basic categories, depending on study objectives. The first category covers all steady state evaluations. The focus is on the power system response to the harmonics injected from a power electronics sub-system. Examples of this type include a study of the steady-state harmonic propagation in a transmission and distribution system, harmonic frequency resonance, system voltage and current distortion, filtering design calculation and performance evaluation, telephone interference analysis and system losses associated with harmonics. In this type of study, the harmonic current injection can often be assumed independent of the voltage variations at a point of common coupling (PCC), an electrically dividing point between the utility system and the customer circuit. Therefore, the power electronics sub-system can be greatly reduced to a shunt circuit equivalent.

The second type of power electronics modeling covers a much more extensive and complex range of practical problems. In many applications, operation of a power electronics sub-system depends closely upon the operation state of the connected system. To evaluate the dynamic and transient performance of a system with power electronics interfaces, the monitoring and control loops of the system, including detailed signal processing and power electronics device firing need to be modeled. Examples of this type of applications can be a SVC system, a Superconducting Magnetic Energy Storage (SMES), active power conditioning system and various adjustable speed drives applications. When modeling these applications, variations of system parameters need to be used to derive the power electronic controls so the output of the power electronics sub-system changes accordingly as demanded. Because in these cases, the power electronics sub-system directly affects overall system operation, a separate treatment of the supply system and the power electronics sub-system is unacceptable.

### 2.2 Frequency Domain and Time Domain Simulation

As far as the solution methods are concerned, there are two basic approaches: the frequency domain solution and the time domain solution. Digital computers can only simulate circuit phenomena at discrete frequencies or at discrete intervals of time (step size $\Delta f$ or $\Delta t$). This leads to truncation errors in all digital simulations.

Compared with the time domain calculation, a frequency domain simulation is more robust because a circuit solution is found at each individual frequency and truncation errors are not accumulated. The programs using this solution method often treat the non-linearity of a system as known current sources. For a harmonic evaluation, the frequency domain solution usually requires less computation time compared with a time domain solution. However, most available frequency domain solution programs have difficulties in handling the system dynamics, control interfaces and fast transients. The time domain solution is based on the integration over a discrete time interval. The numerical methods applied in different programs can use either iterative techniques or direct solution methods. The solution stability and accuracy achieved are closely related to the time step size selection. Because truncation errors can accumulate from step to step, the solution may diverge from the true solution if an improper time step is selected. The time domain simulation has great advantages over a frequency domain simulation in handling the system dynamics, power electronic interface and transients.

### 2.3 Tools for Power Electronics Application Simulation

According to their main functions, commonly used tools for power electronics related simulations can be classified into three groups.

1. Power electronics simulation tools
2. General transients simulation tools or EMTP type of programs
3. General harmonics simulation tools or frequency domain simulation tools

The tools of the first group may offer the best productivity if a detailed application topology and complicated operation controls need to be simulated and if the main interest of the study is the power electronics sub-system. These tools often have difficulties when an extensive utility network needs to be included in the simulation or when the main interest of the study is overall system dynamics and transients. In such cases, the EMTP type programs are usually more suitable tools. The currently available versions of the EMTP type programs may be less efficient for detailed power electronics modeling. However, these programs are very attractive for an application oriented power electronics simulation because these programs offer tremendous capability and flexibility in characterizing various types of power system components, including power electronics switches with reasonably simplified characteristics. As graphic interfacing features are gradually incorporated in these programs, a level of difficulty in using these tools will decrease.

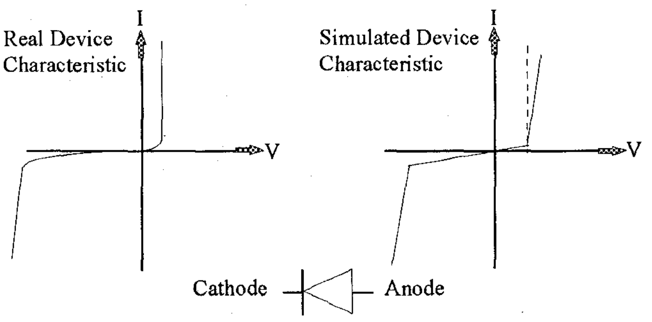
## 3. MODELING GUIDELINES

### 3.1 Representation of Semiconductor Switching Devices

For a power level application, the commonly used switching devices are power diode, thyristor, Gate Turn-Off thyristor (GTO) and Insulated Gate Bipolar Transistor (IGBT). Except for the diode that is a two-terminal, uncontrollable device, the others are three terminal controllable devices.

Thyristors are commonly used in applications where only turn-on control is required. The device can turn-off with the load commutation or by a forced commutation when required. GTOs have found an increased number of applications because of their gate turn-off and high power capabilities. The drawbacks of a GTO is its switching frequency limitation, around 1000Hz, and its high percentage gate turn-off current requirement, 1/7 to 1/5 of a load rating current. IGBT is another alternative that has become popular in industrial applications in recent years. The device has gate voltage control type turn-on and turn-off capability and the device can be switched at frequencies up to several tens of kHz in practical applications. At the present time, IGBT applications are basically limited by its power rating. As of today, 3 MW IGBT based drives are commercially available.

For most power electronic simulations addressed in this document, a simplified device characteristic is acceptable. Therefore, instead of trying to represent the switching characteristic of a diode as shown on the left in Figure 1, a simplified characteristic or an idealized characteristic, shown by solid and dotted lines respectively on the right, can be used.




*Figures 1. Actual and Simplified Switching Characteristic of Diode Device*

Representing the reverse recovery characteristic, leakage current, and forward voltage drop of a diode is often not necessary for an application study. In commonly used simulation programs, the simplified diode model may be available as a built-in device or it can be realized with a voltage controlled switch. If the diode model does not allow to specify on-state and off-state resistances, they can either be neglected with minimal loss of accuracy or can be modeled by inserting a series resistance for on-state loss and a parallel resistance for off-state loss.

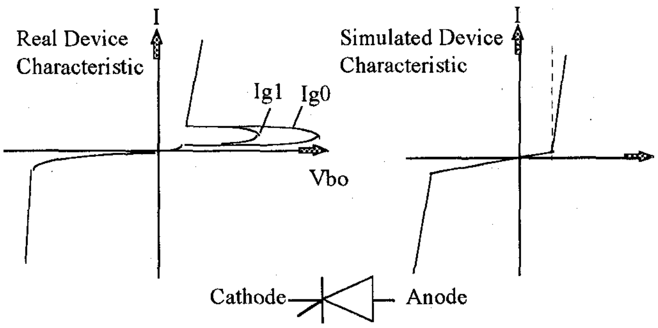



*Figure 2. An Actual and Simplified Switching Characteristic of thyristor Device*

In Figure 2, switching characteristics of an actual, a simplified and an idealized thyristor are compared. To represent the simplified thyristor device, the turn-on control is added on the simplified diode model. If the control is applied continuously, this switch simulates the diode which allows unidirectional current flow when the switch is forward biased. Delaying the gate pulse allows control over the turn-on instant of the forward biased switch.

For numerical simulations, if the gating circuit power requirement is excluded from the study, there is very little difference between modeling a GTO, IGBT or any other three-terminal, controllable, unidirectional current flowing device. The device can all be represented by a simplified switch with gate turn-on and turn-off controls. The different switching characteristics can be realized by applying different firing controls.

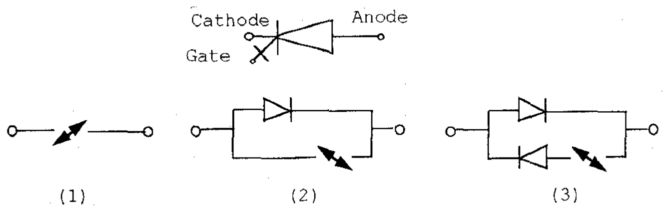



*Figure 3. Alternatives for Three-terminal Controllable Switching Device Representation*

In many actual power electronics applications, in order to provide a continuous current flowing path for an inductive load, a reversal diode (free wheeling diode) is used in parallel with a controllable switching device to form the basic power electronics switching unit. However, several alternatives are available for implementing this basic switching unit in digital simulations.

Considering only the terminal equivalent at the connection point of the application, the simplest model that can be used to present one leg of the bridge rectifier or inverter can be constructed with one simplified bi-directional current flowing switch with gate controls as in Figure 3 (1). This model uses the least number of devices for a given power electronics topology. The problem with this bi-directional current flowing switch representation is that it fails to correctly represent an operation state during the idling period. This can be better explained with an example, Figure 4, of a simplified inverter scheme used in a UPS.

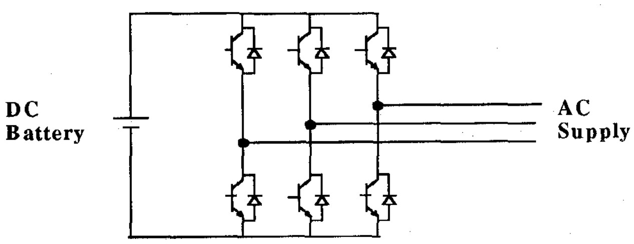



*Figure 4. Simplified Inverter Scheme in a UPS System*

When all the controlled switching devices are blocked, the dc battery is being charged through the rectifier bridge consisting of six reversal diodes. However, if the ideal bi-directional switches are used, while the UPS is idling, the battery will not be charged by the ac supply.

When the idling mode needs to be more realistically represented, the simple bi-directional device model can be improved with a paralleled reversal diode as shown in Figure 3 (2). When not only terminal effects but also individual device current carrying conditions are of interest, a further improvement on the model can be made by adding another diode as shown in Figure 3 (3).

It should be noted that for some programs, multiple switch connections on the same circuit node can lead to a singular system admittance matrix. When using a program with such restriction, a small series resistor or inductor can be used to create intermediate nodes and avoid the problem.

### 3.2 Representation of Power Electronics (PE) System

If every individual power electronic switching device is represented, a system model containing power electronic applications can easily reach a complication level that is hard to be implemented. For an example, a HVDC terminal contains tens to hundreds series and parallel thyristor devices in one converter leg for high voltage and MVA ratings. Obviously, if one wants to represent each individual thyristor device in this HVDC system model, one will quickly end up with a huge model.

Fortunately, (except for some failure mode analyses), for the purposes of most application simulations it is not necessary to represent all individual devices. What need to be simulated usually is the terminal characteristics of a power electronic sub-system and how it interfaces with the connected system. Thus, the following procedures can be used to reduce the modeling complexity:

- Using one or a few equivalent devices to represent series and parallel combination of a group of devices
- Represent power electronic loads with similar characteristics by an equivalent
- Use the simplest device model which is appropriate for the application
- Represent a power electronic sub-system by equivalent source injection whenever it is acceptable
- Represent only the front end of the drive system when the major concern is utility interfacing
- Include the system dynamic and controls only when necessary
- Use modular approach for large scale model development

In this guideline, detailed considerations related to applying these system reductions are presented. Some important issues addressed are:

- Harmonic cancellation when multiple loads are represented by their lumped equivalent
- Existing system distortion.
- Appropriate source topology for PE sub-system representation
- System unbalance
- Effects of a dc link or the inverter side connection on the front end interface with the power supply system
- Current or voltage sharing among the parallel or series switching devices
- Switching loss prediction

### 3.3 Representation of the Power System

Similar to the situation in a power electronics sub-system, a power supply system can easily extend to a large electrical and geographic radius and become too complicated to model. Therefore, the power system needs to be simplified. The proper level of system reduction depends on the study objectives.

If the purpose is to characterize the harmonics generated by a particular type of power electronics application, the power system model can be significantly reduced. When a pre-existing voltage distortion level at a power electronics interfacing bus is low, the rest of the power system can be satisfactorily represented by one or a set of first order equivalents connected to the bus at a higher system voltage level. For an example, if the power electronics application interfaces with the system at the low voltage bus of a step-down transformer, the equivalent of the system can be placed on the high voltage bus of the transformer. When a pre-existing voltage distortion level is greater than 2%, one needs an adequate harmonic source to properly represent the background distortion.

If the objective is to evaluate effects of the power electronics on a connected utility system, the model shall be extended to cover all sensitive loads (i.e. rotating machines and all other major power electronics) within a concerned electrical radius. Special attention is needed if an unbalanced system condition is involved.

Extensive power system model is required for a harmonic propagation and resonant study. The main system components and dominant topology need to be kept in the power system model. Capacitor and filter banks, all nonlinear passive circuit components, and all other harmonic injection sources should be represented. Frequency dependent characteristics of the system components might need to be considered.

### 3.4 Representation of System Controls

The system control is one of the most important aspect of a power electronics simulation. As illustrated in this paper, a switching device is greatly simplified. The proper switching performance of a device is realized via appropriate gate controls. Modeling of power electronic controls consists of three steps:

1. Monitoring and sampling
2. Signal processing and control reference derivation
3. Device gating signal generation.

Most simulation tools provide some means to implement system controls. In some later developed programs, the control block diagram and flow-chart structures are supported for modeling different levels of system controls. Using these tools, a user can define the specified controls in a simulated system with great flexibility. Some key issues ensuring a correct control modeling is briefly mentioned below. These issues are more thoroughly treated in the guideline with illustration examples.

- For a time domain simulation, the highest resolution for a signal sampling is determined by a selected time step. In general, this presents no problem for analog control. However, for digital control simulation, if the selected time step is too large and if the simulated sampling resolution is significantly different from the real system sampling resolution, significant errors can be introduced and even lead to instability.
- For a time domain simulation, the computation time does not reflect the simulated control logic response time. User should always remember to introduce a reasonable time delay to match with the limitations of the control hardware and software.
- When modeling a control response, it is important to understand the program introduced time delay between the primary system and the control interface. For an example, the control model may introduce one (could be more than one) time step delay because of structure and solution method of the program. This may not cause problems in some simulations. However, if the modeled control logic makes this time delay caused error accumulate over the time, it can eventually result in the solution divergence. The problem can be corrected in most cases by reducing the size of the time step or avoiding the possible accumulation mechanism in the control model.
- Different methods may be used to synchronize power electronics gating signals with required system references. In many cases, a real phase-locked-loop (PLL) can be greatly simplified to reduce the modeling system complexity. However, when the system contains significant waveform distortions, either harmonics or transient disturbances, a practical PLL with all signal filters should be carefully implemented in the control model in order to accurately predict control response. This is particularly important when the objective of the simulation is to verify control design and to evaluate the response of a power electronic application to primary system dynamics.
- All power electronic devices have their limit in switching frequency. When a load commutation or a standard PWM type scheme is simulated, the highest switching frequency in the simulation is controlled by the system frequency or by a carrier frequency. Even considering a variable carrier frequency, the number of switching per fundamental frequency cycle is known and the highest switching frequency can be made under a physical limit of the simulated device. However, if the device firing is determined by a simple comparison between the system control reference and the system output, a device switching may take place in simulation whenever a comparison difference is detected. Therefore, the switching frequency becomes highly dependent on the time step size, and the average switching frequency becomes unpredictable. When using this type of firing logic, user should always take extra measures, such as introducing a hysteretic loop, to ensure that the modeled device is working under its physical switching capability.

### 3.5 Snubber Treatment in PE Modeling

The simulation programs using trapezoidal integration method are inherently prone to spurious oscillations (also known as chatter) in capacitive and inductive circuits when subjected to sudden changes such as step change in voltage, current injection and switching. Some EMTP type programs take special measures to detect and remove these oscillations in which case it is not a concern to the simulation engineer. Otherwise, some of the measures listed later in this section may have to be implemented to obtain correct results.

The finite nature of the simulation time step of the EMTP type programs also poses another problem for power electronic circuit simulation which necessitates use of snubber circuits across fast acting power electronic switches. Note that in some situations the snubber R and C values of the actual system may or may not work in simulations using some programs. In this case, the R and C values of the snubbers needed for stable simulation is primarily dependent on the time step and secondarily on system configuration (capacitors and inductors in the system), and the load current level. Programs using special features such as variable time steps (very short time steps during switching) or interpolate switching (simulate the switching very close to the required instant using linear interpolation between time steps) do not require fictitious snubber circuits. For using a program that does not address these problems, one of the following measures or their combinations can be taken to prevent numerical instability in the simulation:

- Select a smaller time step
- Use artificial snubber circuits
- Introduce a small smoothing reactor for dc links
- Introduce proper stray capacitances in the system model
- Provide a parallel damping for lumped system

### 3.6 Simulation Errors and Control

Errors in a PE simulation can come through the following channels:

- switching device approximation and system reduction
- added circuit elements for numerical oscillation control
- control system simplification
- time step related truncation
- program structure and solution method introduced interfacing time delay
- incorrect system initial conditions

For application simulations, some errors resulting from the system simplification and measures of numerical oscillation control are acceptable. The fourth and fifth items in the list can be controlled by reducing the time step size. A recommended time step size should not be greater than 1/5 to 1/20 of the period of the highest concerned frequency cycle. For an example, for an IGBT inverter simulation with 5000Hz PWM switching, a selected time step could be 10 μs. However, if the objective of the simulation is to see the detailed transient at the terminal of the induction motor which is fed by the inverter through a section of the cable with an 1.0 μs travel time, an adequate time step should be 0.2 μs or smaller.

Errors caused by incorrect system initial conditions can be reduced by just letting the simulation run for a period of time to reach a corrected initial condition. This takes more computing time, but saves in model construction, especially if the program allowed to restart. There are some methods developed which help to accelerate the system into the correct initial condition quickly. The examples of using some of these methods can be found in the related reference listed in this paper.

## 4. SUMMARY OF DOCUMENTED EXAMPLES

Summary of three simulation examples related with power electronics application are presented in this paper. The example can be either a real case study or exercise for illustration purposes. For each example, the following important items are documented.

- Objectives of simulation and major considerations
- Configuration of modeling system, important system components and parameters
- Assumptions and specified accuracy requirement
- Procedures of system simplification
- Control block diagram, detailed control function description and complete listing of the control constants.
- Table or figure summary of important simulation results

The details of these examples are given in a separate document.

### 4.1 Simulation of the Pulse Width Modulation (PWM) Voltage Source Inverter (VSI) Adjustable Speed Drive (ASD)

The first example is a PWM-VSI ac drive simulation using EMTP. The ac drive consisting of a three-phase diode bridge rectifier, capacitive dc link and three-phase PWM output inverter. The switching losses of the drive are a secondary order consideration in the analysis and the idealized switching characteristics are used.

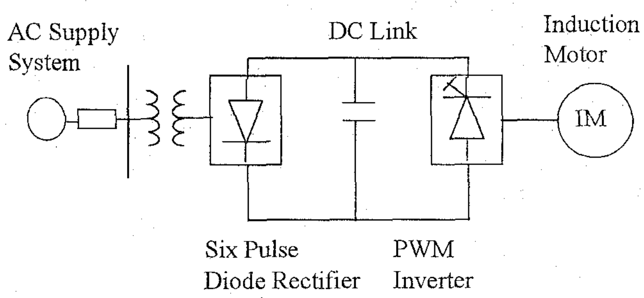



*Figure 5. Electrical Circuit Configuration of an Adjustable Speed Drive*

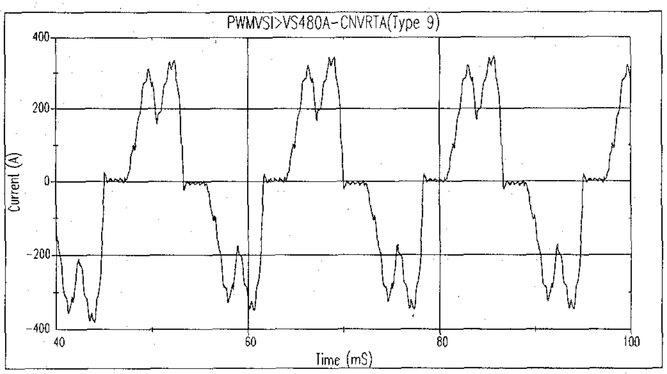



*Figure 6. Simulated AC Input Current of A PWM-VSI Adjustable Speed Drive*

The built-in diode models are used to construct the front end rectifier. The same switching devices with added open/close controls are used to represent output inverter

IGBTs. The EMTP input data modules are used to build this example case. Both the output reference frequency and the PWM carrier frequency are made to be controllable. Modeling of a signal processing and firing pulse generation is illustrated in this example. The motor load of the drive is represented by its R+jX equivalent branch. The simulated ac input current, carrier and reference signal for the PWM control, ac output voltage and current are presented in Figure 6 through Figure 8.

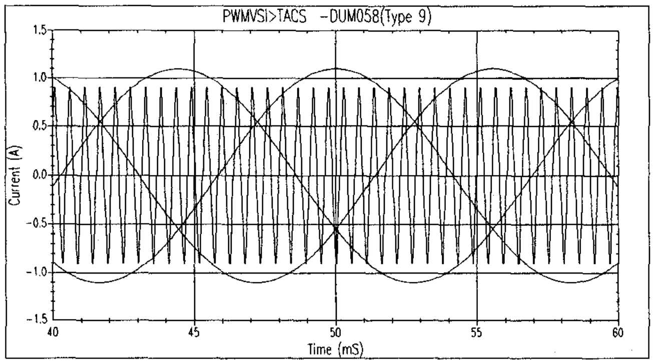



*Figure 7. Simulated Carrier and Reference Signals for A PWM- VSI Adjustable Speed Drive Firing Control*

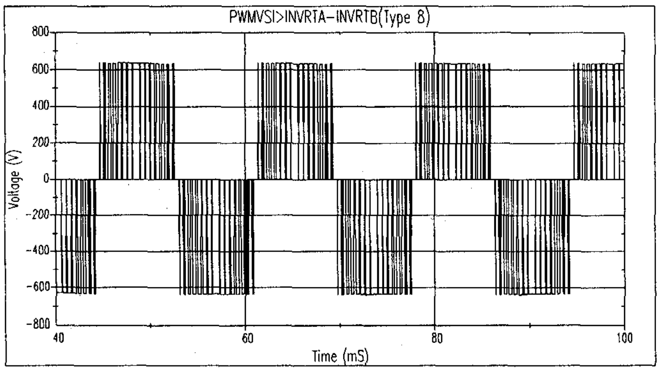



*Figure 8. Simulated AC Output Line-to-line Voltage of A PWM-VSI Adjustable Speed Drive*

## 4.2 Simulation of Voltage Notching Caused by Operation of Current Source Inverter (CSI) ASD

The second example is based on a case study. The involved system is illustrated by the one line diagram in Figure 9. The 25 kV distribution system is supplied through a 10 MVA transformer from the 144 kV transmission system. The customer causing the voltage notching problems has a 6000 hp induction motor supplied through a CSI adjustable speed drive[2]. This drive is at a 4.16 kV bus supplied through a 7.5 MVA transformer. Harmonic filters (5th, 7th, 11th) are included to control the lower order characteristic harmonics of the six pulse drive. The actual adjustable speed drive and motor load were represented to reproduce the notching oscillations observed in the measurements.

Operation of the 6000 hp motor and drive resulted in significant oscillations on the 25 kV supply system. These oscillations caused clocks to run fast at the customer with the 6000 hp motor (clocks were fed separately from the 25 kV system) and failure of surge capacitors on the 800 hp motor at the customer located on the parallel feeder. The objective of the simulation is to identify the power quality problem associated with this 6000 HP, CSI ASD operation. The simulation was carried out using EMTP.

The worst notching problems are associated with a firing angle at about 70% load. The simulated waveform for the 25 kV bus voltage is shown in Figure 10. The oscillations at each commutation point are in good agreement with the measurement results.

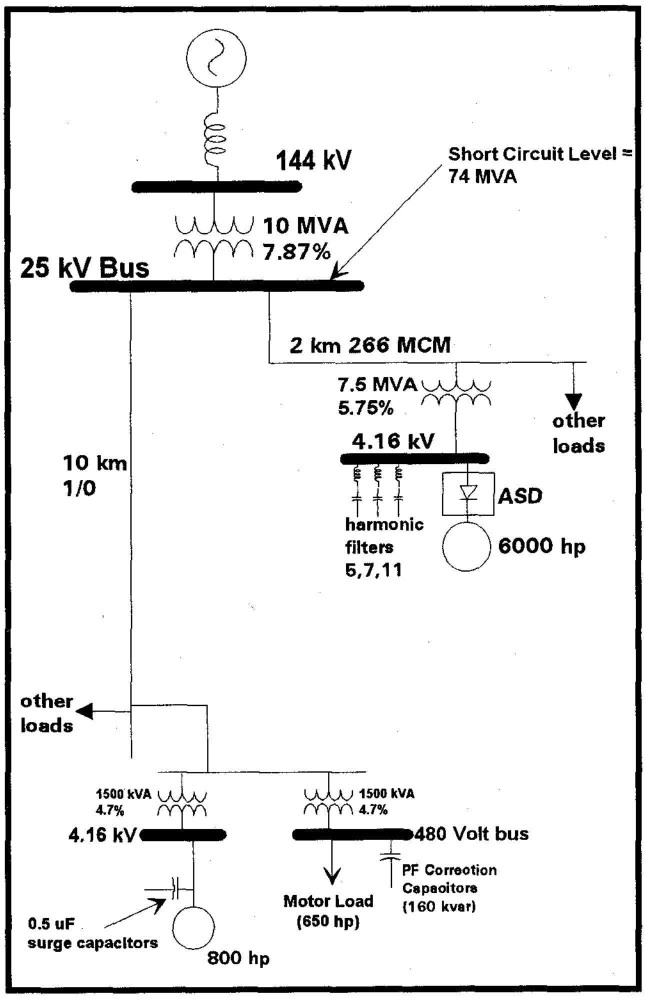



*Figure 9. One line diagram for the first example system.*

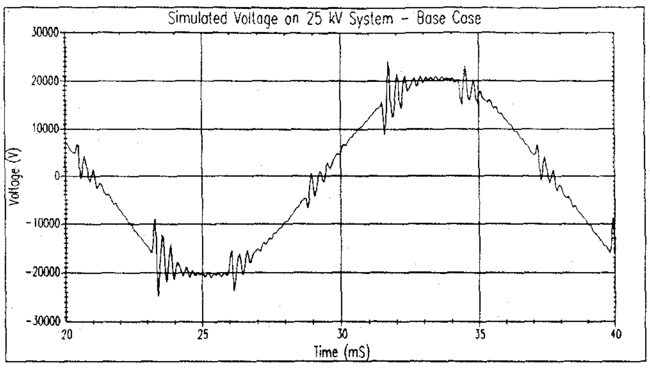



*Figure 10. Simulated 25 kV system voltage with drive operating.*

Figure 11 illustrates the voltage waveform at the 4.16 kV bus where the 800 hp motor surge capacitors cause magnification of the oscillations. The potential for problems at this location is quite evident.

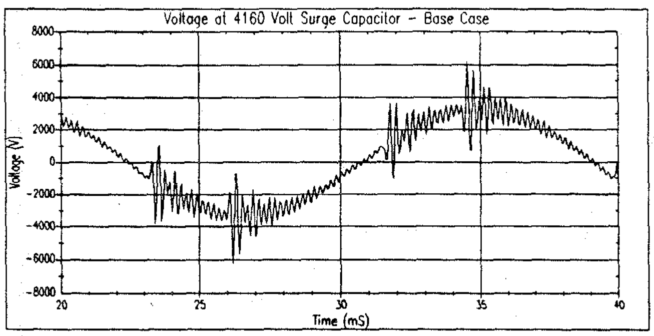



*Figure 11. Simulated waveform at surge capacitor location (4.16 kV bus of customer on parallel feeder)*

### 4.3 Simulation of HVDC Terminal and Shunt TSC/TCR Compensation

The third example is an illustration case for modeling of an HVDC system with shunt TSC/TCR compensation at the inverter bus [3]. The simulation example is made using PSCAD/EMTDC. The schematic system shown in Figure 12 is a modified version of the GIGRE Benchmark Model for HVDC Control Studies [4].

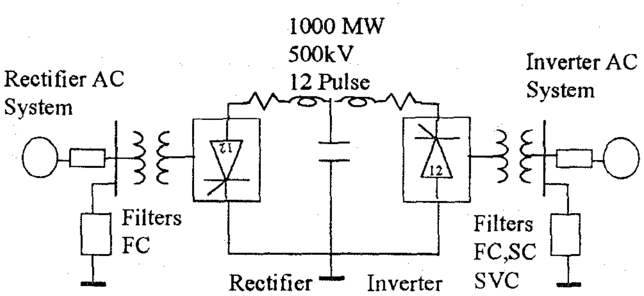



*Figure 12. Study System*

The inverter short circuit ratio has been reduced from it original value of 2.5 to 1.5 to make the study more interesting. The dc link is a 1000MW, 500kV, 12 pulse monopolar system. There are damped low and high pass filters at each converter terminal to reduce the distortion on the ac bus. The control scheme for the HVDC system consists of a rectifier current controller with the gamma controller.

The SVC system is a -200/+300 MVAr, 12 pulse, TCR and TSC (two stage) combination connected to the inverter bus through a step up transformer. The SVC controls are designed to coordinate the control of TCR and TSC in such a way that the combined susceptance of the SVC is continuous over its entire operating range. The basic control mode is voltage control and has as a voltage droop built into the controls. Several studies to evaluate the recovery to full power after a contingency were simulated [3]. The performances of several compensation options were compared. These options included fixed capacitors (FC), SVC, synchronous condenser (SC) and half-and-half mix of the two (SVC+SC).

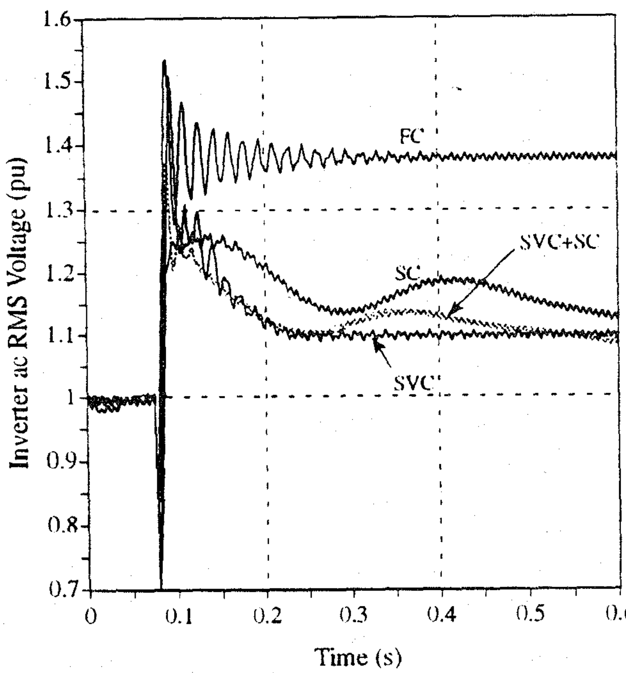



*Figure 13 Inverter AC Voltage Following a Permanent DC Block*

Figure 13 shows the typical results obtained from the simulation for a permanent dc block. The fixed compensator case does not control the overvoltage; however, all other options do. The SVC option is the fastest to respond followed by the SVC+SC option and lastly the SC option. This simulation setup can be used to conduct almost any type of performance study including a thyristor miss-fire in HVDC valve group or in the SVC itself.

## 5. CONCLUSIONS

The appropriate characterization of the power electronics is very important in power system simulations involving power electronics operations. In most these simulations, detailed representations of the power electronics are not necessary. Depending on the objective of a study, the involved power electronics sub-system can be always reduced to some extent with minimal loss of accuracy.

Numbers of the digital computation tools are capable of simulating power electronics. However, in power systems engineering community, the EMTP type of programs are more commonly used. This results mainly from the great capabilities and flexibility of these programs in handling conventional power system dynamics and electro-magnetic transients beside their capabilities of handling power electronics. With an adequate power electronics device and circuit simplification, the EMTP type of programs are powerful for modeling various types of power electronics applications. Because these programs are based on the time domain solution method, the dynamic interaction between the power electronics and the rest of the system can be easily incorporated in simulation.

The important considerations for simulating power electronics applications have been summarized in this guidelines. Three modeling examples using the EMTP type of programs were presented. The procedures used to implement power electronics models in these examples are valuable for using other digital simulation tools.

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