

TIME DOMAIN METHODS FOR THE CALCULATION OF HARMONIC PROPAGATION AND DISTORTION

By
C.J. Hatziadoniu

Department of Electrical Engineering
Southern Illinois University
Carbondale, IL 62901-6603
hatz@siu.edu

8.1 INTRODUCTION

Numerical methods for the computation of harmonic propagation and distortion differ in the manner in which they represent the harmonic sources and the system impedance. Iterative methods (e.g. harmonic load flow) use a phasor representation of these parameters. Time domain methods, on the other hand, use a time representation of the system elements and the harmonic sources. Thus, they are generally more accurate than the iterative methods.

The simplest system modeling for harmonic calculations considers rigid harmonic sources and linear system impedance [1-3]. A rigid harmonic source produces harmonics of only characteristic orders with a pre-defined and constant magnitude and phase. The linear impedance is the result of mainly transmission lines and compensation devices. A model which includes rigid harmonic sources and linear elements can be solved by an iterative method with the same accuracy as a time domain simulation. This is because a linear model has a phasor representation and the principle of superposition is applicable.

The presence of non-linear and time varying elements in the system model can significantly change the manner by which harmonic currents and voltages propagate through and interact with the network. Some of the effects that may appear and which are better studied by time simulation are [3-7]:

a) Under ideal conditions, harmonic devices (converters, transformers, etc.) produce harmonics of characteristic orders. For example, in symmetric saturation a transformer produces all odd orders, if its terminal voltage is near sinusoidal. An ac/dc 6-pulse converter produces orders such as 1,5,7,11,13..., if its terminal voltage is nearly sinusoidal and balanced and

its dc current is nearly free of ripple. Most of these devices will produce uncharacteristic orders if their terminal conditions are not ideal. Examples are the inrush current in a transformer and converters operating with unbalanced voltages.

b) The switching function of power converters is equivalent to a modulation\demodulation between ac and dc quantities [8,9]. This results in interactions between harmonics of different order. Such interactions are not predictable by linear time invariant models. The study of this phenomenon is important, especially in systems likely to have significant harmonic distortion because a path is provided through the converter for unrelated harmonics to interact.

c) The gate control of power converters may interact with harmonics on the system through the synchronizing loop. This interaction in combination with the modulation\demodulation property of power converters can provide a feedback loop with significant gain for the amplification of harmonics. Extreme phenomena that can result from these interactions include limit cycles and harmonic instability.

The following sections summarize the methods for the simulation in the time domain of non-linear and time varying systems. The methods discussed are suitable for widely used programs such as EMTP.

8.2 REPRESENTATION OF SYSTEM IMPEDANCE

There are two approaches for the representation of the system harmonic impedance that are used in time simulations. The first approach requires the detailed representation of the network devices, which are primarily responsible for the impedance properties.

The second approach uses the dynamic equivalent of the impedance.

A. Detailed Modeling. Detailed modeling of the network involves 3-phase models of the network devices. The following is a summary of the modeling approach for various devices. A detailed description of network modeling is presented in a previous chapter [2,3].

The classification of transmission line length is determined by the wave length of the highest harmonic frequency of interest. Long transmission lines are represented by distributed parameter models. Medium lines can be represented by cascaded Pi-equivalents. Short transmission lines are usually represented by their sequence impedance using lumped RLC branches. In some distribution systems the capacitance may be neglected for the overhead lines. Mutual inductance may be included for medium and short lines to reflect coupling between the phases.

Saturation and hysteresis modeling is required for transformers, if significant overvoltage is anticipated at the transformer terminals.

Compensation and harmonic filters are modeled by lumped RLC branches.

System load contributes significantly to the damping around resonant frequencies. Normally, a parallel RL representation is used based on the aggregate power of the load.

B. Dynamic Equivalent Modeling. This approach yields a network model which retains only a selected group of the buses (those of interest to the study). Subsequently, lumped RLC branches are used to represent the driving point and transfer impedances of the selected buses.

The driving point impedance is equivalent to the Thevenin impedance of a system bus. Physically, the driving point impedance shows the effect of the bus harmonic current injections on the bus voltage, as in (8.1).

With reference to (8.2) the transfer impedance between two buses, k and m, shows the effect of current injections into bus m on the voltage of bus k and vice versa.

$$V_h^k = Z_h^{kk} \cdot I_h^k \quad (8.1)$$

$$V_h^k = Z_h^{km} \cdot I_h^m \quad (8.2)$$

The driving point and transfer impedances can be calculated either from measurements or from frequency scans of the complete network model. Subsequently, the values of equivalent RLC branches

between the selected buses are calculated. Usually, several series RLC branches are connected in parallel to approximate the multiple resonances of the system impedance. The resulting model is a linear, lumped, 3-phase circuit and it contains the system resonant frequencies and their damping for the desired range of frequencies. Inclusion of non-linear elements is done externally to the model.

C. Simulation of Large Networks. With reference to Figure 8.1, large networks are modeled by a combination of the two approaches. A detailed network model is obtained for the part of the network that is of immediate interest. The remaining network is approximated by its dynamic equivalent at the interconnection buses.

This modeling philosophy effectively decreases the size and length of a time domain simulation. Routines that assemble the network dynamic equivalent are available in programs such as EMTP [10].

8.3 REPRESENTATION OF HARMONIC SOURCES

There are three approaches for representing harmonic sources in a time domain simulation: by voltage or current injection through a rigid source, by the switching function of the converter, or by a detailed model of the converter.

A. Rigid Harmonic Sources. The generation of

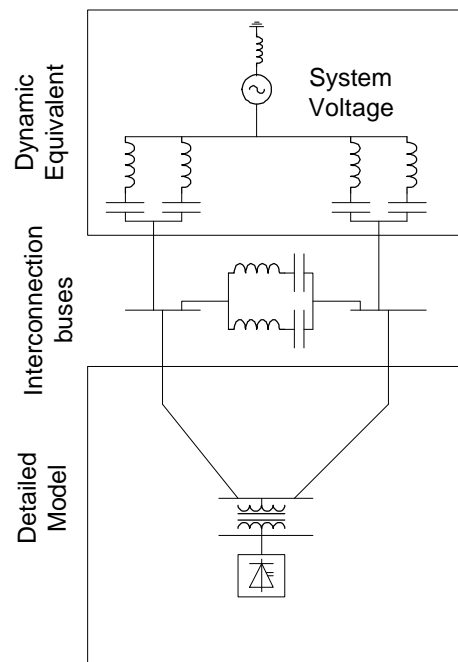


Figure 8.1. Simulation of large networks using the detailed and dynamic equivalent approaches

harmonics by commercial loads has a distributed nature. An aggregate model can be constructed for such loads using ideal circuit sources (usually current sources) [1]. The equivalent source is composed of the harmonic spectrum of the load and does not change according to the network response (i.e. a rigid source).

The value of the rigid harmonic source is given in time according to (8.3) for the desired number, N, of studied harmonics. The magnitude of the fundamental can be obtained from the aggregate power of the load. The magnitude of the harmonics can be obtained from measurements.

$$i(t) = I_1 \cdot \cos(\omega t + \varphi_1) + \sum_2^N I_h \cdot \cos(h \cdot \omega t + \varphi_h) \quad (8.3)$$

The phase angle of the fundamental in (8.3) is obtained from the system load flow and the load power factor. The phase angles of the harmonics are not critical for the calculation of distortion in models containing one harmonic source. In the presence of multiple sources, harmonics of the same order may be amplified or attenuated according to their relative phases. Therefore, the correct estimation of the harmonic phase angle should be used in (8.3). If the harmonic source has odd symmetry with respect to its fundamental, the harmonic phase angle can be computed directly from the phase of the fundamental, according to (8.4).

$$\varphi_h = h \cdot \varphi_1 + (h + 1) \frac{\rho}{2} \quad (8.4)$$

An expression in the form of (8.3) is included in the time step loop of the simulation for each phase. The expression is evaluated at each integration step and the corresponding network source is updated. In ATP [12] this can be done by coding (8.3) into MODELS and using a controlled source in the network. In PSCAD\EMTDC the network source of (8.3) can be directly written in FORTRAN as a user defined model [11]. Modeling is possible using TACS controlled sources in conjunction with "FORTRAN" statements. However, this is not an efficient method if a large number of harmonics is simulated.

B. The Switching Function. The terminal characteristics of many converters can be approximated in the time domain by the converter switching function [1,8,9]. Two typical applications are presented for the definition of the switching function.

a) Thyristor Controlled Reactors. With reference to Figure 8.2, the switching function of the TCR (for 1 phase) equals 1 when the phase thyristors are conducting and 0 when the phase thyristors are turned off. At steady state, the switching function of the TCR is symmetric around the voltage zero crossing as is evident in Figure 8.2. Under steady state conditions, the voltage across the inductor of the TCR is shown in Figure 8.3. It can be written as the product between the bus voltage and the TCR switching function according to (8.5). The time function of the current the TCR injects into the system is found from (8.6).

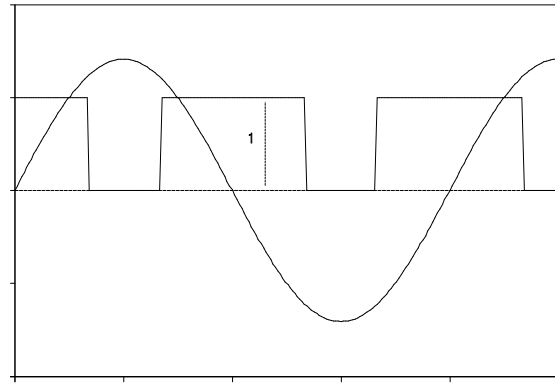


Figure 8.2. Definition of the switching function of a TCR

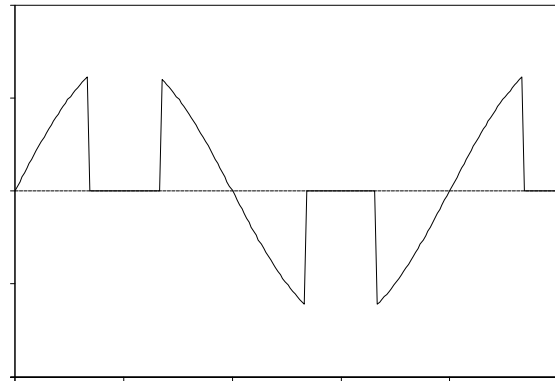


Figure 8.3. The steady state voltage across the inductor of the TCR

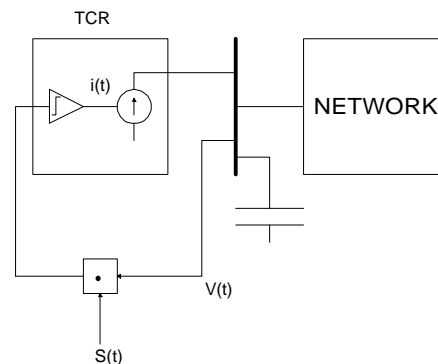


Figure 8.4. Time domain simulation of the TCR through its switching function

$$V_{TCR} = V_{sys} \cdot S(t) \quad (8.5)$$

$$i_{TCR}(t) = \int_0^t V_{TCR} \cdot dt \quad (8.6)$$

Figure 8.4 depicts the simulation of a TCR by its switching function. The device appears as a current source to the system.

b) AC/DC Converter. The switching function of the line commutated ac/dc converter is shown for one phase in Figure 8.5. It is 1, when the dc current flows into the phase in the positive direction. It is -1 one, when the dc current flows in the negative direction and zero otherwise. The switching functions of the three phases are symmetric and balanced. At steady state, they lag the system voltage by the converter delay angle. Equations (8.7) describe the ac current output of the converter. The dc voltage at the converter dc terminals is given by (8.8).

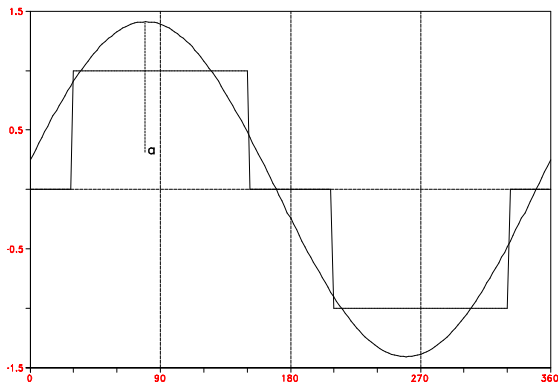


Figure 8.5. Definition of the switching function of a six-pulse ac/dc converter

$$\begin{aligned} i_a(t) &= i_{dc}(t) \cdot S_a(t) \\ i_b(t) &= i_{dc}(t) \cdot S_b(t) \\ i_c(t) &= i_{dc}(t) \cdot S_c(t) \end{aligned} \quad (8.7)$$

$$V_{dc}(t) = V_a(t) \cdot S_a(t) + V_b(t) \cdot S_b(t) + V_c(t) \cdot S_c(t) \quad (8.8)$$

Figure 8.6 shows the time simulation of the converter. The device appears as a current source from the ac side and as a voltage source from the dc side.

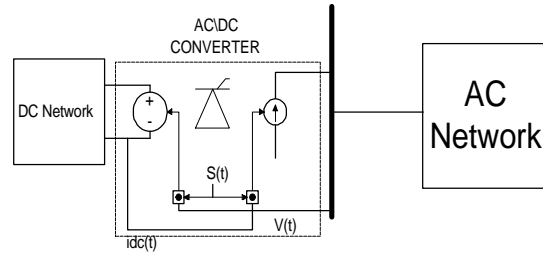


Figure 8.6. Time domain simulation of the six-pulse ac/dc converter

Other converters, such as the forced commutated voltage source inverter, can be represented by an appropriate switching function. The representation of a converter with its switching function allows interaction between the converter input and output quantities. It is, thus, more realistic than the representation by a rigid source. Some of the phenomena that can be studied through the switching function and that cannot be studied by the rigid source representation are: the modulation\demodulation properties of the converter, which account for interaction between different harmonic orders; the generation of non-characteristic harmonics; the propagation of dc harmonics in the ac side; and operation under unbalanced voltage or current.

The switching function is primarily a steady state concept. Thus, it is assumed that the control system delivers the ignition pulses at regular intervals and uninterrupted. It is also assumed that line commutation is completed successfully. Therefore, detailed representation of the converter control system is not required. Some types of interactions between the network harmonics and the converter controls (such as the onset of harmonic instability) can be detected, however, by introducing some detail in the representation of the synchronizing loop [9].

Figure 8.7 shows a possible simulation in the EMTP of the synchronizing loop of an ac/dc converter in conjunction with its switching function. With reference to this figure, the switching function is represented by a user defined point-by-point function. Its x-axis corresponds to the equivalent of one period. A ramp is used to scan the switching function. The ramp is synchronized with the commutating voltage of the corresponding phase. A circuit detects the voltage zero crossings and resets the ramp. The phase lag with the line voltage can be obtained by comparing the ramp with the converter delay angle.

The model of Figure 8.7 allows for interaction between voltage harmonics and the gate control. In the constant current operating mode of the converter, the use of a voltage controlled oscillator (VCO) desensitizes the synchronizing loop from the system

voltage waveform [8]. This model, therefore, could be more appropriate for inverter operation, since the firing pulses are then more susceptible to jitter by harmonics in the line voltage. Thus, certain phenomena resulting from this interaction, such as harmonic instability, can be detected without using a complex model of the converter.

Another system study that can be conducted with the switching function is the harmonic interaction between two or more converters in near proximity. The network is represented by its dynamic equivalent. This may include only the buses of the interacting converters, such as in Figure 8.1. Each converter is then represented by its switching function and its synchronizing loop. A time simulation of the system can predict with fair accuracy the changes in the system harmonic propagation and distortion as result of the interaction among the converters.

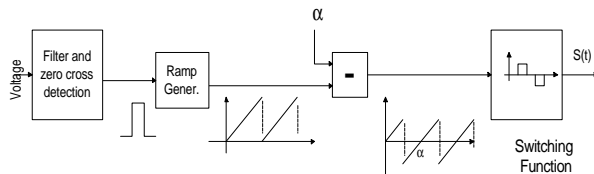


Figure 8.7. Time domain representation of the synchronizing loop in conjunction with the switching function of a converter

C. Detailed Simulation of the Converter. This requires the detailed representation of the converter controls and the converter circuit [1,4-7]. Simulation of a detailed converter model is time consuming. Therefore, this model is not recommended for a general purpose harmonic study. It is more suitable for verifying the design of the converter control and studying its response to transient phenomena.

8.4 TIME SOLUTION OF THE SYSTEM MODEL

There are three stages in obtaining a time solution of the system model.

A. Steady State. Most transient simulation programs, such as EMTP, can calculate the system steady state for the linear part of the network excited by the sinusoidal sources only. Some non-linear elements in the system model must be initialized separately. The flux of non-linear inductors is one of the variables that must be initialized in this manner, so that symmetric saturation can be observed. If the flux is not initialized properly, the ensuing transient from the inrush current may last for several seconds. In some programs, initialization of the non-linear inductor is obtained approximately by involving the element's unsaturated

inductance in the steady state solution. In this manner, the dc offset of the flux is minimized and the duration of the transient is reduced.

The part of the system model that involves the simulation of the converter synchronizing loop and switching function requires separate initialization. This can be done approximately as follows: First a steady state solution is obtained by representing the converter as an independent source at fundamental frequency. The source can be calculated from the converter's power and power factor. Subsequently, the steady state solution at the converter terminals can be used to initialize the phase of its switching function along with the other variables in the synchronizing loop.

B. System Run. Start-up of the simulation is followed by a transient interval. There are two distinct causes for this: The excitation of the network natural frequencies and the interaction of the system current and voltage with the converter controls. The latter occurs at low frequencies and may last for a few seconds. The former lasts for a few fundamental cycles. The transient can be as short as one or two fundamental cycles, if the system model is properly initialized.

Usually, a run of ten fundamental cycles is obtained. At the end of the run the system steady state is verified. Verification of steady state for non-linear inductors could be done by checking the symmetry of the current and flux. Verification of steady state for an ac/dc converter represented by its switching function could be done by checking of its average dc current. The average dc current can be observed from a low pass filter. At steady state, this current is constant.

C. Derivation of Frequency Response. The last stage of the solution is to obtain the frequency components of the desired voltages and currents and evaluate their distortion. This is done for the last fundamental cycle of the system response obtained from the time solution. Most programs, including EMTP and PSCAD\EMTDC, have appropriate utilities for this purpose [10,11].

8.5 SUMMARY

Harmonic load flow and linear time domain simulation are widely used methods for the preliminary study of harmonics. They represent the system by rigid harmonic injection sources. They are successful in systems with low voltage and current distortion. In these systems the effects of non-linearity and converter modulation\demodulation are not

pronounced and they do not significantly alter the harmonic profile of the currents and voltages.

Weak systems can produce significant harmonic distortion. Then, a detail representation of system non-linearity and power converters is required to accurately assess the harmonic profile of the system. Non-linear time domain simulation is more appropriate for this purpose. This can be conducted in programs such as EMTP and PSCAD\EMTDC.

Non-linear time domain simulation is time consuming and it is not, therefore, the most desirable means of study. Some savings in complexity can be gained by these two modeling approaches. The use of dynamic equivalents of the network can significantly reduce the system complexity. The representation of the converters by their switching function provides good accuracy with less complexity compared to the detailed modeling of the converter.

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