MODELS OF A DISTRIBUTION STATIC CONDENSER (STATCON) FOR EMTP

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Abstract: **This paper describes simulation models developed for a distribution level Static Condenser (STATCON), a Custom Power Device. Depending on the time constants involved, the simulation studies for a STATCON are classified into three types - dynamic, slow transient and fast transient studies. STATCON models are developed for each type of study. The various components of a STATCON such as the dc/ac inverter, the gate trigger generator, the control system and the output filter are modelled using a modular approach. The three models differ only in the modules used for the dc/ac inverter and the gate triggering circuit. Different switch modeling techniques are used for each model. A new switch model, called the transient behavioral model, developed by the authors, is used for the slow transient model. The consistency of the switch models is demonstrated first using a buck converter and then a STATCON. Finally the use of the STATCON models is demonstrated on a 15-kV distribution feeder. The models are developed using the EPRI version of the EMTP.**

1. INTRODUCTION

Due to the increasing number of sensitive electronic loads, there is a demand that utilities provide high power quality. In response to this demand, the Electric Power Research Institute (EPRI) has initiated a program to develop Custom Power Devices (CPDs). The Static Condenser (STATCON) is a shunt connected CPD [1], intended to perform functions such as voltage regulation, reactive power compensation and harmonic current elimination. The Dynamic Voltage Restorer (DVR) and the Solid State Breaker (SSB) are two other CPDs being developed under EPRI sponsorship.

Before installing any CPD in a distribution system, two tasks need to be performed -- (i) analysis and identification of the power quality problems in the system and (ii) selection of CPD to be used and the required rating and optimal location. Transient simulation studies are imperative for such planning and operation of distribution systems. Therefore there is a need to develop detailed simulation models for CPDs. Since the EMTP [2] is the most popular simulator in the power utilities, there is a need to develop CPD models for the EMTP.

Transient simulation studies may be classified into three types, depending on the time constants involved in the phenomena:

- *Dynamic studies*: such as the study of the response of a power converter to a line to ground fault. Typically, the time period of interest is greater than 100ms.
- *Slow transient studies*: such as the study of harmonics caused by a rectifier load. Typically, the time period of interest is 10 ms to 100 ms.
- *Fast transient studies*: such as the study of voltage across dc/ac inverter switches. Typically, the time period of interest is less than 10ms

Previously, the ideal switch model and the variable impedance model of a switch have been used to model Static Var Compensators and HVDC converters [3-6]. These models have been used for all the types of studies mentioned above. However, for dynamic and slow transient studies, the detailed waveforms within the converter may not be of interest. Hence, the use of the ideal switch model or the variable impedance switch model is not efficient for such studies.

In this paper, three different STATCON models with varying levels of complexity are developed, one for each of the above types of studies. A STATCON consists of some basic functional modules such as a dc capacitor, a dc/ac inverter, a gate trigger generator, a control system, a output filter and a coupling transformer (Figure 1). The elegance of the modeling approach in this paper lies in the fact that the three STATCON models differ only in the dc/ac inverter and the gate trigger generator modules. This approach yields three models that give consistent results with varying degrees of complexity.

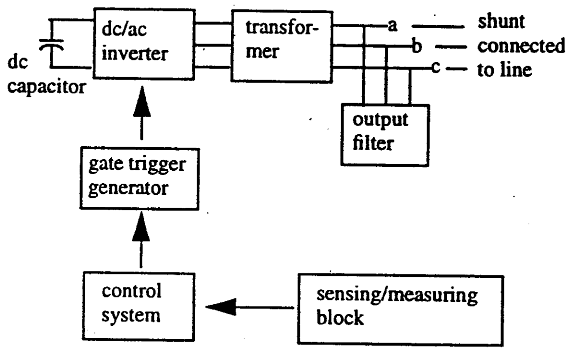

Figure 1 Basic functional modules of a STATCON.

The different accuracy versus speed trade offs for the dc/ac inverter module (and the STATCON model) are obtained using three different switch models (Table 1).

The transient behavioral model (TBM) has been

Switch Model	Type of Model
average switch model (ASM) [7]	dynamic
transient behavioral model (TBM)	slow transient
ideal switch model (ISM)	fast transient

Table 1. Different switch models used to develop different types of STATCON models.

developed by the authors with the intention of studying harmonics in a power system with power converters. It avoids the problems associated with the digital simulation of switches. Section 2 describes the TBM of a switch. In Section 3, the three switch models are demonstrated with the help of a buck converter. In Section 4, the various modules of the STATCON model are described. In Section 5, the models are demonstrated by operating the STATCON in open loop. In Section 6, the dynamic model of the STATCON is used to study its flicker compensation capability. In Section 7, a discussion and conclusion of the work is given.

2. THE TRANSIENT BEHAVIORAL MODEL

The switch configuration of Figure 2 is typical for many power converters. The input signal (v_i) generated by a control system is compared to a triangular carrier wave (v_c) to generate the gate triggering signal (v_g). For fast transient

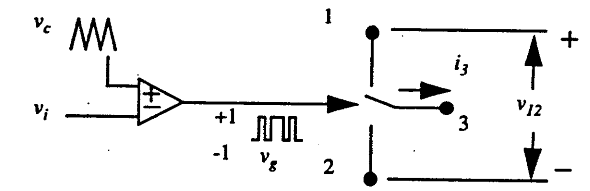

Figure 2 Typical switch configuration used in most PWM converters.

studies, this configuration is modeled using gate controlled ideal switches.

The configuration may also be modeled using the ASM (Figure 3). This model averages the behavior of a pulse width modulated (PWM) switch over each PWM cycle. v_i is assumed to be constant within one switching period. Hence, for a given v_c, the duty ratio (d) can be computed as a function of v_i. The ASM is useful for dynamic studies.

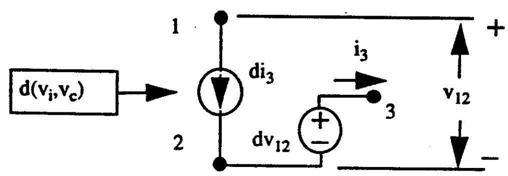

Figure 3 Average switch model of a PWM switch.

The TBM is developed by modifying the ASM as shown in Figure 4. Instead of controlling the ASM by the duty ratio (d), it is controlled by a signal h. If h assumes the value 1 or 0 and has a waveshape similar to v_g (Figure 2) the arrangement yields results identical to the ISM. Now if h is approximated by a fourier series

$$h(v_i, v_c) = A_0 + \sum_1^{\infty} A_n \cos\omega_s nt + \sum_1^{\infty} B_n \sin\omega_s nt$$

where ω_s is the switching frequency and A_0, A_n and B_n are functions of v_i and v_c, then depending upon the number of fourier terms included, the accuracy of the TBM can be varied from that of the ASM to that of the ISM.

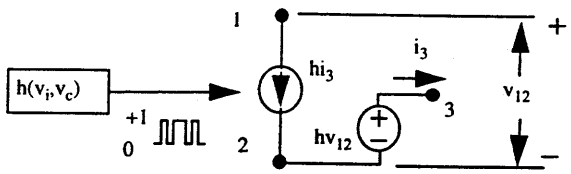

Figure 4 Transient behavioral model of a PWM switch.

3. DEMONSTRATION OF THE SWITCH MODELING TECHNIQUES

Consider the buck converter shown in Figure 5. The converter is simulated using the three different switch models. Figure 6 shows the voltage across switch S2. The ISM is the most accurate since it shows the square-wave shaped voltage across S2. The TBM approximates the switch voltage by neglecting the higher order harmonics. The ASM approximates the switch voltage even further by neglecting all but the dc component. Figure 7 shows the inductor current using the three models. Results with all three models show inductor current dynamics (i.e. the rise from zero to its steady state value). Results with the ISM and TBM also show ripple (harmonics) in the inductor current. The CPU time required to simulate the buck converter using the three models is shown in Table 2. The simulations are performed on an HP Series 700 workstation. Note that for the dynamic model, the simulation is possible using large time steps, whereas for the ideal switch model, the simulation has to be performed with small time steps in order to avoid numerical errors. Thus it is seen that the switch models give consistent results with varying levels of accuracy versus speed trade off.

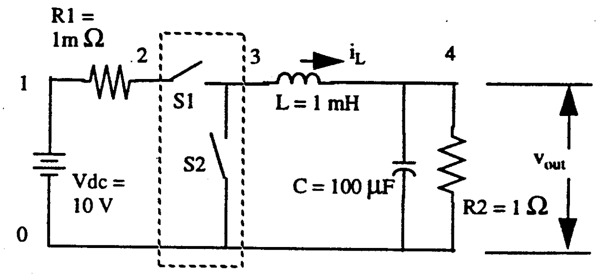

Figure 5 Circuit of buck converter used to demonstrate different switch models.

Note that the case of a power electronic converter installed in a power system is similar to the buck converter

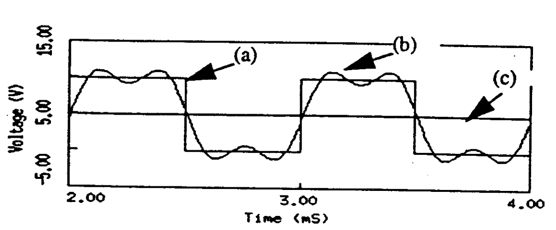

Figure 6 Voltage across switch 2 - (a) ISM, (b) TBM, (c) ASM.

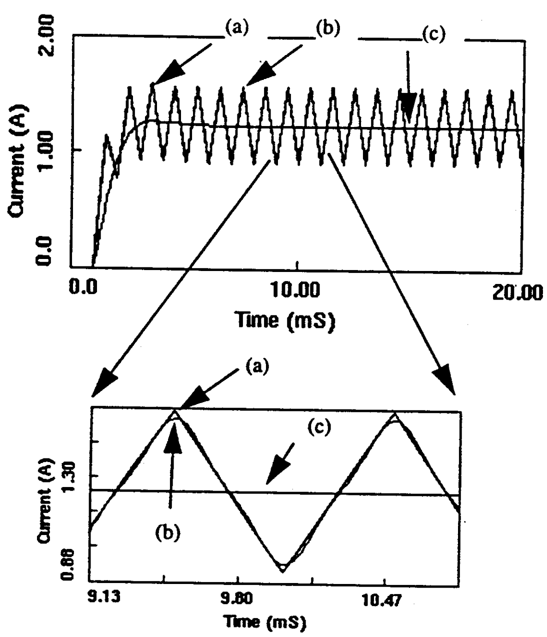

Figure 7 Current through inductor - (a) ISM, (b) TBM, (c) ASM.

Switch model	time step (μs)	CPU time (s)
ASM	100	1.5
TBM	10	3.6
ISM	1	8.0

Table 2. CPU time for simulation of buck converter over a period of 100ms.

circuit, in the sense that the entire power system, seen from the output of the power electronic converter, corresponds to the resistive load on the buck converter. Thus the ASM is efficient for study of slowly varying dynamics of the power system. The TBM is efficient for harmonic studies of the system. The ISM is necessary only if the waveforms within the converter are desired.

The results obtained by using the TBM are similar to those obtained by using the generalized average switch model [8]. In [8], the state variables of a system have been replaced by a fourier series to yield a new system of state equations with the fourier coefficients as the state variables. In contrast, the TBM is obtained by approximating the control signal of a PWM converter with a fourier series and the switch configuration by controlled sources. The rest of the converter circuit is not changed. Hence, the approach described in this paper is well suited for implementation in digital simulators such as the EMTP [9] and SABER [10] whereas the approach described in reference [8] is suited for analytical studies.

4. DESCRIPTION OF STATCON MODEL

A modular and hierarchical approach is used to develop the STATCON model. The EMTP Data Module (EDM) feature has been used. The EDM for the dynamic model of the STATCON is shown in Appendix A. Note that the EDM of the dynamic model of the STATCON uses the EDM for the dynamic model of the dc/ac inverter and the corresponding gate trigger generator (Figure 1).

To provide flexibility to the user, the various parameters of the STATCON modules (such as coupling transformer impedance, control system gains, etc.) are passed as arguments to the individual modules from the topmost level of hierarchy.

4.1 Dc/ac voltage source inverter (VSI)

A PWM inverter using six switches is modeled. Three modules are developed using the three different types of switch models. The modules are implemented using a combination of TACS and electrical network components.

4.2 Gate trigger generator module

Three gate trigger generator modules are developed - one for each type of inverter module. The gate trigger module receives input from the control system module. Using this input, the appropriate gate signals are generated. The module is implemented using TACS blocks.

4.3 Control system module

The primary functions of the STATCON modelled here are -- (i) to regulate the fundamental voltage at the coupling point by injecting appropriate amounts of fundamental reactive current and (ii) to inject harmonic currents to compensate the load harmonic currents.

The control is implemented using two loops (Figure 1) - the outer loop determines the amount of current to be injected by the STATCON. The inner loop controls the inverter so as to inject the currents determined by the outer loop [11]..

The outer loop converts the sensed voltages (v_{abc}) from *abc* to *dq* coordinates [12]. The error in the *d* component is processed through a PI block to generate the amount of instantaneous reactive current i^*_q required. The error in the capacitor voltage (v_{cape}) is processed through a PI block to determine the amount of instantaneous real current i^*_d required. The i^*_d and i^*_q are transformed into the *abc* coordinates to determine the amount of fundamental current ($i^*_{f\_abc}$) to be injected.

The outer loop also computes the amount of harmonic current in the load ($i^*_{h\_abc}$). The total current to be injected by the STATCON (i^*_{abc}) is supplied as input to the inner control loop.

Based on the current demand, the inner control loop generates the input signals inp_{abc} for the gate trigger generator. For the fast transient model of the gate trigger generator, these signals are compared to a triangular carrier wave to generate the PWM gate triggers [13].

4.4 Sensing module

This module senses the line voltages and currents required as inputs to the control system. The module consists of ideal transformers and noise filters.

4.5 Coupling transformer

This module consists of a wye-delta transformer modelled using the standard EMTP model library.

4.6 Output filter

This filter is required to remove the switching frequency harmonics caused by the dc/ac inverter. The simplest implementation of this filter, a series LC, is modeled.

5. STATCON IN OPEN LOOP

The STATCON model is inserted in the model of a 15-kV distribution feeder (Figure 9) [14]. In this simulation study, the STATCON is operated so that it injects a predetermined amount of reactive current into the system (i.e. the outer control loop is kept open). The purpose of this simulation study is to compare the performance of the three types of models.

At 60 ms, the inner control loop is given a command to inject 70 A of reactive current. Figure 10 shows the line to neutral voltage at node 3. All the models show the boost in the line to neutral voltage obtained by injection of reactive current. Figure 11 shows the phase A STATCON current. The slow transient and fast transient model show the harmonic content in the current. The simulation times on a HP series 700 workstation are summarized in Table 3.

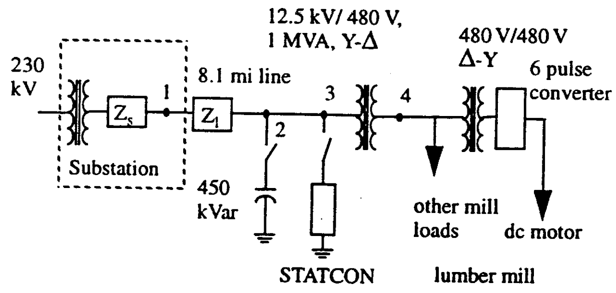

Figure 9 One line diagram of 15 kV distribution feeder.

Switch model	time step (μs)	CPU time (s)
ASM	10	74
TBM	1	801
ISM	0.1	6900

Table 3. CPU time for simulation of STATCON in open loop..

6. VOLTAGE FLICKER COMPENSATION

The aim of this simulation study is to analyze the voltage flicker problem caused by the load and the effectiveness of the STATCON in solving the flicker problem. First, the simulation is performed without the STATCON. For simplicity, the non-linear part of the load ("6 pulse converter") is kept off in this particular study. The linear part of the load ("other mill loads") are split into two parts. The first part is switched on at 80ms and kept on. From 150 ms onwards, the second part of the linear load is switched on

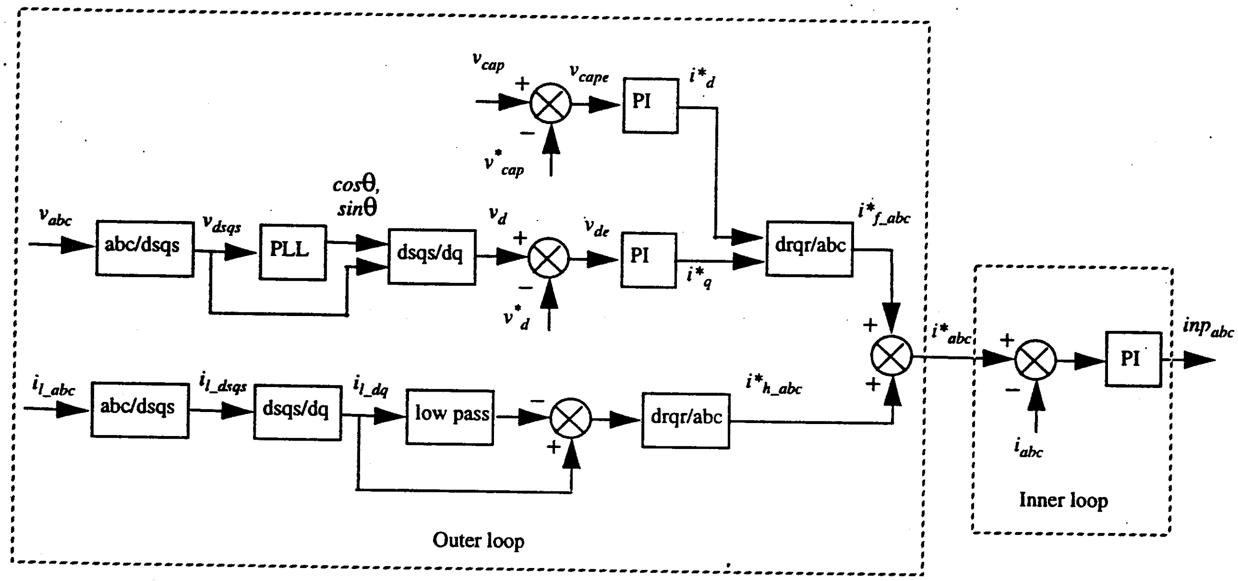

Figure 8 Control system of the STATCON.

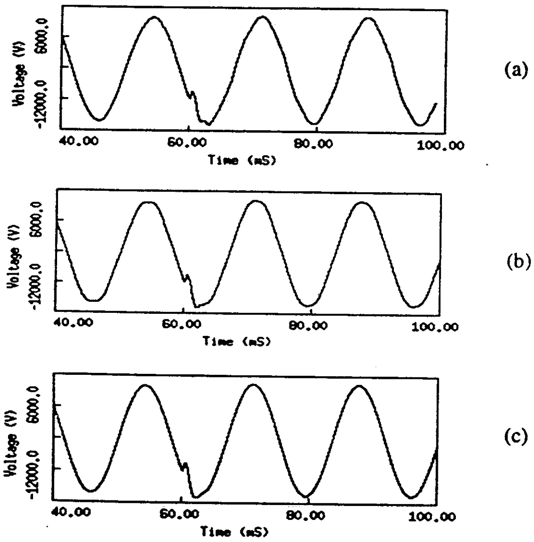

Figure 10 Line to neutral voltage at node 3 - (a) ISM, (b) TBM, (c) ASM.

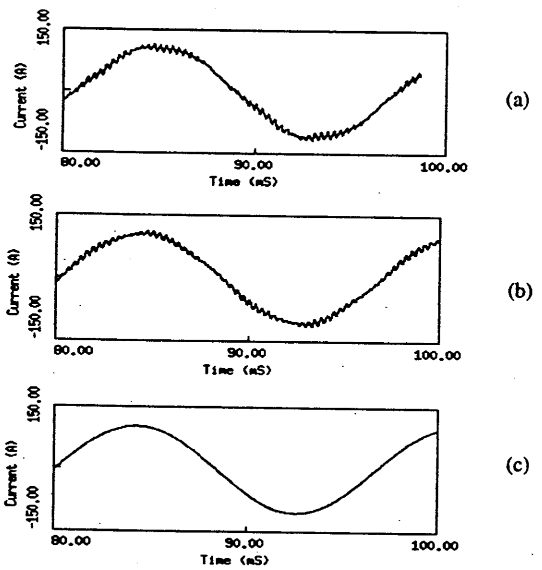

Figure 11 Phase A STATCON current injected into the system - (a) ISM, (b) TBM, (c) ASM.

and off with a time period of 200 ms. This fluctuation of the load causes fluctuation in the line voltage. Since the voltage fluctuates with a time period of 200 ms (frequency of 5 Hz), the fluctuation would be perceived as flicker by the human eye. Figure 12 shows the line to neutral voltage at node 3.

Next the simulation is performed with the STATCON model inserted at node 3. Since the time constants involved in this phenomena are large, the dynamic model of the STATCON is used. Figure 13 shows the current injected by the STATCON in response to the load variation. Figure 14 shows the line to neutral voltage at node 3. Following each load change, the voltage rises (or drops). The STATCON maintains the voltage at a constant value after a delay in response time of about one cycle. Comparison of Figure 12 and Figure 14 shows that the STATCON effectively compensates for voltage flicker.

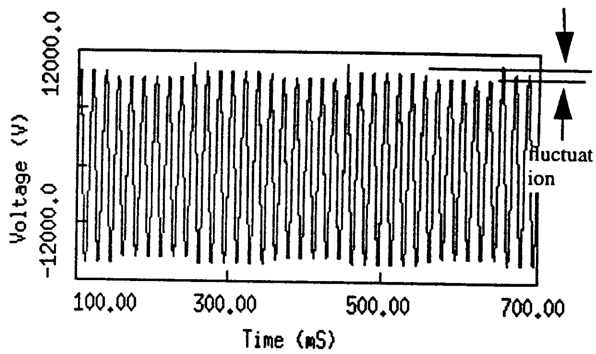

Figure 12 Phase A line to neutral at node 3 - case without STATCON.

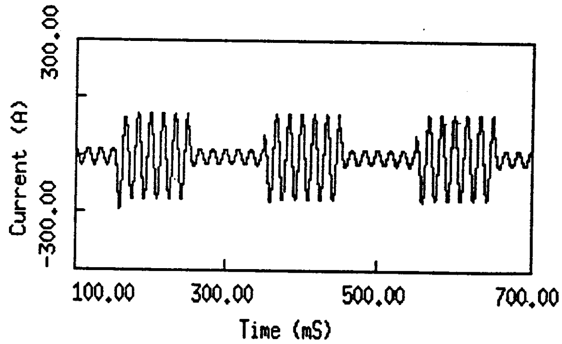

Figure 13 Current injected by STATCON into the system.

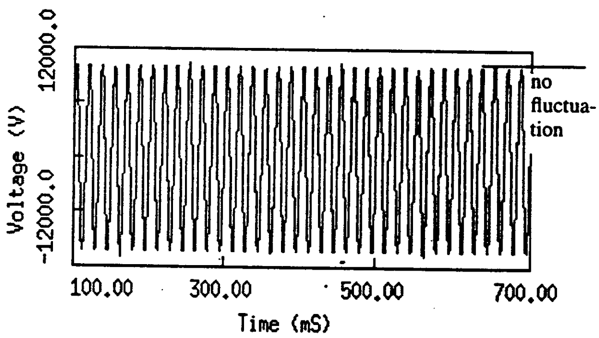

Figure 14 Phase A line to neutral voltage at node 3 - case with dynamic model of STATCON.

7. CONCLUSIONS

Three models for a distribution level STATCON are developed for three levels of simulation studies. Based on accuracy versus speed trade offs, each STATCON model uses a different type of switch model. The three STATCON models differ only in the inverter module and the gate trigger module. In this way, the models give consistent results with varying levels of computational speed. One of the switch models used (the transient behavioral switch model) is developed by the authors for use in harmonic studies of power converters installed in power systems. The accuracy of the slow transient model (using the TBM) is controlled by the number of fourier terms included. Therefore the transition from a simple model to a more complex model can be done effectively by varying the number of fourier terms included.

The consistency, accuracy and speed of the three types of models are demonstrated first in a buck converter circuit and then in the open loop operation of the STATCON.

The dynamic model of the STATCON model is inserted in the model of a 15 kV distribution feeder to study its interaction. The STATCON is shown to respond fast enough to solve voltage flicker problems.

The models developed may be used by utilities for their planning studies just as they are or, since the models are modular, they may be easily modified for a different topology or configuration of the STATCON. Thus a user may easily perform studies such as the effect of different control strategies or the effect of different output filters on the performance of the STATCON. Work is in progress to develop similar models for a DVR and a SSB. Methods to initialize the models are also being investigated.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

[1] H. Mehta, "Recent development: EPRI's Custom Power concept," *Official Proceedings of the Seventh International Power Quality Conference*, Irvine, CA, USA, October 1993.

[2] H. W. Dommel, "Digital Computer Solution of Electromagnetic Transients in Single and Multiphase Networks," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-88, No. 4, April 1969.

[3] R. H. Lasseter, S. Y. Lee, "Digital Simulation of Static Var System Transients," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-101, No. 10, October 1982.

[4] S. Lefebvre, L. Gerin-Lajole, "A Static Compensator Model for the EMTP," *IEEE Transactions on Power Systems*, Vol. 7, No. 2, pp. 477-86, May 1992.

[5] S. Y. Lee, S. Bhattacharya, T. Lejonberg, A. Hammad, S. Lefebvre, "Detailed Modelling of Static Var Compensators using the Electromagnetics Transients Program (EMTP)," *IEEE Transactions on Power Delivery*, Vol. 7, No. 2, April 1992.

[6] A. M. Gole, V. K. Sood, "A Static Compensator Model for use with Electromagnetic Transients Simulation Programs," *IEEE Transactions on Power Delivery*, Vol. 5, No. 3, July 1990.

[7] *Principles of Power Electronics*, by J. G. Kassakian, M. F. Schlecht and G. C. Veghese, Addison-Wesley Publishing Company, Inc., June 1992.

[8] S. Sanders, J. Noworolski, X. Liu, G. Verghese, "Generalized Averaging Method for Power Conversion Circuits," *presented at the Power Electronics Specialists Conference*, 1990.

[9] *EMTP Rule Book*, 1992, Electric Power Research Institute, Palo Alto, CA 94304.

[10] *SABER User Manual*, 1993, Analogy, Inc., Beaverton, OR 97075.

[11] L. Gyugyi, "Dynamic Compensation of AC Transmission Lines by Solid-State Synchronous Voltage Sources," presented at the *IEEE Power Engineering Society Summer Meeting*, Vancouver B.C., Canada, 1993.

[12] C. Schauder, H. Mehta, "Vector Analysis and Control of Advanced Static Var Compensators," *presented at the 5th IEE International Conference on AC and DC Power Transmission*, London, September 1991.

[13] J. Holtz, "Pulsewidth Modulation for Electronic Power Conversion," *Proceedings of the IEEE*, Vol. 82, No. 8, August 1994.

[14] R. A. Kagalwala, S. S. Venkata, M. A. El-Sharkawi, et. al., "Transient Analysis of Distribution Class Adaptive Var Compensators: Simulation and Field Test Results," *IEEE Transactions on Power Delivery*, April 1995.

10. APPENDIX

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C 'statcon_dyn.mod'
C EMTP data module for dynamic model of STATCON
C
ARG xxxxxA, - ; phase A connection to line
xxxxxB, - ; phase B connection to line
xxxxxC, - ; phase C connection to line
xxxxxN, - ; neutral
ISRAx1,ISRNx1,ISRCx1, - ; phase A,B,C source current (from node)
ISRAx2,ISRBx2,ISRCx2, - ; phase A,B,C source current (to node)
ILDAx1,ILDBx1,ILDCx1, - ; phase A,B,C load current (from node)
ILDAx2,ILDBx2,ILDCx2, - ; phase A,B,C load current (to node)
DCxCAP, - ; dc capacitor value
DCxRES, - ; dc resistor (in parallel with cap) value
XFRxxL,XFRxxR - ; coupling xfr inductance and resistance
xxxxLF,xxRxLF, - ; filter inductance and its resistance
xxxxCF,xxRxCF, - ; filter capacitance and its resistance
xxxRON,xxROFF, - ; on and off state resistance of inverter switches
xxCSNB,xxRSNB, - ; snubber capacitor and resistor for inverter value
CONTRLxEN1,CONTRLxEN2, - ; control circuit enable #1 and #2
FxBASE, - ; base frequency (50 or 60 Hz)
xxxxxxxxK1, - ; control system parameter #1
xxxxxxxxK2, - ; control system parameter #2
xxxxxxxxK3, - ; control system parameter #3
xxxxxxxxK4, - ; control system parameter #4
xxxxxxxxK5, - ; control system parameter #5
xxxxxxxxK6 ; control system parameter #6
C
C sensing block
$INCLUDE sens1 xxxxxA,xxxxxB,xxxxxC,xxxxxP,xxxxxM, -
ISRAx1,ISRBx1,ISRCx1,ISRAx2,ISRBx2,ISRCx2, -
ILDAx1,ILDBx1,ILDCx1,ILDAx2,ILDBx2,ILDCx2, -
xxxxA4,xxxxB4,xxxxC4,xxxxA3,xxxxB3,xxxxC3, -
xxxxVA,xxxxVB,xxxxVC,xxxxVP,xxxxVM, -
xxISRA,xxISRB,xxISRC,xxILDA,xxILDB,xxILDC,xxIINA,xxIINB,xxIINC
C
C coupling transformer
$INCLUDE coupling_xfr
xxxxA2,xxxxB2,xxxxC2,xxxxSN,xxxxxA,xxxxxB,xxxxxC,XFRxxL,XFRxxR
C
C output filter
$INCLUDE out_fltr xxxxA3,xxxxB3,xxxxC3,xxxxA2,xxxxB2,xxxxC2,xxxxSN, -
xxxxLF,xxRxLF,xxxxCF,xxRxCF
C
C inverter module
$INCLUDE inv_dyn xxxxxP,xxxxxM,xxxxA4,xxxxB4,xxxxC4, -
IxxxDA,IxxxDB,IxxxDC, -
xxxRON,xxROFF,xxxRON,xxROFF,xxRSNB,xxCSNB
C
C dc capacitor
$INCLUDE cap xxxxxP,xxxxxM,DCxCAP,0
$INCLUDE res xxxxxP,xxxxxM,DCxRES,2
C
C control module
$INCLUDE kontrol1 xxxxVA,xxxxVB,xxxxVC,xxxxVP,xxxxVM, -
xxISRA,xxISRB,xxISRC,xxILDA,xxILDB,xxILDC,xxIINA,xxIINB,xxIINC, -
xxINPA,xxINPB,xxINPC, - ;
CONTRLxEN1,CONTRLxEN2,FxBASE, -
xxxxxxxxK1,xxxxxxxxK2,xxxxxxxxK3,xxxxxxxxK4,xxxxxxxxK5,xxxxxxxxK6
C
C gate/duty signal generator
$INCLUDE trg1_dy xxINPA,xxINPB,xxINPC, -
I1xxDA,I1xxDB,I1xxDC,I2xxDA,I2xxDB,I2xxDC
C
/ENDMODULE
$EOF
```