North American Power Symposium (NAPS), Laramie, Wyoming, October 1997, pp. 49–54.

Fundamental Frequency Model of Static Synchronous Compensator

Edvina Uzunovic Claudio A. Cañizares John Reeve
University of Waterloo
Department of Electrical & Computer Engineering
Waterloo, ON, Canada N2L 3G1

Abstract—**A balance, 60 Hz model of the Static Synchronous Compensator (STATCOM), a FACTS controller based on voltage-sourced converters with Gate Turn-Off (GTO) thyristors, is proposed in this paper. Electromagnetic Transient Program (EMTP) simulations are carried out in a sample system with variable load, to compare the operation of the detailed controller representation and its suggested reduced model. The proposed quasi-steady-state model is suitable for transient stability studies as well as other system analysis techniques, such as voltage collapse studies, that required accurate representation of fundamental frequency operation and control of power system controllers.**

Keywords: FACTS, STATCOM, EMTP, fundamental frequency models.

I. INTRODUCTION

Today's power systems are highly complex, sometimes made of thousands of buses and hundreds of generators. New power generation is primarily determined based on environmental and economic reasons, and are somewhat inexpensive and relatively easy to build and operate, especially nowadays with the availability of "cheap" natural gas and high performance gas turbines. On the other hand, new transmission systems are expensive and take considerable amount of time to build. Hence, in order to meet increasing power demands, utilities must rely on power export/import arrangements through existing transmission systems. While the power flow in some of these transmission lines is well below their thermal limits, certain lines are overloaded, which has the effect of deteriorating voltage profiles and decreasing system stability. This requires the review of traditional transmission methods and practices, and the creation of new concepts to allow for the use of existing transmission systems without reduction in system security.

Flexible AC Transmission Systems (FACTS) is a new approach to a more efficient use of existing power system resources based on the utilization of high-current, high-voltage power electronic controllers [1, 2, 3, 4]. The authors in [2, 3] propose the use of a Static Synchronous Compensator (STATCOM) as a FACTS controller. It is basically a voltage-sourced inverter using GTOs and dc capacitor to generate a three phase synchronous voltage at fundamental frequency. The STATCOM is shunt-connected to the transmission system via a step-down transformer; it can generate or absorb reactive power to regulate the voltage profile of the bus at which it is connected [5].

It should be noted that the STATCOM may be known by other terminology, and that several application variations are possible. For example, if the voltage-sourced inverter is employed in series with the transmission line via a series transformer, the device is referred to as a Static Synchronous Series Compensator (SSSC). This can also generate or absorb reactive power from the series connected line, and in that way change the series impedance of the transmission line as well as the power flowing through it [6]. Also, two series and shunt connected voltage-sourced inverters, coupled by a common dc capacitor, become the Unified Power Flow Controller (UPFC) [7]. The UPFC offers the unique opportunity to directly exchange active power with the ac system, in addition to independently control shunt and series reactive power compensation.

Before these controllers are installed in a power system, it is important to investigate and clearly identify the potential application and benefits arising from the installation. In order to do so, it is necessary to equip power system engineers with all tools necessary to accomplish this task, i.e. adequate models and software tools to accurately represent these controllers in different types of studies. Several authors have demonstrated the importance of realistic modeling of FACTS controllers for steady-state and transient studies [8, 9, 10]. In the current literature, the STATCOM is modeled in steady-state as part of the UPFC [11, 12]; the STATCOM is decoupled from the SSSC and represented usually by a voltage or current source. These voltage or current sources are modeled without limits and, therefore, the STATCOM is represented as capable of generating or absorbing unlimited amounts of reactive power. The current paper proposes a fundamental frequency model of this controller so that operating and control limits are represented in a more realistic manner. A rather detailed model for the STATCOM, suitable for Electromagnetic Transient Program (EMTP) types of studies, is used as a test-bed for the development of the proposed fundamental frequency model.

In Section II. the basic operating principles of the STATCOM are described, and a detailed EMTP model of this controller is discussed. The results of using this device in a test system that simulates a variable load are also presented in this section. Section III. discusses the development of a 60-Hz model for the STATCOM, and presents the results of using this model in the same test system, comparing the results obtained for both detailed and 60-Hz models. Finally, Section IV. summarizes the main ideas presented in this paper as well as discussing future research directions.

II. STATCOM Detailed Model

A. Basic Operation

The basic electronic block of the STATCOM is the voltage-sourced inverter that converts an input dc voltage into a three phase output voltage at fundamental frequency. The steady-state characteristics of the STATCOM are similar to those of a rotating synchronous compensator but with no inertia, so that its response is basically instantaneous and it does not significantly alter the existing system impedance; the latter is an advantage over Static var Compensators (SVCs).

In its simplest form, the STATCOM is made up of a coupling transformer, a voltage-sourced inverter and a dc capacitor. In this arrangement, the steady-state power exchange between the device and the ac system is mainly reactive. A functional model of the STATCOM is shown in Figure 1.

The reactive power exchange of the STATCOM with the ac system is controlled by regulating the amplitude of the STATCOM output voltage. If the amplitude of the STATCOM output voltage is increased above the amplitude of the ac system voltage, the current flows through the transformer reactance from the STATCOM to the ac system, and the device generates reactive power (capacitive). If the amplitude of the STATCOM output voltage is decreased to a level below that of the ac system, then the current flows from the ac system to the STATCOM, resulting in the device absorbing reactive power (inductive). If the amplitudes of the STATCOM output voltage and the ac system voltage are equal, the reactive current is zero and the STATCOM does not generate/absorb reactive power. Since the STATCOM is generating/absorbing only reactive power, the output voltage and the ac system voltage are in phase, when neglecting circuit losses. The current drawn from the STATCOM is 90° shifted with respect to the ac system voltage, and it can be leading (generates reactive power) or lagging (absorbs reactive power).

A capacitor is used to maintain dc voltage to the inverter. The inverter itself keeps the capacitor charged to the required levels. Thus, by controlling the inverter output voltage lead or lag with respect to the ac system voltage, the capacitor voltage can be decreased or increased, respectively, to control the reactive power output of the device. When the inverter voltage *leads* the bus voltage, the capacitor *supplies active power* to the system, reducing its voltage; on the other hand, when the inverter voltage *lags* the bus voltage, the capacitor is charged by *consuming active power* from the system. In steady-state, the output voltage of the inverter slightly lags the ac system voltage, so that the inverter absorbs a small amount of real power from the ac system to replenish its internal losses and, thus, keep the capacitor voltage constant.

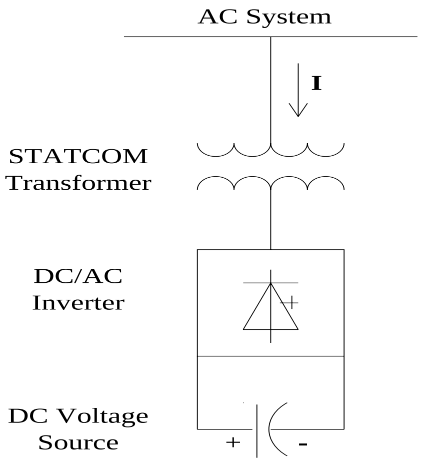

Fig. 1. STATCOM functional model.

B. EMTP Modeling

A three phase voltage-sourced inverter is typically made of six controlled switches (GTO valves) to shape the output waveform. There are also six uncontrolled switches (diodes) to provide a path for inductive output current whenever the controlled switches are switched off. The twelve switches form two bridges connected in antiparallel. Each GTO valve and diode within a switch carries alternatively a 90° segment of the output current in each cycle; thus, the current ratings of the GTO valve and diode are the same. When the output current is capacitive, the GTO valve has to be turned off at the peak of the current, whereas in inductive operation the valve commutates naturally when the current drops to zero.

The inverter bridge within the STATCOM is typically made of several 6-pulse inverters to reduce the harmonics present in the output current. The 6-pulse inverter output voltages are combined by means of an array of several coupling transformers to form a multi-pulse "sinusoidal" voltage. In practice, for transmission line applications, a 24 or higher pulse arrangement is required to achieve adequate waveform quality without the need of passive filters. In 1995, a ±100 Mvar STATCOM with eight inverters, to produce a 48-pulse output voltage waveform, was commissioned for the Tennessee Valley Authority (TVA) [13].

In this paper, a 12-pulse STATCOM is modeled in the EMTP to obtain the basic waveforms and to illustrate the operation of this device. This detailed model is then used to validate the proposed 60 Hz model. Due to the "low" number of inverter pulses used, filters are added to improve the output voltages and currents. The control part of the STATCOM is modeled using TACS (Transient Analysis of Control Systems), which basically uses a PI controller to directly change the phase-shift, within limits, between the inverter output ac voltage and the bus

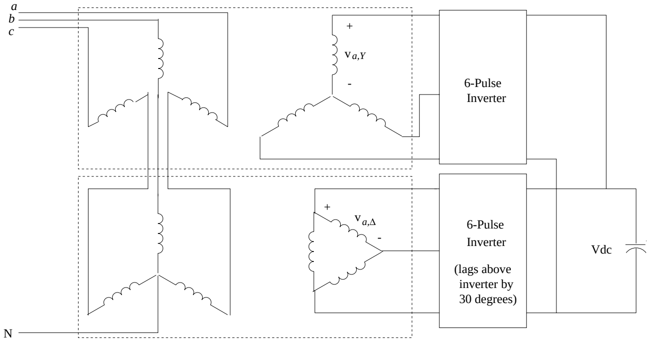

Fig. 2. Twelve-pulse STATCOM arrangement.

voltage and, hence, control the charging and discharging of the capacitor as previously indicated.

Figure 2 shows a typical 12-pulse inverter arrangement utilizing two transformers with their primaries connected in series.

The first inverter is connected to the system through a Y-Y arrangement, whereas a Y-Δ connection is used for the second inverter. Each inverter operates as a 6-pulse inverter, with the Y-Δ inverter being delayed by 30° with respect to the Y-Y inverter. The instantaneous STATCOM output voltage for phase a can be computed in this case as

$$v_a \quad = \quad a_1\; v_{a,Y} + a_2\; \frac{v_{a,\Delta}}{\sqrt{3}}$$

where a_1 and a_2 are the voltage ratios of the corresponding inverter transformers. The current flowing into each inverter is the same, scaled by the transformer ratio, as the current being drawn from the system by the STATCOM; for the Y-Δ inverter, the current is also delayed by 30° with respect to the current of the Y-Y inverter. The STATCOM output voltage and input currents, as well as the corresponding dc current and voltage, are depicted in Figure 3 for the device operating in capacitive mode.

The 5-bus test system depicted in Figure 4 is used here to illustrate the STACOM operation in a variable load environment. This system is based on a test system introduced in [15] to test SVCs. Initially, a shunt capacitor bank is connected at Bus 2 to bring the initial voltage close to 1 p.u.; these capacitors are then replaced by a STATCOM connected to Bus 2 through a 100 MVA, 138/6 kV transformer. The transformer resistance and magnetizing reactance are assumed to be very small and are, therefore, neglected; the leakage reactance is assumed to be 14.5 %. The inverter transformers are rated at one half of the total MVA transformer output, i.e., 50 MVA. The load is modeled using TACS controllable current sources to simulate a variable RL load, and is assumed to increase to full load in two steps to bring the voltage down and, thus, activate the STATCOM.

The voltage of the ac system is subjected to dynamic variations due to load changes at 0.4 s and 0.8 s. The proper function of the STATCOM is to minimize the magnitude and duration of these disturbances by regulating the voltage at Bus 2. For the system with fixed capacitive

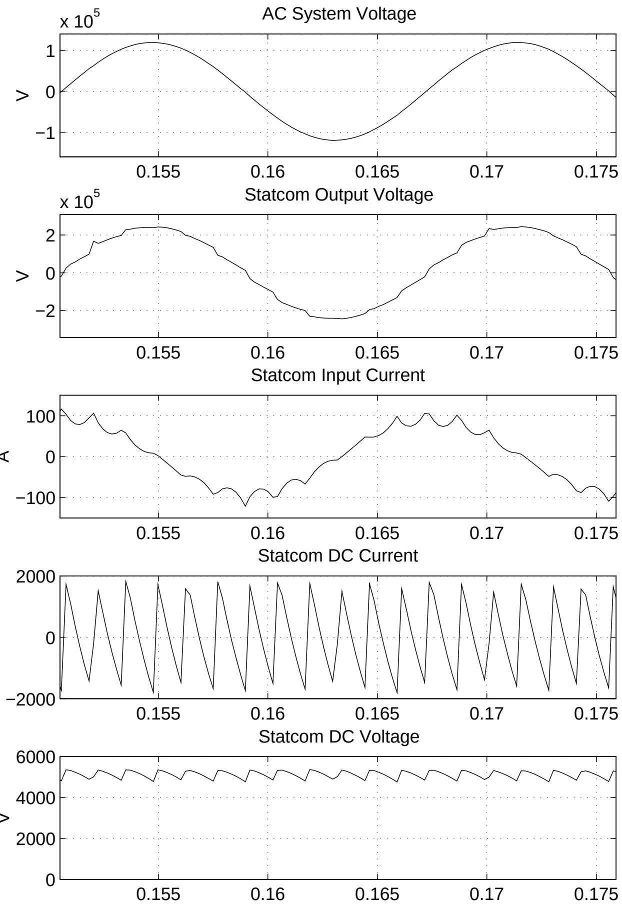

Fig. 3. STATCOM waveforms for capacitive operation.

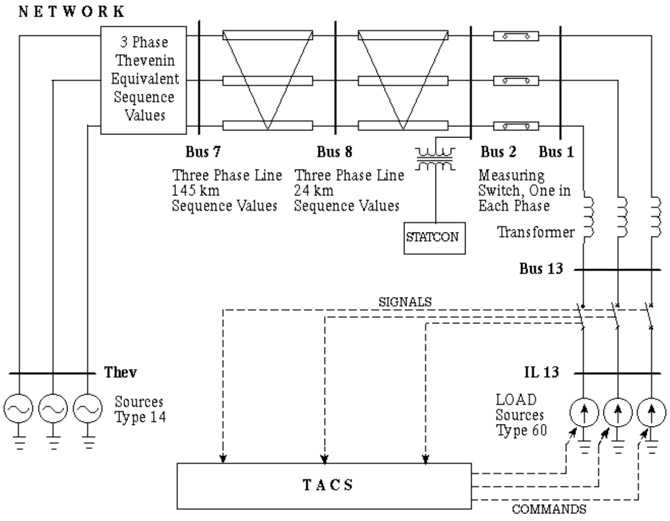

Fig. 4. Test system.

support, Figure 5 shows the active power load demand as well as the instantaneous load phase voltage and its magnitude; observe the low p.u. voltage levels as the load is increased.

Hence, to keep the voltage in the system at acceptable levels, a ±100 Mvar STATCOM is then connected at Bus 2, replacing the capacitor bank, to bring the voltage to the desired 1 p.u. The results with the STATCOM added to the system are depicted in Figure 6 which indicates adequate load voltage regulation.

III. Fundamental Frequency Model

In order to develop a 60 Hz, balanced model of the STATCOM, a power balance technique, somewhat similar to the one proposed in [14] for d-q axis control strategies, is used here. Thus, the instantaneous power flowing into the inverter from the ac bus, when neglecting transformer losses, may be represented by

$$p = 3\,\frac{V_{ac}V_{inv}}{X}\sin\alpha$$

where V_{ac} is the rms voltage of the sinusoidal STATCOM bus voltage; X is the coupling transformer equivalent impedance; α is the phase shift between the bus phase voltage v_{ac} and the corresponding output voltage of the inverter v_{inv}, i.e.,

$$\begin{aligned} v_{ac} &= \sqrt{2}\,V_{ac}\sin(\omega t+\theta) \qquad (1)\\ \Rightarrow\quad v_{inv} &= \sqrt{2}\,V_{inv}\sin(\omega t+\theta-\alpha) \end{aligned}$$

i.e., when $\alpha > 0°$ ($p > 0$), the inverter output voltage lags the bus voltage (the capacitor charges), whereas for $\alpha < 0°$ ($p < 0$), the inverter ac voltage leads the bus voltage (the capacitor discharges). V_{inv} is the rms value of the inverter output voltage on the primary side of the coupling transformer, i.e.,

$$V_{inv} = k\,V_{dc} \qquad (2)$$

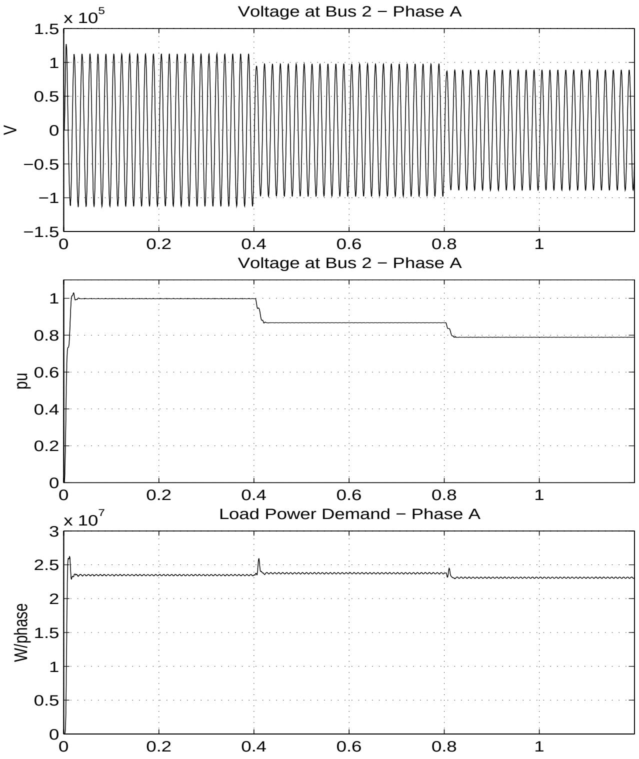

Fig. 5. Test system results without STATCOM.

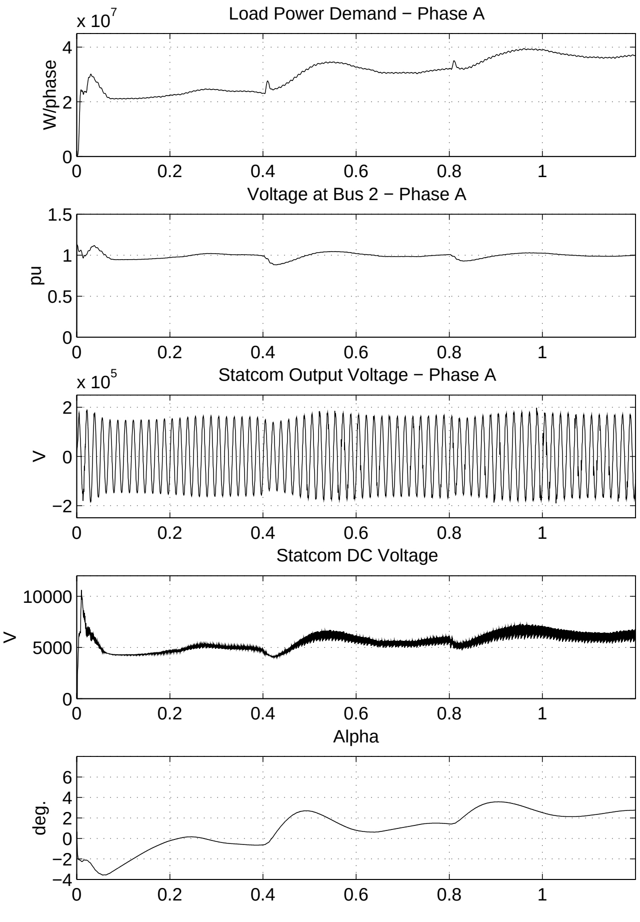

Fig. 6. Test system results with detailed STATCOM model.

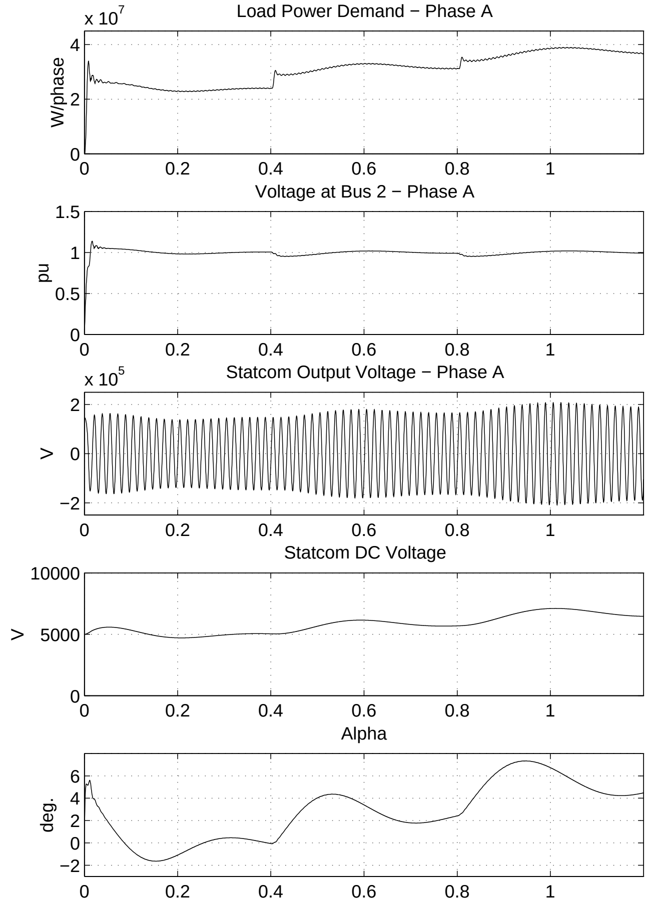

Fig. 7. Test system results with 60 Hz STATCOM model.

where V_{dc} is the average dc voltage on the capacitor, and k is a constant corresponding to the fundamental frequency representation of the inverter output voltage and the total transformer voltage ratios, e.g., $k = 0.9\ a$, $a = V_1/V_2$, for a 12-pulse inverter.

If inverter losses are neglected as well, the power balance between the ac and dc sides is given by

$$\begin{aligned} 3\,\frac{V_{ac}V_{inv}}{X}\sin\alpha &= V_{dc}\ I_{dc} \qquad (3)\\ &= C\ V_{dc}\ \frac{\mathrm{d}V_{dc}}{\mathrm{d}t} \end{aligned}$$

Hence, from (2) and (3), it follows that the V_{dc} voltage becomes a nonlinear, differential function of α, i.e.,

$$\frac{\mathrm{d}V_{dc}}{\mathrm{d}t} = \frac{3\ k}{C\ X}\,V_{ac}\sin\alpha \qquad (4)$$

Observe that for $\alpha > 0°$, $\mathrm{d}V_{dc}/\mathrm{d}t > 0$, i.e., the capacitor charges; for $\alpha < 0°$ $\mathrm{d}V_{dc}/\mathrm{d}t < 0$, i.e., the capacitor discharges; and for $\alpha = 0°$, $\mathrm{d}V_{dc}/\mathrm{d}t = 0$, i.e., the V_{dc} voltage remains constant.

Inverter losses can be easily introduced into these equations by adding a resistance R in parallel with the capacitor. Thus,

$$\frac{\mathrm{d}V_{dc}}{\mathrm{d}t} = \frac{3\ k}{C\ X}\,V_{ac}\sin\alpha - \frac{1}{RC}\,V_{dc} \qquad (5)$$

In this case, steady-state operation requires a small, positive value $\alpha = \alpha_o$, i.e., a small amount of power flowing from the system to supply for the inverter losses, as previously discussed. Thus, α_o can be determined from the following equation:

$$\frac{3\ k}{X}\,V_{ac}\sin\alpha_o = \frac{V_{dc_o}}{R}$$

This equation may also be used to determine the value of R from the value of α_o obtained in the detailed simulations shown in Figure 6.

With the help of a voltage tracking system described in [15], the inverter is represented in the EMTP as a TACS controlled voltage source based on equations (1) and (5); all basic α control equations are identical to the ones used in the detailed model. In order to obtain adequate results, much care must be taken when choosing the values of k and X, as well as properly initializing the dc voltage V_{dc}. The inverter losses represented by R must also be modeled in this case in order to be able to obtain similar results with both the detailed model and the fundamental frequency model. In the results of the simulation for the 60 Hz model in Figure 7, all results for the same load variation in the test system are similar except in the start-up period due to the "forced" initialization of V_{dc}, which is not necessary when the detailed model is used. These results fully validate the proposed 60 Hz model.

IV. Conclusions

This paper presents an operative description and detailed EMTP implementation of a STATCOM. The results of using the detailed controllers model for load voltage control in a test system are used as a benchmark to evaluate the behavior of a proposed 60 Hz, balanced model with the help of the EMTP. The simulation results demonstrate the validity of the proposed fundamental frequency model, which can be used for transient as well as steady-state power system analyses.

The development of 60 Hz models of FACTS device is important to allow for a more accurate representation of these devices in a variety of power system studies, so that reliable results can be obtained for integrated ac/dc/FACTS systems in planning as well as system operation. Similar models for the SSSC and UPFC, as well as an improved version of the proposed STATCOM model, so that GTO current limits can be directly represented are being developed.

References

[1] N. G. Hingorani, "Flexible AC Transmission Systems," *IEEE Spectrum*, April 1993, pp. 40–45.

[2] L. Gyugyi, "Dynamic Compensation of AC Transmission Lines by solid-state Synchronous Voltage Sources," *IEEE Trans. Power Delivery*, Vol. 9, No. 2, April 1994, pp. 904–911.

[3] L. Gyugyi, N. G. Hingorani, P. R. Nannery, and N. Tai, "Advanced Static Var Compensator using Gate Turn-Off Thyristors for Utility Application," *CIGRE*, paper 23-203, Paris, August 1990.

[4] P. G. Therond, P. Cholley, D. Daniel, E. Joncquel, L. Lafon, and C. Pomarede, "FACTS Research and Development Program at EDF," IEE Colloquium on FACTS–The Key to Increased Utilization of Power, Digest No. 1995/004, 1994, pp. 6/1–6/15.

[5] C. Schauder, M. Gernhardt, E. Stacey, T. Lemak, L. Gyugyi, T. W. Cease, and A.Edris, "Development of a ±100 MVAr Static Condenser for Voltage Control of Transmission Systems," *IEEE Trans. Power Delivery*, Vol. 10, No. 3, July 1995, pp. 1486–1493.

[6] L. Gyugyi, C. D. Schauder, and K. K. Sen, "Static Synchronous Series Compensator: A Solid-state Approach to the Series Compensation of Transmission Lines," *IEEE Trans. Power Delivery*, Vol. 12, No. 1, January 1997, pp. 406–417.

[7] L. Gyugyi, C. D. Schauder, S. L. Williams, T. R. Rietman, D. R. Torgerson, and A. Edris, "The Unified Power Flow Controller: A new Approach to Power Transmission Control," *IEEE Trans. Power Delivery*, Vol. 10, No. 2, April 1995, pp. 1085–1093.

[8] D. N. Koseterev, "Modeling Synchronous Voltage Source Converters in Transmission System Planning Studies," IEEE/PES SM, paper 465-5 PWRD, Denver, July 1996.

[9] S. Arabi and P. Kundur, "A Versatile FACTS Device Model for Power Flow and Stability Simulations," IEEE/PES WM, paper 258-4 PWRS, Baltimore, January 1996.

[10] Z. T. Faur and C. A. Cañizares, "Effects of FACTS devices on System Loadability," *Proc. North American Power Symposium (NAPS)*, Bozeman, Monatana, 1995, pp. 520–524.

[11] E. Lerch, D. Povh, R. Witzmann, R. Hlebcar, and R. Mihalic, "Simulation and Performance Analysis of Unified Power Flow Controller," *CIGRE*, paper 14-205, Paris, August 1994.

[12] M. Rahman, M. Ahmed, R. Gutman, R. J. O'Keefe, R. J. Nelson, and J. Bian, "UPFC Application on the AEP System: Planning Considerations," IEEE WM, paper PE-582-PWRS-0-01-1997, February 1997.

[13] C. Schauder, M. Gernhardt, E. Stacey, T. Lemak, L. Gyugyi, T. W. Cease, and A. Edris, , "Operation of ±100 MVAR TVA STATCON," IEEE/PES WM, paper PE-509-PWRD-0-01-1997, New York, January 1997.

[14] C. Schauder and H. Mehta, "Vector Analysis and Control of Advanced Static Var Compensators," *IEE Proceedings–C*, Vol. 140, No. 4, July 1993, pp. 299–306.

[15] R. H. Lasseter, *Electromagnetic Transient Program (EMTP)–Volume 4: Workbook IV (TACS)*, EL-4651, Vol. 4, RP 2149-6, EPRI, June 1989.

Edvina Uzunovic was born in Sarajevo, Bosnia-Herzegovina. She was graduated from the University of Sarajevo in Electrical Engineering in 1990. After professional positions in Sarajevo, she joined the Department of Electrical & Computer Engineering at the University of Waterloo as a graduate student in 1993, where she completed her M.A.Sc. degree with a research thesis in voltage stability of ac/dc transmission systems in 1995, and is currently a Ph.D. student.

Claudio A. Cañizares was born in Mexico, D.F. in 1960. In April 1984, he received the Electrical Engineer diploma from the Escuela Politécnica Nacional (EPN), Quito-Ecuador, where he held different positions from 1983 to 1993. His MS (1988) and PhD (1991) degrees in Electrical Engineering are from the University of Wisconsin–Madison, where he attended as an EPN, Organization of American States (OAS) and Fulbright Scholar. Dr. Cañizares is currently an Assistant Professor at the University of Waterloo, Department of Electrical & Computer Engineering, and his research activities are mostly concentrated in computational, modeling, and stability issues in ac/dc/FACTS systems. He is a Professional Engineer in the province of Ontario, Canada, and an active member of IEEE, CIGRE and Sigma Xi.

John Reeve received the B.Sc., M.Sc., Ph.D. and D.Sc. degrees from the University of Manchester (UMIST). After employment in the development of protective relays for English Electric, Stafford, between 1958 and 1961, he was a lecturer at UMIST until joining the University of Waterloo in 1967, where he is currently an Adjunct Professor in the Department of Electrical & Computer Engineering. He was a project manager at EPRI, 1980-81, and was with IREQ, 1989-1990. His research interests since 1961 have been HVDC transmission and high power electronics. He is the President of John Reeve Consultants Limited. Dr. Reeve was chair of the IEEE DC Transmission Subcommittee for 8 years, and is a member of several IEEE and CIGRE Committees on dc transmission and FACTS. He was awarded the IEEE Uno Lamm High Voltage Direct Current Award in 1996.