IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 20, NO. 2, APRIL 2005

# Review of Electromagnetic Transient Models for Non-VSC FACTS

## IEEE Working Group on Dynamic Performance and Modeling of HVDC and Power Electronics for Transmission Systems

M. O. Faruque, Venkata Dinavahi, *Member, IEEE*, Surya Santoso, *Senior Member, IEEE*, and Ram Adapa

***Abstract*—This paper documents electromagnetic transient simulation models for conventional flexible AC transmission systems (FACTS) that do not employ voltage-sourced converter (VSC) technology. The FACTS controllers included in this document are classified into four categories: (1) shunt controllers (2) series controllers (3) combined shunt and series controllers (4) auxiliary controllers. Modeling techniques of these controllers are reviewed and the key aspects of each model are summarized. A comprehensive list of references is also included in this paper to provide further detailed information to the readers.**

***Index Terms*—Digital simulation, electromagnetic transients program (EMTP), flexible AC transmission systems (FACTS), modeling.**

## I. INTRODUCTION

Due to the availability of high power semiconductor devices, flexible AC transmission systems (FACTS) [1]–[3] have become an essential and integral part of modern power systems. Modeling and digital simulation plays an important role in the analysis, design, testing and commissioning of such controllers. Based on their evolution, FACTS controllers can be distinctly divided into two generations.

The first generation of FACTS such as thyristor controlled reactor (TCR), thyristor switched reactor (TSR), static VAr compensator (SVC), Thyristor Controlled Series Capacitor (TCSC), voltage regulating transformer (VRT), phase angle regulator (PAR) and "Sen" Transformer (ST) are those in which the basic unit of the controller is a power electronic device such as a thyristor or a gate turn-off thyristor (GTO). Whereas the second generation of FACTS, such as static compensator (STATCOM), static synchronous series compensator (SSSC), and unified power-flow controller (UPFC), contain a voltage-sourced converter (VSC) as the basic building block. Over the years, several models [4]–[8] for both types of FACTS controllers have been developed for transient simulation using the electromagnetic transient program (EMTP) and EMTP-type programs such as ATP, MICROTRAN, EPRI-DCG, PSCAD/EMTDC, NETOMAC, and HYPERSIM. As part of the mandate of the IEEE Working Group 15.05.02, efforts are being made to consolidate currently available models of FACTS into publications that can serve as reference material for both the industry and the academia.

This paper focuses on electromagnetic transient simulation models for conventional FACTS controllers not using VSC technology. Nearly all of these controllers employ either naturally commutated thyristors or forced commutated GTOs as switching elements. The most commonly used simulation programs model the thyristor by adding a turn-on control on the diode model (an ideal voltage controlled switch with on-state and off-state resistances). A GTO is represented by a simplified switch with gate turn-on and turn-off controls. In many applications, a free wheeling diode is used in parallel with the controllable switching device to provide a continuous current flowing path for an inductive load. Snubber circuits are used either for mitigating numerical oscillations or for protecting the device. Detailed guidelines for modeling switching devices, power electronic system, system controls, power system and snubber treatment can be found in [7].

The FACTS controllers reviewed in this paper are classified as follows:

- Static Shunt Controllers
    1) Thyristor Switched Reactor (TSR)
    2) Thyristor Switched Capacitor (TSC)
    3) Thyristor Controlled Reactor (TCR)
    4) Static VAr Compensator (SVC)
    5) Thyristor Controlled Braking Resistor (TCBR)
- Static Series Controllers
    1) Thyristor Switched Series Capacitor (TSSC)
    2) Thyristor Controlled Series Capacitor (TCSC)
    3) GTO Thyristor Controlled Series Capacitor (GCSC)
    4) Advanced Series Compensator (ASC)
- Combined Shunt and Series Controllers
    1) Static Phase Shifter (SPS)
    2) Thyristor Controlled Phase Angle Regulator (TCPAR)
    3) Thyristor Controlled Voltage Magnitude Regulator (TCVMR)
    4) "Sen" Transformer (ST)
- Auxiliary Controllers
    1) NGH-SSR Damper
    2) Thyristor Controlled Voltage Limiter (TCVL)
    3) Solid State Breaker (SSB) and Fault Current Limiter (FCL)

---

Manuscript received September 9, 2003; revised January 23, 2004. This work was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada and the University of Alberta. Paper no. TPWRD-00456–2003.

M. O. Faruque and V. Dinavahi are with the University of Alberta, Edmonton, AB T6G 2V4, Canada (e-mail: dinavahi@ece.ualberta.ca).

S. Santoso is with the University of Texas, Austin, TX 78712-1024 USA.

R. Adapa is with the Electric Power Research Institute (EPRI), Palo Alto, CA 94304 USA.

Digital Object Identifier 10.1109/TPWRD.2004.838514

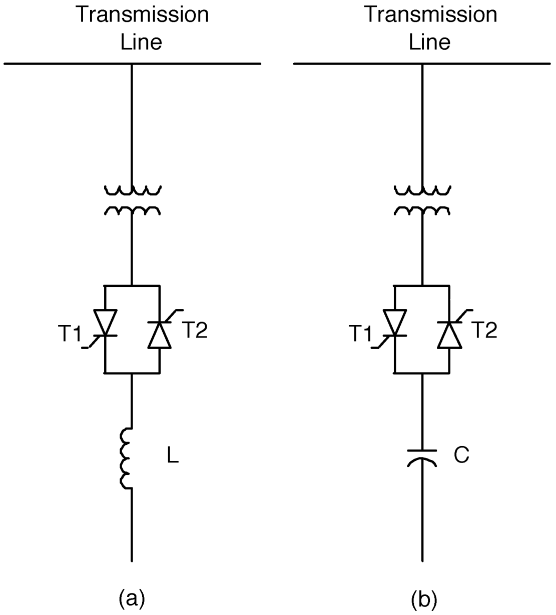

Fig. 1. Schematic diagram of (a) TSR (b) TSC.

The paper is organized as follows. For each of the above controllers a brief explanation of the structure, operating principle and typical application, precedes the EMTP modeling details. Section II deals with static shunt controllers. Section III addresses static series controllers. Section IV deals with combined shunt and series controllers and Section V presents the auxiliary controllers. Conclusions are presented in Section VI.

## II. STATIC SHUNT CONTROLLERS

Shunt reactive power compensators are generally used to supply or absorb reactive power at their point of connection. The earliest form of shunt compensation include saturable reactors (SR) and synchronous generators. The development of power electronics has made it possible to replace them with modern shunt compensators such as TSR, TSC, TCR and SVC.

### *A. Thyristor Switched Reactor (TSR)*

A TSR, shown in Fig. 1(a), is defined as a shunt connected thyristor-switched inductor whose effective reactance is varied in a step-wise manner by full or zero conduction operation of the thyristor valve [1]. TSR is a subset of a static VAr compensator (SVC) which is made up of several shunt connected inductors that can be switched in and out by thyristor switches without any firing angle controls, providing the required step changes in the reactive power. Owing to its simple configuration and an absence of stand-alone use (TSR appears as an integral part of SVC in most applications), there has not been enough literature modeling TSR separately. However, an EMTP model of TSR, in general, would include type-11 switches representing the anti-parallel thyristors working in series with an inductor.

### *B. Thyristor Switched Capacitor (TSC)*

TSC (Fig. 1(b)) is another subset of SVC that can be defined as a shunt connected thyristor-switched capacitor whose effective reactance is varied in a step-wise manner by full or zero conduction operation of the thyristor valve [1]. This allows a step-wise selection of reactive power supplied to the system. One specific model of TSC has been developed [9] to run in ATP and PSCAD/EMTDC. The power circuit of the model comprises of the basic TSC with its capacitor in series with the thyristor switches. More than one modules of capacitors could be considered in series or parallel. The control system for the TSC uses a closed loop PI controller.

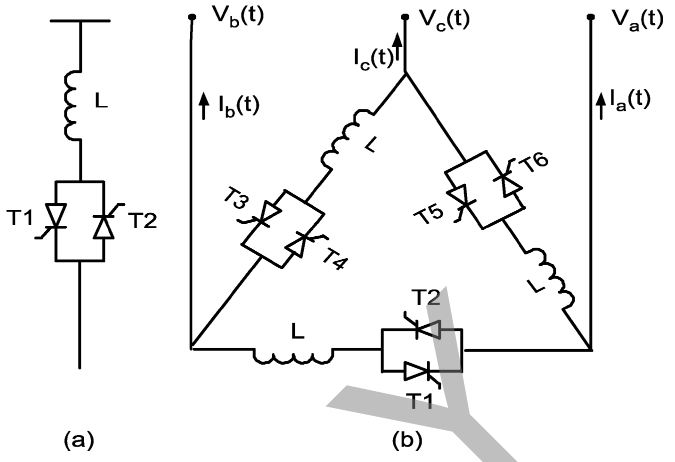

Fig. 2. (a) Basic TCR (b) 6-pulse TCR bridge.

### *C. Thyristor Controlled Reactor (TCR)*

Fig. 2(a) shows a TCR which consists of a linear inductor and anti-parallel thyristors connected in series [1]–[3]. TCR is usually applied to regulate the reactive power balance of a system by means of compensating for the surplus reactive power generation. Reactors are normally disconnected at heavy load and are connected to the lines at light load. The simplest design of TCR uses three single phase thyristor valves connected in delta making a six pulse unit as shown in Fig. 2(b). The variation of current is obtained by controlling the firing angle of the thyristor and thus through a variable conduction angle for the inductor. The six pulse scheme does not produce substantial third harmonics but it produces considerable fifth and seventh harmonics that might in most cases require the use of harmonic filters to minimize distortion in the power supply. TCR is generally used with Fixed Capacitor (FC) or a TSC in order to supply reactive power as it is required by the system.

Although the physical connections of TCR and TSR are the same (a series or parallel combination of the reactors with the thyristors), their difference lies in their control strategy. The effective reactance of a TCR is controlled continuously by partial conduction control (firing at different angles) but in TSR the effective reactance is controlled by full or zero reactance (no partial conductance by firing at variable firing angle). Several models [10]–[14] of TCR have been used for simulation in EMTP and the most commonly applied models are described in this section.

*1) Simplified ATP Model of TCR [10]:* Shunt reactor current interruption produces extremely high over-voltage due to the interruption of inductor current before its natural zero crossing. In order to investigate the turn-to-turn over-voltages a comprehensive computer model of the reactor and the surrounding network

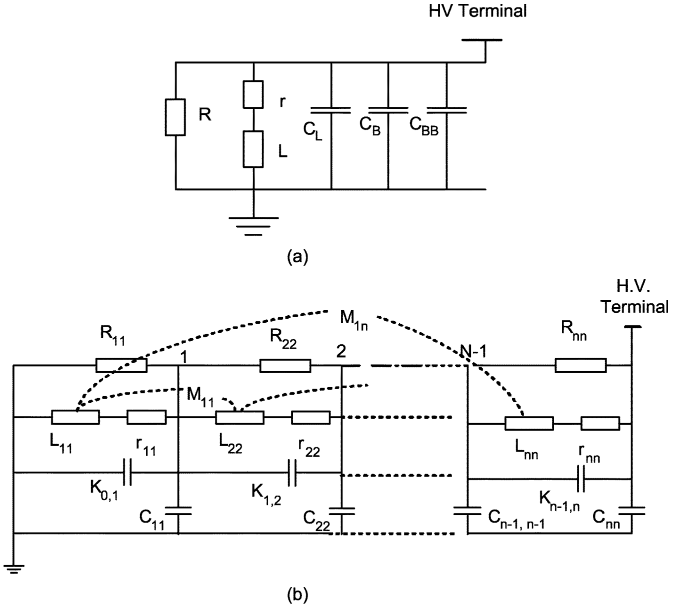

Fig. 3. (a) Simple TCR model: $r = 20\,\Omega, R = 2\,\mathrm{M}\Omega, L = 6\,\mathrm{H}, C_L = 3\,\mathrm{nF}$, $C_B = 0.6\,\mathrm{nF}$, $C_{BB} = 2\,\mathrm{nF}$, (b) detailed model of TCR.

needs to be considered. Fig. 3(a) represents the TCR model where turn-to-turn stresses due to over-voltage has not been considered, however, surrounding apparatus such as bus-bar capacitance, bushing capacitance, and resistance of the reactor are considered. In its simplest form, a shunt reactor is modeled as a two port equivalent of an inductor in parallel with a capacitor. The linear unsaturated inductance, $L$ and capacitance, $C$ are related by the equation

$$C = (4\pi^2 f^2 L)^{-1} \tag{1}$$

Where $f$ is the frequency of the free oscillation. The capacitance $C$ is comprised of reactor capacitance $C_L$, bushing capacitance $C_B$ and the bus-bar capacitance $C_{BB}$

$$C = C_L + C_B + C_{BB} \tag{2}$$

The copper losses, dielectric losses and core losses of the reactor have been represented by lumped serial/parallel resistances. Typical values of model parameters for a shunt reactor bank that consists of three 110 MVAr single phase units are shown in Fig. 3(a).

*2) Detailed ATP Model of TCR [10]:* The simplified model fails to provide any information about the internal stresses of the reactor and it would not be able to predict the local over-voltages accurately. Therefore, a comprehensive EMTP model is shown in Fig. 3(b) that is based on $n$ part inductively coupled elements. The homogeneous single-layer winding consists of $n$ pieces of part-windings with self inductance $L_{ii}$ and $(n-1)$ mutual inductances $M_{ij}$ to the others. The shunt capacitors $C_{ii}$, series capacitors $K_{i-1,i}$ and the resistors $r_{ii}$ and $R_{ii}$ represent the losses in part-windings. The mutual inductance between two coupled coils is given as a function of the self inductances and the coupling factor $q$

$$M_{ij} = q\sqrt{L_{ii}L_{jj}} \tag{3}$$

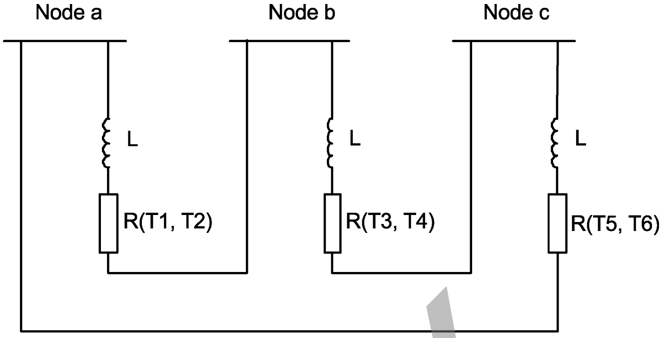

Fig. 4. Model of a 6-pulse TCR.

In case of homogeneous winding the mutual inductance between the two neighboring windings is equal to $L_{ii}q$ and the mutual inductance between the $i$-th and $j$-th part of the winding can be expressed as

$$M_{ij} = L_{ii}q^{i-j} \tag{4}$$

The inductance matrix $\mathbf{L}$ of the reactor contains $n$ elements of $L_{ij}$ in the main diagonal and $(n-i)$ elements of $L_{ii}$ multiplied by the $i$-th power of $q$ in the $i$-th parallel sub-diagonal. Since the total inductance of the entire winding must remain the same regardless of the number of the pieces the winding has been split into, the sum of the elements of the matrix must be equal to the resultant inductance of the entire winding. Then, the elements of $\mathbf{L}$ can be derived as

$$L_{ii} = L\left[n + 2\sum_{k=1}^{n-1}(n-k)q^k\right]^{-1} \tag{5}$$

*3) Discrete-Time Domain Model of TCR [11]:* A three-phase delta-connected TCR (Fig. 2(b)) has been modeled in [11] using a voltage control algorithm and then a discrete-time model has been formulated for EMTP simulation. Fig. 4 shows the developed model where, each TCR is represented by an inductor in series with a time-varying resistor whose value depends on the firing angle of the thyristors. Bidirectional thyristor switches are denoted by $R(T1, T2)$, $R(T3, T4)$ and $R(T5, T6)$ and they are brought together in a diagonal matrix for the three-phase six-pulse configuration. Then the resistance matrix $\mathbf{R}$ can be expressed as, $\mathbf{R} = diag[R(T1, T2), R(T3, T4), R(T5, T6)]$ where, $R(Tx, Ty) = 0$ when either $Tx$ or $Ty$ conduct and $R(Tx, Ty) = \infty$ when both $Tx$ and $Ty$ do not conduct. The details of the nodal analysis and integration of TCR model into the discrete-time network model can be found in [11].

*4) Other TCR Models:* Another work [12], characterized TCR as an inductance in parallel with bi-directional thyristor switch and showed that it can be used in series with capacitance to control the power flow and short circuit current. The value of the inductance and hence the voltage across the inductance is controlled by regulating the firing angle of the thyristor. Numerical analysis and EMTP simulation have been performed and it has been shown that current can be controlled effectively and it contains less harmonics than the inductance voltage. A study on experimental laboratory modeling of nonlinear loads and reactive shunt compensation has been reported in [13]. The six-pulse delta connected TCR in this study is similar to the

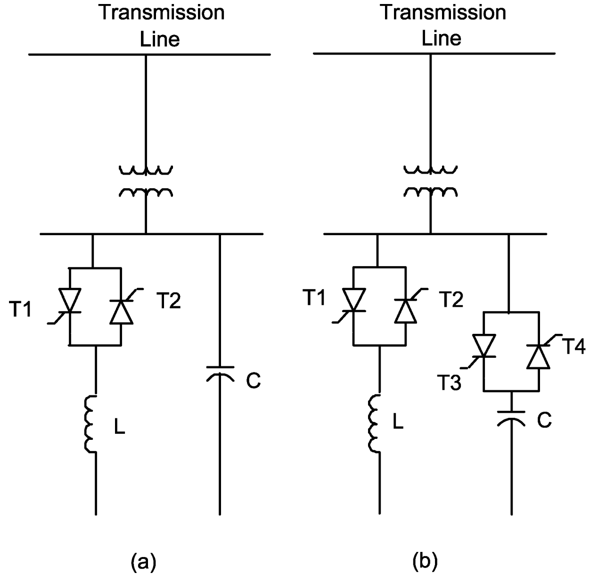

Fig. 5. One line diagram of SVC (a) TCR-FC (b) TCR/TSR-TSC.

one in [11]. The control system uses microprocessor based fast voltage controlled algorithm.

Modeling guidelines for producing benchmark models for TCR based compensators such as SVC and TCSC are described in [14]. The benchmark models are aimed for use with EMTP-type programs. One of the proposed model portrays TCR as a linear reactor connected in series with back-to-back connected thyristors. The susceptance of the TCR as a function of the firing delay angle $\alpha$ can be expressed as

$$B_L(\alpha) = \frac{I_L(\alpha)}{V} = \frac{1}{\pi\omega L}(2\pi - 2\alpha + \sin 2\alpha) \qquad (6)$$

where $I_L(\alpha)$ is the TCR fundamental current. Equation (6) can also be expressed in terms of conduction angle $\sigma(= 2\pi - 2\alpha)$.

For incorporating this model into a power system network, the three-phase power circuit including transformers with appropriate wye-delta phase shifts needs to be modeled in detail. A basic PLL control system is employed to track the ac voltage and to generate the gating pulses for the thyristors.

### D. Static VAr Compensator (SVC)

SVC is a reactive power generator [1]–[3] whose output is varied to maintain or control specific parameters such as voltage level or reactive power flow of the power system. SVC provides controlled reactive impedance employing thyristor-controlled and thyristor-switched reactors and capacitors and thus either absorbs or generates shunt reactive power at its point of connection. Based on the combination of its constituent reactive elements SVC can be categorized into three types: (1) thyristor control reactor and fixed capacitor (TCR-FC) (2) thyristor switched reactor and thyristor switched capacitor (TSR-TSC) (3) thyristor controlled reactor and thyristor switched capacitor (TCR-TSC). Fig. 5 shows one line diagrams of different types of SVC. In three-phase systems the SVCs are connected in Y or $\Delta$. In order to reduce current harmonic injection into the power system 12-pulse configurations are often used [14]. SVCs are typically used for providing dynamic voltage and reactive power support and thereby improving power quality and stability of the system.

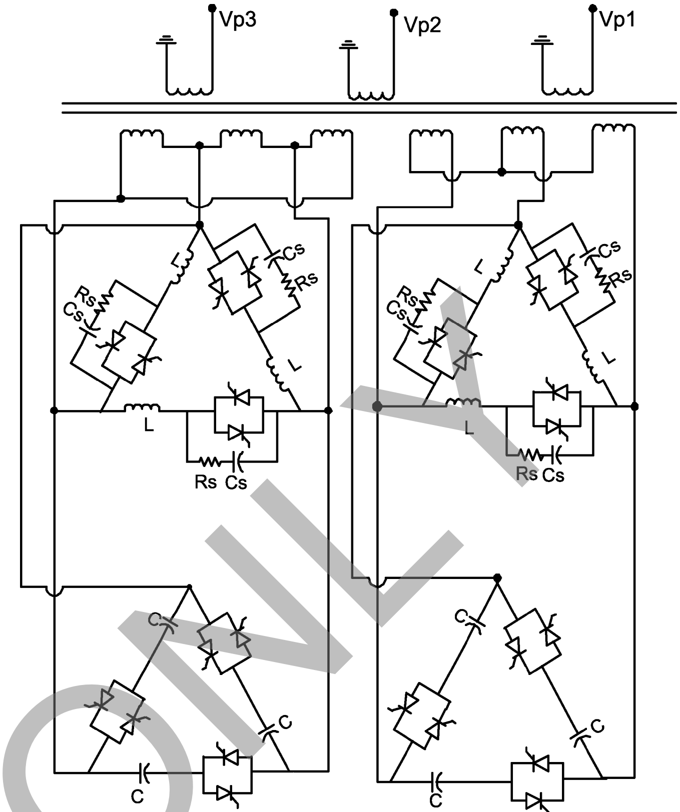

Fig. 6. SVC circuit diagram.

*1) State-Space Based SVC Model [15]:* SVC model based on state variable approach which is capable of being interfaced to a host EMTP or EMTDC program has been described in [15]. During thyristor switching, the SVC model uses smaller time-steps than the one used by host electromagnetic transient program. After the switching the SVC model is capable of reverting back to a larger time-step that is compatible with the one used by the parent program. Fig. 6 shows the schematic diagram of the SVC that has been modeled using EMTDC. The model has used an SVC transformer which consists of nine magnetically coupled windings on the same core with three windings for primary, and three each representing Y and $\Delta$ secondaries. The $\Delta$ connected TCR elements are modeled as inductances in series with the thyristor switches modeled as variable resistors and the snubber circuits are modeled as R-C elements. The TSC branches are modeled as single equivalent capacitors with initial voltages regardless of the number of the capacitors in each branch/phase. This has the advantage of using only one state variable for each phase. For simplicity, the current limiting series inductance is not considered.

Saturation of the transformer is represented by flux-dependent current sources in parallel with the transformer windings. The flux has been calculated along the integral of the voltages across the winding. A flux vs magnetizing current curve is then built to determine the extra amount of magnetizing current to be injected. Hysteresis loss has not been considered but core loss has been modeled using a shunt resistor across each winding.

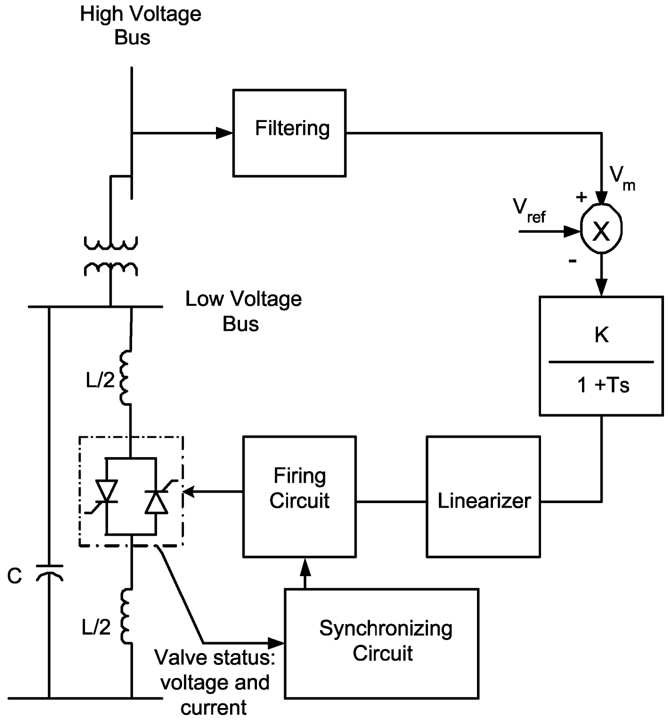

Fig. 7. SVC with its control system.

The model uses a total of 21 state variables to describe the SVC. The matrices in the state-space equation are functions of the states of the thyristors, and the appropriate entries are re-calculated when the firing logic requires the turning on and off of thyristors. The capacitor voltages and the capacitor values are also initialized when the TSC operates.

*2) SVC Model Based on Nodal Analysis [16]:* The simplest SVC with TCR-FC has been modeled and then integrated into EMTP through a user-defined data module [16]. It includes a reactor in series with a bi-directional thyristor-valve pair and a fixed capacitor. The reactor is split into two units with one unit on either side of a valve, in order to limit valve fault currents. The TCR is considered as a controllable susceptance $\mathrm{B}(\alpha)$ given by (6).

Using trapezoidal method and nodal analysis, the network equations are formulated by the well known equation $\mathbf{YV} = \mathbf{I}$. In EMTP, thyristor valves are modeled as a switch and SVC is incorporated into the $\mathbf{Y}$ matrix. The switching of a thyristor is a time-varying topology requiring $\mathbf{Y}$ to be rebuilt and re-triangulated. In this case, SVC modeling has been carried out by using nested EMTP Data Modules (EDM) which allows variables to be substituted. A module is simply an ASCII file describing EMTP data or models from the TACS where SVCs of different ratings can be connected at arbitrary buses. All equations associated with EDM are automatically discretized either into the $\mathbf{Y}$ matrix of EMTP or that of TACS which is used to model the TCR-FC controls. The SVC model in Fig. 7 is constructed from basic modules consisting of transformers, thyristor valves (switches and snubbers), reactors, shunt capacitance banks and harmonic filters.

1) `Transformers` This module consists of interconnected single-phase saturable transformers and linear leakage reactance simulated by standard EMTP.
2) `Thyristor Valves` Thyristor valves are modeled as grid controlled switches. A damping RC circuit in parallel with the valves is used to reduce numerical oscillations. The valves are connected as delta and the required grid signal is produced from the controller modeled by TACS.
3) `Control System` This module consists of several sub-modules including measurement circuit, voltage regulator, linearization circuit, conduction angle order $\sigma$, the synchronizing circuits and the firing pulse generator entirely described by TACS statements. It is possible in the control module to change the main settings of the input filters, the slope and the time constant of the regulators through modification or creating sub-modules.
4) `Filtering` This module can be modified by the user and may vary somewhat but its general characteristics remain the same. The dc side typically uses 60-120-360 Hz notch filter and ac side uses high-pass filters to eliminate harmonics.

*3) Detailed EMTP Model of SVC [17]:* A detailed and flexible model of SVC employing TSCand TCR has been developed in [17]. The salient features of this model are as follows:

- The model is flexible enough to represent different SVC configuration including the two most widely used FC-TCR and TSC-TCR.
- The two main components of the SVC control system are: the PLL and the voltage regulator loop, both modeled with TACS.
- A modeling technique based on EMTP data modularization has been adopted. The steady-state model initialization is improved by using EMTP Data Modularization.
- The model has been developed with the EPRI-DCG EMTP version 2.0.

The major elements of SVC system are described below:

1) `TCR` A three-phase TCR is modeled by three delta-connected single phase branches each having anti-parallel thyristor valves connected in series between two reactor units. The thyristor valves are controlled as a six-pulse group by gate signals coming from TACS.
2) `TSC` A three phase TSC unit consists of three delta connected branches each having a pair of anti-parallel thyristor valves in series with a capacitor bank and a tuning and/or current limiting reactor. A TSC firing circuit controls the TSC unit which allows the capacitor bank either fully on or off. The model allows connection of a number of TSC unit in parallel to achieve a multiple step control of capacitive MVAr.
3) `Harmonic Filters` The SVC model considered two types of harmonic filters: single tuned band-pass type and the high-pass type damped filter. A three phase filter unit consists of three identical filter branches in a wye-connection with the neutral floating or grounded through an impedance branch.
4) `PLL Control` The phase locked loop (PLL) produces an output pulse train in response to an input ac voltage

signal, reducing the phase error between the signals by negative feedback control. The phase locked loop consists of four functional blocks: a phase comparator, a PI regulator, a voltage controlled oscillator and a frequency divider. The output signal of the phase locked loop is used as the reference for the firing angles of the TCR and TSC.

5) `Voltage Regulator` The voltage regulator performs the closed loop voltage control. The difference between the voltage reference and the network voltage response is fed as the control error signal to a PI regulator which changes the total SVC susceptance with the aid of higher level control blocks.
6) `Allocator` The allocator converts the susceptance reference signal obtained from the voltage regulator to logical orders (On/Off) for the TSCs and arithmetic orders for the TCRs. The output of the module contains two quantities: The number of TSC unit required to be in the circuit and the susceptance order for the TCR.
7) `Linearizer` The linearizer converts the susceptance order from the allocator to a firing angle order $\alpha$ which is measured from the time of the last voltage peak.
8) `TCR Firing Circuit` The TCR firing circuit generates firing pulses to the three-phase TCR unit. The synchronizing signal from the PLL circuit and the firing angles determined by the linearizer are the inputs to the TCR firing circuit. The pulse is directed to one of the anti-parallel thyristor valves.
9) `TSC Firing Circuit` The TSC firing circuit generates firing pulses to the three-phase TSC unit. Each TSC unit is assigned a priority number by the user and they are turned on sequentially from the lowest priority number to the highest.
10) `Measurement Circuit` The purpose of measurement circuit is to provide the voltage regulator with the power system voltage response. The model allows different techniques for the representation of the measurement circuit.

In addition to the above elements, some typical SVC control functions such as TCR over-current control, secondary overvoltage limiter, under-voltage strategy are also included in the model. Further details can be found in [17]. A similar detailed EMTP-TACS model of an actual SVC was presented in [18] and the transient simulations were verified using TNA studies. Main components of the SVC such as power circuit, control system, measuring circuits and voltage regulators, synchronizing and firing circuits, current limiter are discussed comprehensively. In addition, the Under-voltage Blocking Scheme (UBS) and the BOD Blocking Scheme (BBS) are the two special features described in this work.

*4) SVC Model Using EMTP Data Modularization [19]:* A digitally controlled SVC used for optimal load compensation has been studied in [19] using ATP. The major units of the SVC are the power circuit that consists of TCR and FC unit and the control system. The power circuit is formed by three delta-connected single-phase branches each one having anti-parallel thyristors in series with a reactor unit and three delta connected fixed capacitors. Surrounding power system components such as the sources, lines, switches and the digital controller are modeled using EMTP Data Modularization technique described in [20]. Details of these rules can be found in [21]–[23].

*5) Detailed Model of SVC Using PSCAD/EMTDC [24]:* Transient performance of SVC has been studied using PSCAD [24] mainly during faults, switching, load rejection and energizing of transformers and shunt reactors. The SVC model including its control system has the following main components.

1) `TCR and Phase Control` The TCR reactor is considered as a continuously variable reactor and delta connected with each leg comprising air cored inductors in series with anti-parallel line commutated thyristors. A TCR controller is implemented as standard model block in PSCAD/EMTDC and for each independent phase consists of a phase locked oscillator, firing latch and a triggering pulse generator.
2) `TSC and Harmonic Filters` The SVC model includes shunt capacitor banks which allow it to supply reactive power to the supply system and provide voltage support. Dynamically controlled capacitive support is supplied by TSCs and adjusted by control of relatively smaller TCR. Each TSC comprises delta connected legs with a capacitor bank and air-cored inrush-limiting inductor in series with anti-parallel line commutated thyristors. An iron-cored transformer together with resistors in each phase are used to reduce the voltage stress on the thyristors after turn-off. Surge arrestors across the thyristor valves are used to protect against excessive transient voltages. Two filter banks tuned at 5th and 7th harmonics frequencies are used to absorb the dominant harmonics produced by the TCR.
3) `Other SVC Equipment` The SVC step-down transformer model in PSCAD includes representation of its leakage reactance and magnetizing current which is dependent on the level of magnetic saturation in its iron core. For fast transient analysis stray capacitances between windings and to earth is also considered. The SVC bus-bar is represented by distributed transmission lines.
4) `Other SVC Control Systems` Other than the main SVC control, a supplementary control loop is introduced to allow co-ordination with other reactive power sources.

*6) Other SVC Models:* A model similar to [17] for digital simulation of SVC using TCR-FC has been presented in [25]. The method describes simultaneous digital simulation of thyristors, their Gate Pulse Generating (GPG) circuit and the interface with the power system. The model consists of digital representations for the individual components found in the circuit, the logic elements in the GPG which is simulated using TACS. Linear elements such as TCR reactors are represented by lumped parameters. The coupling transformer is modeled as interconnected single-phase saturable transformers and linear reactors. Thyristor valves are modeled as grid controlled switches using TACS. Snubbers are used to prevent numerical oscillations.

A simple model of SVC (power circuit and control) is discussed in [14]. In that model, TCR is paired with either a set of

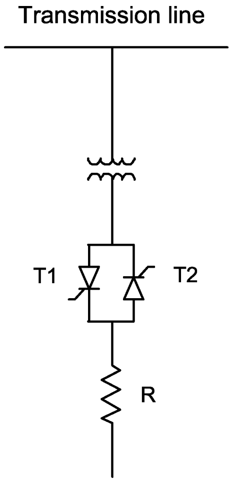

Fig. 8. Schematic diagram of TCBR.

TSR or TCR and TSC modules. Multiple levels of control are employed and synchronization of TCR firing is done with respect to phase voltage. Protection circuits for over-current in the thyristors and over-voltage on the capacitors are also included.

A comparative analysis of the field tests and digital simulations using EMTP-TACS for the commissioning of a $-50/+70$ MVAr SVC in Brazil has been reported in [26]. The SVC consisted of TSC (60 MVAr), TCR (60 MVAr) and a fifth harmonic filter (10 MVAr). These units were connected to a 230 kV bus bar system.

### *E. Thyristor Controlled Braking Resistor (TCBR)*

As shown in Fig. 8, TCBR is a shunt connected thyristor switched resistor which is controlled to aid stabilization of a power system or to minimize power acceleration of a generating unit during a disturbance [1]. It is used to damp low frequency oscillations with or without firing control. It involves switching of a resistor (usually linear) by a thyristor based ac switch. The EMTP model of TCBR would mainly consists of anti-parallel switches connected in series with a resistor. The application of a dynamic brake at the generator terminal has been studied in [27]. Two types of dynamic brake configuration have been considered: a three-phase, bi-directional, full-wave, Y-connected phase-controlled ac/ac converter and a three-phase, full-wave, thyristor-controlled rectifier bridge. A simple rule-based on-off control law based on the local measurements of generator output power and its derivative is proposed. The model and its control system has been validated through detailed digital simulation studies using PSCAD/EMTDC.

## III. STATIC SERIES CONTROLLERS

Series controllers [1] are employed in transmission lines in order to control the overall reactive voltage drop across the line and hence to control the transmitted electric power. A series controller could simply be a variable impedance such as capacitive reactance or a quadrature voltage injection obtained using a VSC with or without the aid of an external energy source. Examples of the former category of series controllers include TSSC, TCSC, GTO-CSC and ASC.

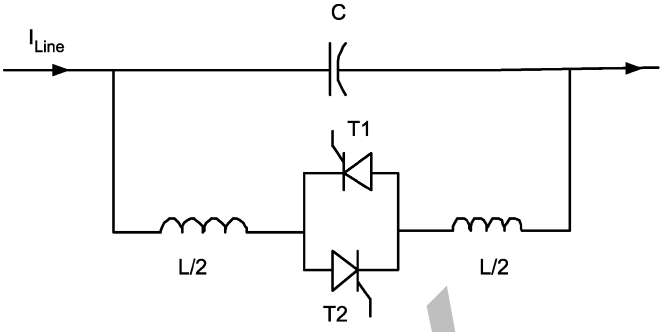

Fig. 9. Schematic diagram of TSSC/TCSC.

### *A. Thyristor Switched Series Capacitor (TSSC)*

TSSC is a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-switched reactor to provide a step-wise control of series capacitive reactance [1]–[3]. By switching the anti-parallel thyristors the capacitor can be placed in and out of the transmission line. Owing to its simple configuration a TSSC can be modeled in EMTP using lumped Cs, Ls and thyristor switches. Such a basic model for TSSC has been developed in [9] and implemented using ATP. Fig. 9 shows the schematic diagram of a TSSC and TCSC which are same in terms of physical connection but different in operation and control.

### *B. Thyristor Controlled Series Capacitor (TCSC)*

TCSC is defined [1] as a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance. TCSC normally employs line-commutated thyristors but self-commutated GTOs are also used. A TCR is connected across the capacitor to provide variable reactance. When the TCR firing angle is 180° the reactor does not conduct and the impedance is capacitive, but for a firing angle of 90° the reactor is in full conduction and the total impedance is inductive. TCSC can be a single large unit or may consists of several small units connected in parallel to yield better control.

Most of the TCSCs applied in power systems work in three different modes: Thyristor Switched Reactor (TSR) mode, Waiting Mode (WTM) and Thyristor Blocked Mode (TBM). In TSR mode the thyristors conduct fully effectively bypassing the capacitor bank through the TCR, and the TCSC impedance changes from a capacitive to an inductive value. This mode provides the means of limiting the line current through the increase of line impedance. In WTM, the TCSC waits for a certain time with a fixed firing angle until another mode of operation is set. In TBM, the control firing signals are blocked and the TCSC becomes a series capacitor.

*1) Simplified TCSC Model [28]:* Fig. 10 illustrates a simplified TCSC model developed using EMTP and MODELS for simulating SSR in a 500 kV network of the N-W American Power System with installed series compensation. The TCSC is modeled by a capacitor, in parallel with anti-parallel thyristor switches and commutation inductor. The TCSC is also equipped with a bypass circuit breaker. Multi-mass model has been used for the mechanical system for studying SSR. Transmission lines are modeled using distributed parameters.

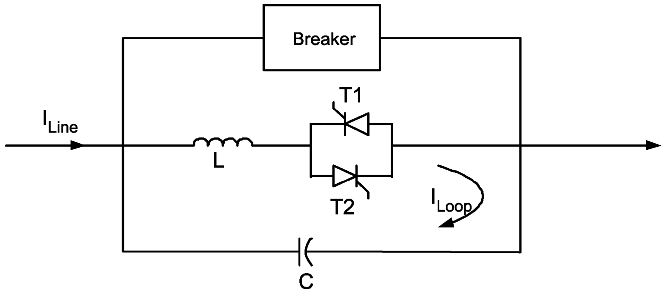

Fig. 10. TCSC model.

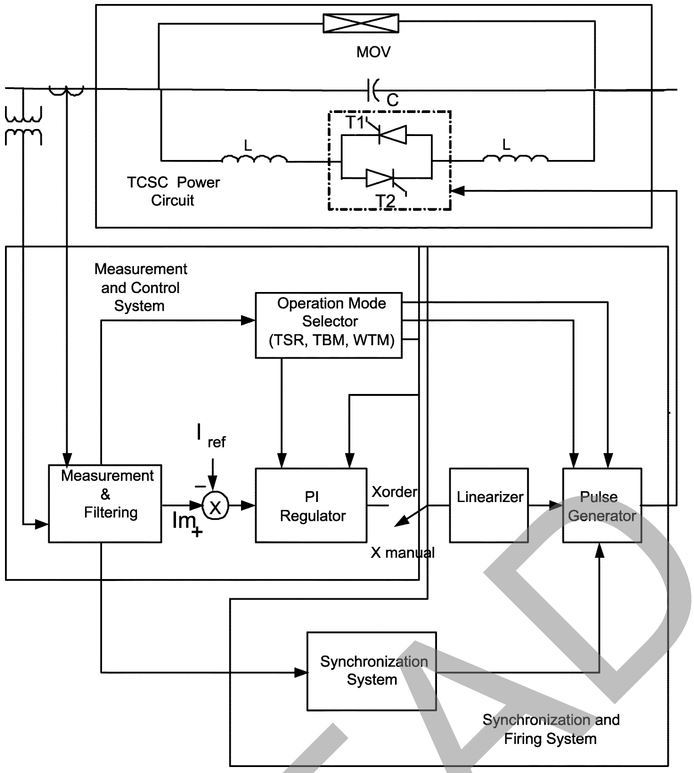

Fig. 11. TCSC and its control system.

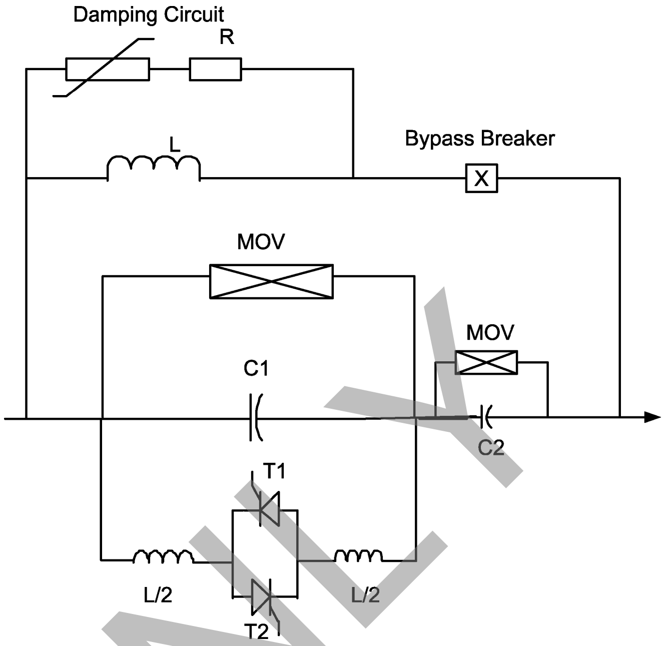

Fig. 12. Model of TCSC with protection system.

*2) Detailed ATP Model of TCSC [29]:* Fig. 11 illustrates the TCSC model developed using ATP. The TCSC controller was developed using both TACS and the MODELS language. Detailed description of the model can be found in [30], [31]. In the model, the TCSC is divided into three distinct systems: a power circuit, a measurement and control system, and a firing and synchronizing system.

1) Power Circuit The power circuit comprises of a capacitor bank in parallel with a thyristor controlled reactor and a MOV arrestor and a snubber circuit to protect the capacitor and to mitigate numerical oscillations. The MOV arrester was represented by an exponential gap-less surge arrester (type-92 device). Thyristor valves were represented as ideal AC switches in series with a small resistance that accounts for conduction losses.
2) Measurement and Control System The measurement and control system work independently in each phase and consists of a band pass filter (tuned to the fundamental), two notch filters (for 2nd and 4th harmonics), a current quadratic measurement device, an active power measurement device and a PI controller. The operation mode selector in Fig. 11 is capable of acting automatically or manually and it operates the TCSC in two main modes: Closed Loop Current Control (CLCC) and Open Loop Impedance Control (OLIC). In addition, it can also select the operation strategy from TSR, TBM and WTM.
3) Firing and Synchronization This system consists of a linearization curve, a pulse generating unit and a synchronization unit that is based on either an individual firing pulses or an equidistant firing pulses such as a PLL. The operation mode selection of TCSC is performed using logical equations in MODELS. The linearization curve was modeled by a TACS device-56. The pulse generating unit is based on a sawtooth generator that adjusts its frequency to follow the line current zero crossings. It also includes an *unconditional fire* feature which is used for firing the thyristors continuously and to put the TCSC in TSR mode or to provide protective firing. The synchronization signal which is based on line current zero-crossing detection is fed to a filter which provides a phase-shift of 90°. Therefore, in steady state the synchronization signal remains in phase with the capacitor voltage.

*3) TCSC Model With Multi-Level Control [14]:* A TCSC model with three control levels for transient analysis using an EMTP-type program is described in [14]. The model consists of the basic power circuit and control system as its two main components. External over-voltage protections such as MOVs and bypass breakers are also included in the model. The power circuit (Fig. 12) is similar to the one described in Section III-B-2. The three-level control system is the key feature of this model. The lower level control creates the firing pulses for the thyristors. A PLL is used to synchronize the switching with the power system frequency, based on either voltage or current measurements. The lower level control also generates the gate pulses with the required phase delay as commanded by the intermediate level controller. One source of concern in obtaining an accurate model is the impact of the time-step discretization on the gate pulses. Some EMTP-type programs are capable of adjusting this through interpolation during switching and then using larger time-steps for the remainder of the simulation. Others use smaller time-steps throughout to avoid difficulties with switching between time-steps. The intermediate level controller provides the control objective for the converter. For example, the TCSC could be controlled to insert a specific reactance or voltage in the line, or to provide damping of SSR. The control quantities would then be used to produce the necessary firing delay angle. The outer control level represents the converter protection functions.

*4) Analytical Models of TCSC [32]–[38]:* Most of the analytical models in the literature aim to predict the behavior of TCSC and its interaction with the power system using differential equations. However, nonlinear phenomena such as thyristor switchings and passive damping make it difficult to model the system accurately. Linearization is then adopted to express the system equations in a form amenable to digital simulation. Simulation results are then validated by using EMTP-type programs. The analytical models have been mainly used to study SSR phenomenon.

Details of TCSC dynamics for three operating modes based on state-space analysis are reported in [32]. Transient characteristics as well as steady-state characteristics of the TCSC are studied using a system of one machine connected to an infinite bus through a thyristor controlled series compensated transmission line. The switching of the thyristor is linearized using a switching function [33]. The TCSC transmission system is modeled using nonhomogeneous differential equations with periodic coefficients. State-space techniques are then used to solve the analytical equations. Simulations are performed using MATLAB and then validated using EMTP.

An accurate analytical model of the TCSC which is valid in the frequency range from 0 Hz to twice the operating frequency is presented in [34]. The objective of the study was to develop a continuous-time model of the main circuit of the TCSC which accounts for the effects of thyristor switchings on capacitor voltage. The model incorporates the thyristor triggering logic, the synchronization system and higher level control loops such as power oscillation damping loop. The inputs to the model are the capacitor voltage, $d-q-o$ components of line current and the triggering time. The output of the model is the capacitor voltage after one half cycle. This model is suitable for linearized analysis of a power system using frequency domain methods.

A linear TCSC dynamic model is obtained by linearizing the half-period map associated with sampling the TCSC capacitor voltage twice every cycle in [35]. It also includes passive damping which varies with steady-state conduction angle of the TCSC. Dynamic phasor models [36], [37] have also been used to study SSR in a TCSC compensated transmission line. These models are an alternative to sampled-data models and are based on the representation of voltages and currents as time-varying Fourier series. A comparison based on digital simulation between the quasistatic model and dynamic model of TCSC can be found in [38].

*5) Other TCSC Models:* Digital simulation of a TCSC based EHV transmission system has been performed in [39] where a method for simultaneous modeling of thyristors, their control, firing circuits and protection equipment using EMTP-TACS has been described. The power circuit for the series compensation study includes TCR, fixed and controllable capacitors, and other typical components such as generators, transmission lines, transformers, and breakers. The paper studies a 500 kV system under both normal and faulted conditions. Tools for modeling TCSC along with other FACTS controllers in large ac systems are reported in [40]. Modeling and interfacing techniques for combined transient/dynamic analysis of HVDC and FACTS systems are described in [41]. In this study EPRI-DCG EMTP is interfaced with a Transient Stability Program (TSP) to simulate both HVDC and TCSC based systems.

The application of TCSC as a fault current limiter in distribution systems is investigated using EMTP in [42]. A linearized discrete-time model of a thyristor controlled series compensated transmission line is presented in [43] where a TCR is used as the compensating device. The discretization is performed at the peaks of the capacitor voltage of the series compensator. Digital simulation is used to validate the robustness of a closed-loop controller designed using this model. Several other modeling and simulation studies of TCSC [44]–[55] have been found in the literature. Most of these studies either simulate or validate TCSC models using EMTP.

### C. GTO Controlled Series Capacitor (GTO-CSC)

GTO-CSC (Fig. 13(a)) is a continuously regulated series capacitor [1] that uses GTO switches to regulate the capacitor voltage directly instead of using thyristors in series with a reactor. The basic circuit consists of a capacitor across a pair of anti-parallel GTO switches. Although a GTO-CSC can be switched at zero voltage, care needs to be taken for high $di/dt$. Multi-module (several GTO-CSCs in series) and multi-pulse (6-pulse or 12-pulse) configurations have been used in [56], [57] for reducing or canceling output voltage harmonics.

*1) EMTP Model for GTO-CSC [56], [57]:* Several configurations using different number of modules and different pulse arrangements of GTO based CSC were simulated in EMTP. A GTO device [7] (Fig. 13(b)) can be built in EMTP using a controlled bi-directional current flowing switch (type-13 switch) in series with a diode. Fig. 13(c) shows multi-module configuration where $n$ GTO-CSC modules are modeled. Each module involves a small GTO-CSC with a fixed capacitor. Fig. 13(d) shows the system that has been simulated using a single module GTO-CSC.

### D. Advanced Series Compensator (ASC)

The ASC is made up of a fixed capacitor in parallel with a TCR. The fundamental impedance of the ASC unit is similar to that of a parallel LC tank circuit. As the conduction time of the TCR increases, the equivalent capacitive reactance increases and when the TCR is fully off, the ASC becomes a series capacitor.

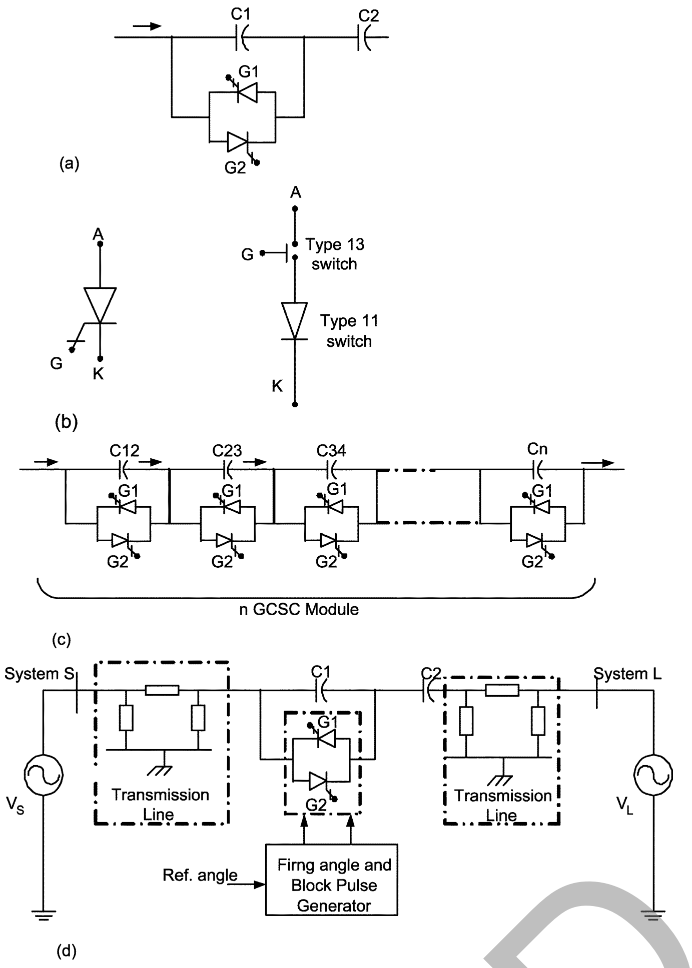

Fig. 13. (a) GTO-CSC (b) EMTP model of a GTO (c) multi-module GTO-CSC (d) test system with GTO-CSC.

*1) ASC Models [58]–[60]:* Several analytical models of ASC have been proposed based on algebraic and differential equations. EMTP has been used to validate the results obtained from these models. The simplest model for ASC would consist of a capacitor in parallel with a series combination of an inductor and anti-parallel thyristors. A stability model of an ASC is described and validated using EMTP in [58]. In [59], an EMTP model of an ASC based *Rapid Adjustment of Network Impedance* (RANI) scheme is described. In this model, a constant current source of 2 kA rms was supplied to the RANI element on a 500 kV transmission line as shown in Fig. 14(a). Another form of ASC [60] includes a series string of capacitor modules (Fig. 14(b)) that are individually switched by anti-parallel thyristor pairs. A novel damping and protection scheme for the capacitor modules has also been proposed. EMTP simulation of this model includes line modeled using distributed parameters and generators modeled as voltage sources behind reactances. A Kalman filter based adaptive protective scheme for ASC based transmission lines is tested using EMTP in [61].

## IV. COMBINED SHUNT AND SERIES CONTROLLERS

Combination of shunt and series controllers are designed to provide best control of both real and reactive power flow by controlling the transmission line voltage, impedance and phase angle simultaneously. Controllers of these kind include static phase shifter (SPS) and thyristor controlled phase angle regulator (TCPAR), thyristor controlled voltage magnitude regulator (TCVMR) and the “Sen” transformer (ST).

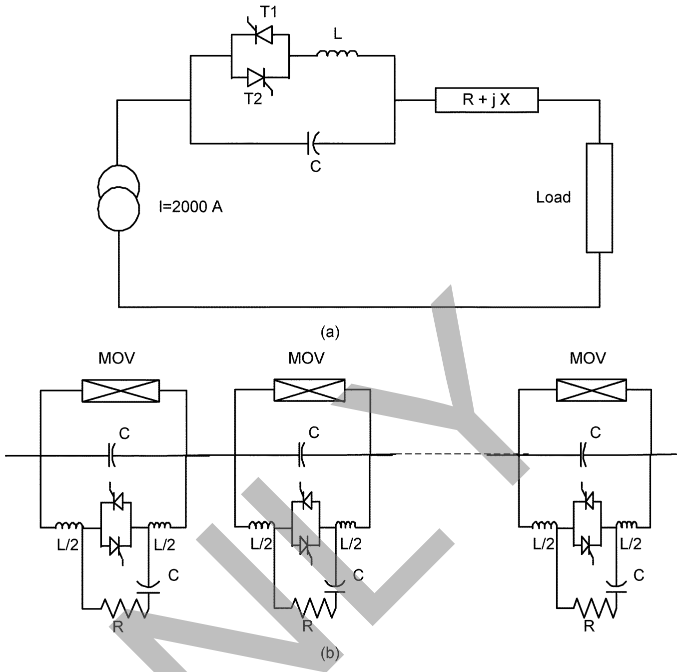

Fig. 14. (a) EMTP model of ASC (b) multi-module ASC.

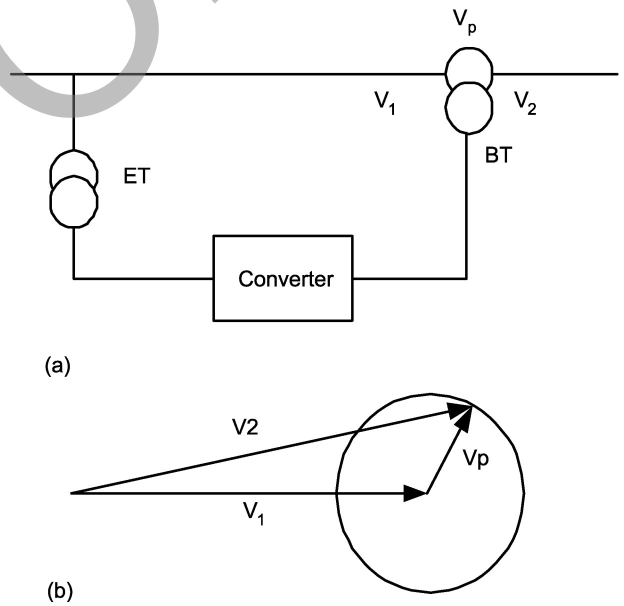

Fig. 15. (a) Schematic diagram of SPS (b) phasor diagram.

### A. Static Phase Shifter (SPS)

The main function of a SPS is to inject an ac voltage of variable magnitude and phase angle in series with a transmission line thereby controlling power flow on the line [62]. Fig. 15(a) shows the schematic diagram of a general type SPS whose input is provided by a shunt connected excitation transformer (ET)

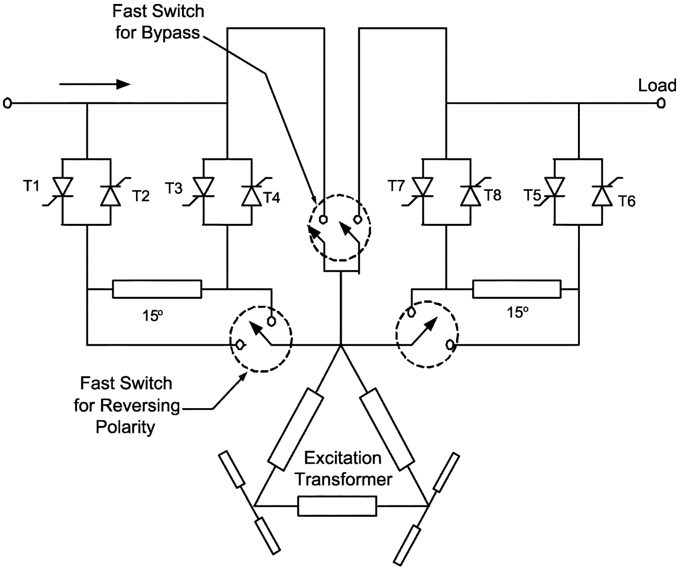

Fig. 16. TCPAR circuit.

and whose output voltage is injected in the system by the series booster transformer (BT). The converter controls the magnitude and/or phase angle of the injected voltage $V_p$. Typical application of SPS include: (1) improving transient stability, (2) damping inter-area oscillation, (3) mitigating SSR and (4) controlling loop power flow.

Depending on the construction and circuit arrangements, SPS has been classified into several categories. A comprehensive review of the various categories can be found in [63], [64]. Of these schemes some use thyristor based converters while others employ VSCs with the capability of injecting real or reactive power as well as controlling the frequency of the injected voltage. The VSC based SPSs are beyond the scope of this paper. A typical thyristor based phase angle regulator and its EMTP model is described in the next section.

### *B. Thyristor Controlled Phase Angle Regulator (TCPAR)*

Phase shifting in TCPAR is achieved by adding a quadrature voltage vector in series with a phase. The voltage vector is derived from the other two phases via a shunt connected transformer and it is made variable with the help of various thyristor topologies. Thus, a controllable voltage injection is obtained where the phase-angle between the voltages at the two ends can be varied in the range of $-\sigma_{max} \leq \sigma \leq \sigma_{max}$, without changing the magnitude of the injected voltage [1], [2]. TCPAR is also referred to as *Thyristor Controlled Phase Shifting Transformer* (TCPST).

*1) EMTP Model for TCPAR [65]:* Fig. 16 shows the circuit topology for a quasi bi-directional single core transformer TCPAR, that has the capability for a multi-step 0 to 30° or 0 to −30° phase-angle regulation. Fig. 17 shows the one-line representation of the EMTP model. All the anti-parallel thyristors ($T_1$ to $T_8$) are modeled as ideal switches and their closing and opening is specified at zero current. The transmission lines at the two ends are represented as lumped T models consisting of series impedances $Z_1$ and $Z_2$ and shunt admittances $Y_1$. $Z_{t1}$ and $Z_{t2}$ represent the impedance of two windings of the transformer.

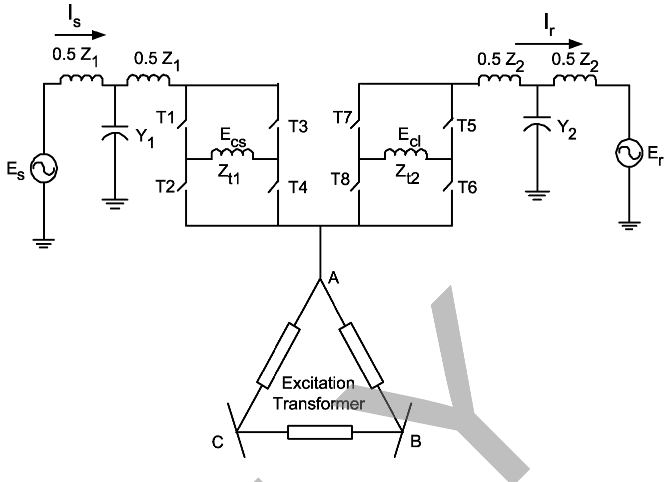

Fig. 17. EMTP model of TCPAR.

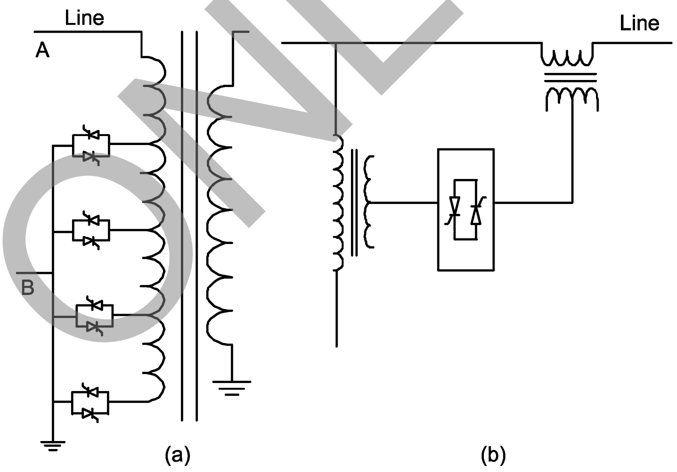

Fig. 18. (a) TCVMR based on tap changer (b) TCVMR based on voltage injection.

### *C. Thyristor Controlled Voltage Magnitude Regulator (TCVMR)*

A TCVMR is either a regular transformer with thyristor controlled tap changer or with a thyristor controlled ac to ac voltage converter for injection of variable ac voltage of the same phase in series with the line [1]. Fig. 18(a) shows a single phase TCVMR based on tap changer. Fig. 18(b) shows another kind of TCVMR that is based on voltage injection in the same phase. EMTP model of a TCVMR includes a transformer with on-line tap changer (OLTC). A change in tap setting can be modeled as a change in the turns-ratio of the transformer. The per-unit leakage reactance and magnetizing currents, specified for 100% tap, are used to calculate admittances for the new voltage rating, corresponding to the selected tap setting by the thyristor switches [66].

### *D. "Sen" Transformer (ST)*

The ST is mainly an autotransformer which connects a compensating voltage of line frequency but variable magnitude and phase angle in series with the transmission line, in order to regulate voltage magnitude, phase angle, impedance or any combination of them on the transmission system [67], [68]. The compensating voltage exchanges both real and reactive

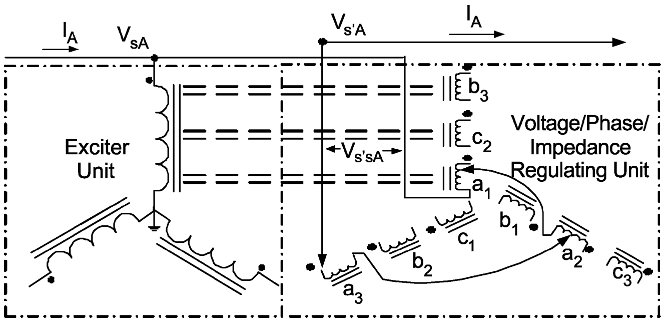

Fig. 19. Circuit diagram of ST.

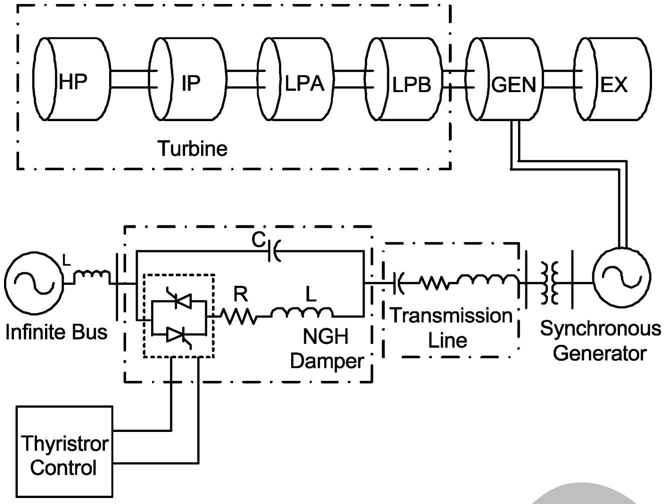

Fig. 20. EMTP model of the first IEEE benchmark system with NGH-SSR Damper.

powers with the line. As shown in Fig. 19, the voltage $V_s$ at any point in the electrical system is applied to a shunt-connected single-core three-phase transformer's primary windings. Nine secondary windings (a1, c2, and b3 on the core of A-phase, b1, a2, and c3 on the core of B-phase, and c1, b2, and a3 on the core of C-phase) constitute the voltage-regulating unit [67]. By choosing the number of turns of each of the three windings and by using taps (mechanical or solid-state), the compensating voltage in any phase is derived from the phasor sum of the voltages induced in a three-phase winding set (a1, a2, and a3 for connection in A-phase, b1, b2, and b3 for connection in B-phase, and c1, c2, and c3 for connection in C-phase). The model of ST can be constructed using built-in auto-transformer models in an EMTP-type program.

## V. AUXILIARY CONTROLLERS

### *A. NGH-SSR Damper*

Despite the numerous advantages of series capacitor compensation in long and medium transmission lines, issues related to the protection of such capacitors during line faults and sub-synchronous oscillations remained a bottleneck for practical implementation. A NGH-SSR Damper [1] is used for mitigating sub-synchronous electrical torque and hence mechanical torque and shaft twisting, and for protecting series capacitors from over-voltages. The basic scheme of an NGH-SSR Damper (Fig. 20) consists of an impedance in series with an ac thyristor switch connected across the capacitor. The objective of the damper is to force the voltage of the capacitor to zero at the end of each half-period if it exceeds the value related to the fundamental voltage component at power frequency.

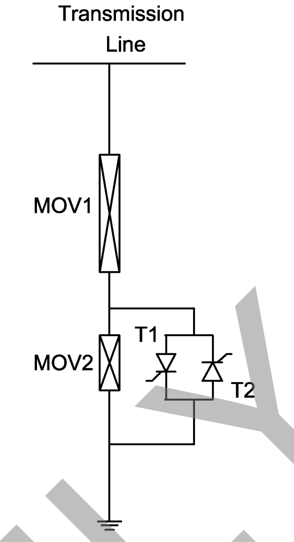

Fig. 21. Schematic diagram of TCVL.

Digital simulation [69], [70] of the first IEEE benchmark model of a series compensated system with NGH damper has been carried out to study the effectiveness of the damper for mitigating torsional interactions. The electrical portion of the system in Fig. 20 consists of synchronous generator, a step-up transformer, a transmission line, fixed series capacitors, NGH circuit and an infinite bus representing an ideal three phase voltage source. In the EMTP, NGH damper has been modeled as a capacitive reactance in parallel with resistors and thyristor valves. The mechanical portion of the system was modeled with six masses, representing high pressure turbine, intermediate pressure turbine, two low pressure turbines, the generator and the exciter which are mechanically coupled in the same shaft.

### *B. Thyristor Controlled Voltage Limiter (TCVL)*

A TCVL [1] is a thyristor switched metal-oxide varistor (MOV) used to limit the voltage across its terminals during transient conditions. Fig. 21 shows a TCVL where anti-parallel thyristors are connected in series with a gap-less arrester. A part of the gap-less arrester can also be bypassed by the thyristor switches. This would allow TCVL to dynamically lower the voltage limiting level. TCVLs are normally applied at capacitor bank locations to limit over-voltage resulting from switching operations. A TCVL can be modeled in EMTP using thyristors and a nonlinear resistor (type-92 device) for the MOV. Detailed operating principle of TCVL and its EMTP simulation for the protection of capacitors can be found in [71]–[73].

### *C. Solid State Breaker (SSB) and Fault Current Limiter (FCL)*

SSB (Fig. 22) is a solid state switching device based on series combination of anti-parallel GTO groups. Although a GTO can interrupt current in the circuit with negligible time delay, a parallel path is still needed to provide sustained fault current to allow time for downstream protection systems to operate. In

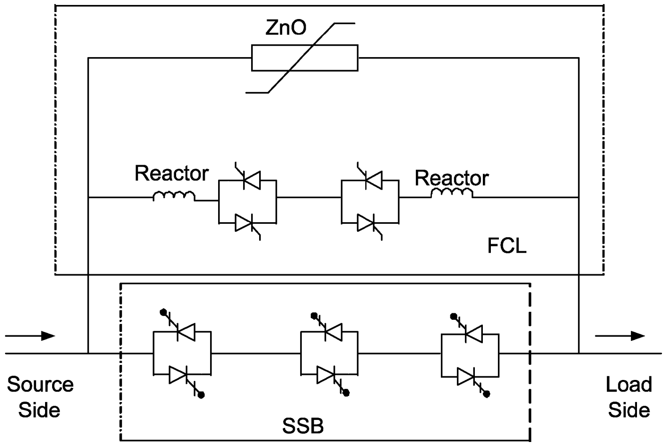

Fig. 22. Schematic diagram of SSB/FCL.

most applications, a solid state fault current limiter (FCL) is also included in the circuit so that once the SSB opens the circuit, the fault current flows through the FCL. An FCL is a reactor in series with anti-parallel thyristors connected across a ZnO arrester. The ZnO arrester is used to limit the voltage across the SSB. In EMTP the SSB and FCL can be represented using models for GTOs, thyristors and lumped inductors. The ZnO arrester can be modeled as a gap switch (type-92 device). A PSCAD/EMTDC simulation of SSB/FCL has been performed in [74].

## VI. CONCLUSIONS

With the development of fast, high-power semiconductor devices, FACTS controllers are finding widespread use in power systems. Detailed and accurate modeling and simulation of such controllers has a significant influence on improving procedures for system planning, analysis and control. At the same time, power engineers now have a host of EMTP-type software programs at their disposal to conduct transient analysis under both off-line and real-time conditions. As these programs increase in their complexity, it is important to keep track of the basic models and algorithms, that form the kernel of these programs, so as to enable future improvements. This paper reviews currently available models for EMTP-type studies involving FACTS controllers that do not employ Voltage-Sourced Converters (VSCs). Transient models for FACTS that use VSCs will be covered in other publications of the IEEE WG 15.05.02. It is expected that this paper will be a valuable reference document for practicing power engineers involved in electromagnetic transient simulations.

## REFERENCES

[1] N. G. Hingorani and L. Gyugyi, *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*. N.Y.: IEEE Press, 2000.

[2] Y. H. Song and A. T. Johns, *Flexible AC Transmission Systems (FACTS)*. London, UK: IEE, 1999.

[3] R. M. Mathur and R. K. Varma, *Thyristor-Based FACTS Controllers for Electrical Transmission Systems*. N.Y.: IEEE Press and John Wiley & Sons, Inc., 2002.

[4] IEEE Working Group (15.05.07) on HVDC Bibliography and Records, "An Annotated Bibliography of HVDC Transmission and FACTS Devices 1991–1993," in *BPA, WAPA*, 1993.

[5] ——, "An Annotated Bibliography of HVDC Transmission and FACTS Devices 1994–1995," in *BPA*, 1995.

[6] ——, "An Annotated Bibliography of HVDC Transmission and FACTS Devices 1996–1997," in *BPA*, Jun. 1998.

[7] A. M. Gole, A. Keri, C. Kwankpa, E. W. Gunther, H. W. Dommel, I. Hassan, J. R. Marti, J. A. Martinez, K. G. Fehrle, L. Tang, M. F. McGranaghan, O. B. Nayak, P. F. Ribeiro, R. Iravani, and R. Lasseter, "Guidelines for modeling power electronics in electric power engineering applications," *IEEE Trans. Power Del.*, vol. 12, no. 1, pp. 505–514, Jan. 1997.

[8] S. Lefebvre, A. M. Gole, J. Reeve, L. Piliotto, N. Martins, and S. Bhattacharya, "Working group on dynamic performance and modeling of DC systems and power electronics for transmission systems: report on test systems for AC/DC interaction studies," *IEEE Trans. Power Del.*, vol. 10, no. 4, pp. 2027–2034, Oct. 1995.

[9] B. K. Johnson, "Simulation of TSC and TSSC," in *IEEE Power Engineering Society, Winter Meeting, 2001*, vol. 2, pp. 637–638.

[10] L. Prikler and G. Banfai, "EMTP models for simulation of shunt reactor switching transients," *Int. J. Electrical Power Energy Syst.*, vol. 19, no. 4, pp. 235–240, May 1997.

[11] T. T. Nguyen and W. D. Humpage, "TCR and SR compensators in composite electromagnetic transient simulation," *IEE Proc.*, pt. C, vol. 136, no. 3, pp. 195–205, May 1989.

[12] P. Parihar and G. G. Karady, "Characterization of a thyristor controlled reactor," *Electric Power Systems Research*, vol. 41, no. 2, pp. 141–149, May 1997.

[13] C. K. K. Tang and D. R. Turner, "Modeling of large nonlinear loads and thyristor controlled shunt compensators," *IEE Proc.*, pt. C, vol. 138, no. 6, pp. 505–517, Nov. 1991.

[14] B. K. Johnson, "Benchmark system for the simulation of TCSC and SVC," in *IEEE Power Engineering Society, Winter Meeting, 2002*, New York, pp. 484–487.

[15] A. M. Gole and V. K. Sood, "A static compensator model for use with electromagnetic transients simulation programs," *IEEE Trans. Power Del.*, vol. 5, no. 3, pp. 1398–1407, Jul. 1990.

[16] S. Lefebvre and L. Gerin-Lajoie, "A static compensator model for the EMTP," *IEEE Trans. Power Syst.*, vol. 7, no. 2, pp. 477–486, May 1992.

[17] S. Y. Lee, S. Bhattacharya, T. Lejonberg, A. E. Hammad, and S. Lefebvre, "Detailed modeling of static VAR compensators using the Electromagnetic Transients Program (EMTP)," *IEEE Trans. Power Del.*, vol. 7, no. 2, pp. 836–847, Apr. 1992.

[18] A. N. Vasconcelos, A. J. P. Ramos, J. S. Monteiro, M. B. V. C. Lima, H. D. Silva, and L. R. Lins, "Detailed modeling of an actual static VAR compensator for electromagnetic transients studies," *IEEE Trans. Power Syst.*, vol. 7, no. 1, pp. 11–19, Feb. 1992.

[19] J. A. Martinez, "EMTP simulation of a digitally-controlled static VAr system for optimal load compensation," *IEEE Trans. Power Del.*, vol. 10, no. 3, pp. 1408–1415, Jul. 1995.

[20] W. S. Meyer, "EMTP data modularization and sorting by class: a foundation upon which EMTP data bases can be built," *EMTP Newsletter*, vol. 4, no. 2, pp. 28–40, Nov. 1983.

[21] *ATP Rule Book*, Leuven EMTP Center (Ed.) , Ed., 1990.

[22] J. A. Martinez, "How to adopt the EMTP for classroom instruction," *IEEE Trans. Power Syst.*, vol. 7, no. 1, pp. 351–358, Feb. 1992.

[23] J. A. Martinez and N. Mohan, "ATP simulation of power electronics systems using a data-module approach," in *Proc. 32nd Universities Power Engineering Conf. (UPEC'97)*, vol. 1, Manchester, U.K., Sep. 10–12, 1997, pp. 495–498.

[24] P. K. Muttik, P. Wang, and M. W. H. Minchin, "Detailed simulation of SVC transient performance using PSCAD," in *Proc. Int. Conf. Power System Technology (PowerCon, 2000)*, Perth, Australia.

[25] A. C. S. de Lima, S. S. Wanderley, and R. M. Stephan, "Modeling a static VAR compensator using EMTP," in *Proc. 38th Midwest Symp. Circuits and Systems*, vol. 2, Rio de Janeiro, Brazil, Aug. 13–16, 1996, pp. 219–222.

[26] W. Geraldes, E. H. Rose, C. Machado, J. T. Honda, and P. M. Vendramini, "Static VAR compensator from Coxipo substation (Brazil), comparison between computer simulations and field tests," in *Proc. 5th Int. Conf. AC and DC Power Transmission*, London, England, pp. 301–306.

[27] B. Das, A. Ghosh, and A. Sachchidanand, "A new control scheme for dynamic brake," in *Proc. 9th Nat. Power Systems Conf. (NPSC '96)*, vol. 2, Kanpur, India, 1996, pp. 501–507.

[28] W. Zhu, R. Spee, R. R. Mohler, G. C. Alexander, W. A. Mittelstadt, and D. Maratukulam, "An EMTP study of SSR mitigation using the thyristor controlled series capacitor," *IEEE Trans. Power Del.*, vol. 10, no. 3, pp. 1479–1485, Jul. 1995.

[29] C. Gama and R. Tenorio, "Improvements for power system performance: modeling, analysis and benefits of TCSCs," in *Proc. IEEE Power Engineering Society Winter Meeting* , vol. 2, Singapore, 2000, pp. 1462–1467.

[30] A. R. M. Tenorio and N. Jenkins, "Use of EMTP-ATP MODELS language for modeling thyristor controlled series capacitors," in *Proc. Universities Power Engineering Conf. (UPEC '98)*, vol. 2, Edinburgh, UK, 1998, pp. 679–682.

[31] A. R. M. Tenorio, J. B. Ekanayake, and N. Jenkins, "Modeling of FACTS devices," in *Proc. IEE Conf. AC and DC Power Transmission*, London, U.K., Apr./May 1996, pp. 340–345.

[32] H.-G. Han, J.-K. Park, and B.-H. Le, "Analysis of thyristor controlled series compensator dynamics using the state variable approach of a periodic system model," *IEEE Trans. Power Del.*, vol. 12, no. 4, pp. 1744–1750, Oct. 1997.

[33] L. J. Bohmann and R. H. Lasseter, "Stability and harmonics in thyristor controlled reactors," *IEEE Trans. Power Del.*, vol. 5, no. 2, pp. 1175–1181, Apr. 1990.

[34] H. A. Othman and L. Angquist, "Analytical modeling of thyristor controlled series capacitors for SSR studies," *IEEE Trans. Power Syst.*, vol. 11, no. 1, pp. 119–127, Feb. 1996.

[35] B. K. Perkins and M. R. Iravani, "Dynamic modeling of a TCSC with application to SSR analysis," *IEEE Trans. Power Syst.*, vol. 12, no. 4, pp. 1619–1625, Nov. 1997.

[36] P. Mattavelli, G. C. Verghese, and A. M. Stankovic, "Phasor dynamics of thyristor controlled series capacitor systems," *IEEE Trans. Power Syst.*, vol. 12, no. 3, pp. 1259–1267, Aug. 1997.

[37] ——, "SSR analysis with dynamic phasor model of thyristor controlled series capacitor," *IEEE Trans. Power Syst.*, vol. 14, no. 1, pp. 200–208, Feb. 1999.

[38] R. J. Davalos and J. M. Ramirez, "A review of a quasistatic and a dynamic TCSC model," *IEEE Power Eng. Rev.*, vol. 20, no. 11, pp. 63–65, Nov. 2000.

[39] A. T. Johns and Q. Y. Xuan, "Digital study of thyristor controlled series capacitor compensated EHV transmission systems," in *IEEE Proc. 10th IEEE Regional Conf. Computer, Communication, Control and Power Engineering (TENCON'93)*, pp. 263–265.

[40] M. R. Sultan, J. Reeve, and R. Adapa, "Transient Behavior of Systems Containing FACTS Devices: Modeling of the Thyristor Controlled Series Capacitor,", EPRI Final Report TR-108191, 2149-15, Jul. 1997.

[41] M. Sultan, J. Reeve, and R. Adapa, "Combined transient and dynamic analysis of HVDC and FACTS systems," *IEEE Trans. Power Del.*, vol. 13, no. 4, pp. 1271–1277, Oct. 1998.

[42] T. F. Godart, A. F. Imece, J. C. McIver, and E. A. Chebli, "Feasibility of thyristor controlled series capacitor for distribution substation enhancements," *IEEE Trans. Power Del.*, vol. 10, no. 1, pp. 203–209, Jan. 1995.

[43] A. Ghosh and G. Ledwich, "Modeling and control of thyristor-controlled series capacitors," *IEE Proc. Generation, Transmission, Distribution*, vol. 142, no. 3, pp. 297–304, May 1995.

[44] S. Al-Senaidi, "An application of thyristor controlled series capacitor to selective pole switching," *Electric Power Components & Systems*, vol. 30, no. 8, pp. 14–20, Aug. 2002.

[45] O. M. Neto, P. C. A. Leao, and A. E. A. Araujo, "Controlled series compensation: dynamic performance under fault conditions," in *Proc. 32nd Universities Power Engineering Conf. (UPEC'97)*, vol. 1, Manchester, U.K., Sep. 10–12, 1997, pp. 5–8.

[46] J. Ndayizamba, S. Lefebvre, and D. D. Xuan, "Torsional interaction in flexible AC transmission systems with a thyristor controlled series capacitor," in *Proc. 5th Electrimacs, Modeling and Simulation of Electric Machines, Converters & Systems*, Saint Nazaire, France, Sep. 17–19, 1996, pp. 1187–1192.

[47] E. A. Leonidaki, B. C. Papadias, N. D. Hatziargyriou, and S. Giorgas, "A physical laboratory model of a thyristor controlled series capacitor," in *Proc. 33rd Universities Power Engineering Conf.*, Edinburgh, U.K., Sep. 8–10, 1997.

[48] O. M. Neto, R. A. Meneguim, F. D. Oliveira, and J. M. Oliveira, "Modeling of a thyristor controlled series capacitor in matlab environment," in *Proc. 32nd Univertsities Power Engineering Conf. (UPEC'97)*, vol. 1, Manchester, UK, September 10–12, 1997, pp. 21–14.

[49] M. Sultan, J. Reeve, and R. Adapa, "Combined transient and dynamic analysis of HVDC and FACTS systems," in *IEEE PES Winter Meeting*, Tampa, Florida, Feb. 1–5, 1998.

[50] E. A. Leonidaki, N. D. Hatziargyriou, and G. J. Georgantzis, "Simulation of thyristor controlled series capacitors and subsynchronous studies," in *Proc. 32nd Universities Power Engineering Conf. (UPEC'97)*, vol. 2, Manchester, U.K., Sep. 10–12, pp. 883–886.

[51] J. Ndayizamba, S. Lefebvre, and D. D. Xuan, "Efficient and flexible thyristor controlled series capacitor simulation in EMTP-TACS," in *Proceedings of 12th Power Systems Computation Conf*, vol. 2, Dresden, Germany, Aug. 20–23, 1996, pp. 1122–1127.

[52] D. D. Xueqiang-Zhao, "Study of TCSC model and prospective application in the power systems of China," in *Proc. Int. Conf. Power Electronics and Drive Systems, (PEDS'99)*, vol. 2, Kowloon, Hong Kong, 1999, pp. 688–691.

[53] Y. Tanaka, H. Taniguchi, M. Egawa, H. Fujita, M. Watanabe, and H. Konishi, "Using a miniature model and EMTP simulations to evaluate new methods to control and protect a thyristor controlled series compensator," in *Proc. 1999 Winter Meeting of IEEE Power Engineering Society*, vol. 2, New York, pp. 1196–1201.

[54] H. Xueqiang-Zhao and H. Chen-Chen, "Circuit analysis of a thyristor controlled series compensation," in *Proc. 1999 Winter Meeting of IEEE Power Engineering Society*, vol. 2, New York, pp. 1067–1072.

[55] M. Junya, I. Keiichi, T. Takeshi, and A. Minoru, "Dynamic performance of a thyristor controlled series capacitor system," in *Proc. 31st Universities Power Engineering Conf.*, vol. 3, Iraklio, Greece, 1996, pp. 961–964.

[56] L. F. W. De Souza, E. H. Watanabe, and M. Aredes, "GTO controlled series capacitors: multi-module and multi-pulse arrangements," *IEEE Trans. Power Del.*, vol. 15, no. 2, pp. 725–731, Apr. 2000.

[57] ——, "GTO controlled series capacitor," in *IEEE Power Engineering Society Winter Meeting, 2000*, vol. 4, 2000, pp. 2520–2525.

[58] S. G. Jalali, R. A. Hedin, M. Pereira, and K. Sadek, "Stability model for the Advanced Series Compensator (ASC)," *IEEE Trans. Power Del.*, vol. 11, no. 2, pp. 1128–1137, Apr. 1996.

[59] S. G. Helbing and G. G. Karady, "Investigations of an advanced form of series compensation," *IEEE Trans. Power Del.*, vol. 9, no. 2, pp. 939–947, Apr. 1994.

[60] B. Pilvelait, T. H. Ortmeyer, and D. Maratukulam, "Advanced series compensation for transmission system using a switched capacitor module," *IEEE Trans. Power Del.*, vol. 8, no. 2, pp. 584–590, Apr. 1993.

[61] A. A. Girgis, A. A. Sallam, and A. K. El-Din, "An adaptive protection scheme for Advanced Series Compensated (ASC) transmission lines," *IEEE Trans. Power Del.*, vol. 13, no. 2, pp. 414–420, Apr. 1998.

[62] M. R. Iravani, P. L. Dandeno, K. H. Nguyen, D. Zhu, and D. Maratukulam, "Applications of static phase shifters in power systems," *IEEE Trans. Power Del.*, vol. 9, no. 3, pp. 1600–1608, Jul. 1994.

[63] M. R. Iravani and D. J. Maratukulam, "Review of semiconductor controlled (static) phase shifters for power system application—part 1," *IEEE Trans. Power Syst.*, vol. 9, no. 4, pp. 1833–1839, Nov. 1995.

[64] ——, "Review of semiconductor controlled (static) phase shifters for power system application—part 2," *IEEE Trans. Power Syst.*, vol. 9, no. 4, Nov. 1994.

[65] D. J. Nyati, S. Eitzmann, M. Kappenman, J. VanHouse, D. Mohan, and A. N. Edris, "Design issues for a single core transformer thyristor controlled phase-angle regulator," *IEEE Trans. Power Del.*, vol. 10, no. 4, pp. 2013–2019, Oct. 1995.

[66] PSCAD/EMTDC Manual, Manitoba HVDC Research Centre, 2001.

[67] K. K. Sen and M. L. Sen, "Introducing the family of Sen transformers: a set of power flow controlling transformers," *IEEE Trans. Power Del.*, vol. 18, no. 1, pp. 149–157, Jan. 2003.

[68] ——, "Comparison of the Sen transformer with the unified power flow controller," *IEEE Trans. Power Del.*, vol. 18, no. 3, pp. 1523–1533, Oct. 2003.

[69] Z. Xu and C. Chen, "Damping subsynchronous resonance using an improved NGH SSR damping," in *IEEE Power Engineering Society Summer Meeting*, vol. 2, Edmonton, AB, Canada, 1999, pp. 780–785.

[70] L. Wang, "Simulations of prefiring NGH damping scheme on suppressing torsional oscillations using EMTP," *IEEE Trans. Power Syst.*, vol. 12, no. 2, pp. 882–888, May 1997.

[71] G. E. Lee and D. L. Goldsworthy, "BPA's Pacific AC inter-tie series capacitors: experience, equipment and protection," *IEEE Trans. Power Del.*, vol. 11, no. 1, pp. 253–259, Jan. 1996.

[72] M. Kezunovic, M. Aganagic, S. McKenna, and D. Hamai, "Computing responses of series compensation capacitors with MOV protection in real-time," *IEEE Trans. Power Del.*, vol. 10, no. 1, pp. 244–251, Jan. 1995.

[73] P. S. S. Holenarsipur, D. J. Christofersen, and N. Mohan, "Thyristor switched arrester for improved protection of power system equipment," in *Proc. Winter Meeting of IEEE Power Engineering Society*, vol. 2, New York, 1999, pp. 1009–1014.

[74] L. Palav and A. M. Gole, "On using the solid-state breaker in distribution systems," in *Proc. IEEE Canad. Conf. Electrical and Computer Engineering*, vol. 1, Waterloo, Ontario, May 1998, pp. 693–700.

**M. O. Faruque** is a Ph.D. candidate in the Department of Electrical and Computer Engineering at the University of Alberta, Canada. He received the B.Sc.Engg. in 1992 from Chittagong University of Engineering and Technology (erstwhile BITC), Bangladesh and the M.Eng.Sc. degree in 1999 from the University of Malaya, Malaysia in the area of power engineering.

His research interest includes FACTS, HVDC and Real-Time Digital simulation of Power Electronics and Power Systems.

**Venkata Dinavahi** (M'00) received the B.Eng. degree in 1993 from Nagpur University, India, and the M.Tech. degree in 1996 from the Indian Institute of Technology, Kanpur, India. He received the Ph.D. degree in 2000 in electrical and computer engineering from the University of Toronto, Canada.

Presently, he is an Assistant Professor at the University of Alberta, Edmonton, Alberta, Canada. His research interests include electromagnetic transient analysis and real-time simulation and control. He is a Professional Engineer in the Province of Alberta.

**Surya Santoso** (M'96–SM'02) earned the B.S. degree from Satya Wacana Christian University, Indonesia in 1992, and the MSE and Ph.D. degrees in electrical and computer engineering from the University of Texas at Austin, Texas, in 1994 and 1996, respectively.

He re-joined the University of Texas at Austin as an Assistant Professor in fall 2003. Prior to joining the University, he was a Consulting Engineer with Electrotek Concepts, Inc. in Knoxville, Tennessee for seven years. His primary research interests include development of intelligent systems for analyzing raw power quality measurement data, power system modeling and studies, and wind power. He co-authored *Electric Power Systems Quality* published by McGraw-Hill Professional Series in 2002.

**Ram Adapa** received the Ph.D. in electrical engineering from the University of Waterloo, Ontario, Canada.

He joined the Electric Power Research Institute (EPRI), Palo Alto, California in June 1989. At EPRI, he is currently a Technical Manager, Increased Power Flow, in the Transmission & Substations area of Power Delivery & Markets Sector. Prior to joining EPRI, he was a Staff Engineer in the Systems Engineering Department of McGraw-Edison Power Systems (presently known as Cooper Power Systems), Franksville, Wisconsin. His areas of interest include increased power flow, dynamic thermal circuit ratings, FACTS, phasor measurements, grid operations, grid planning, and grid reliability.

Dr. Adapa is a Senior Member of the IEEE Power Engineering Society. He received the 2001 IEEE Regional Outstanding Engineer award for Region 6 for his outstanding contributions to the Power Engineering Profession and to the IEEE Power Engineering Activities in Region 6. He is a Registered Professional Engineer in the State of Wisconsin.