Paper

A Nonlinear Generalized Switching Function Model For SVC And TCSC Devices

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Abstract

This work presents the application of generalized switching functions to the modeling of Thyristor Controlled Reactors (TCRs). The development of detailed nonlinear and linear analytical models of TCRs are presented. These models allow for the precise analysis of the TCR transient phenomena for a frequency range of up to some tens of Hz. Validation of the models was done by comparing simulated results obtained with the proposed models with those obtained with a traditional electromagnetic transients program (EMTP). The nonlinear model for the TCR was developed using generalized switching functions. Based on this model, a detailed linear model was derived. This linear model allows for the analysis and precise understanding of the behavior of a TCR under small disturbances both in the time and frequency domain. Interactions between voltage controllers of two SVCs in the subsynchronous frequency range were analyzed for a specific example. It was shown that the analytical linear model is a very precise and powerful tool to evaluate such interactions. The model predicts system instabilities, which could not be predicted at all by traditional models. With the proposed model it is possible to design the controllers of SVCs in an integrated form so that the risk of instabilities can be avoided.

Keywords: Generalized Switching Function, Thyristor Controlled Reactor, SVC, TCSC, FACTS

1 Introduction

Power System engineers are currently facing challenges to increase the power transfer capability of existing transmission systems. Controllers of Flexible AC Transmission System (FACTS) [1] offer a technical and possibly economical solution to accommodate that need while maintaining sufficient steady state and transient stability margins. These devices are now a reality and will soon change the way engineers plan and operate power systems.

The first generation of FACTS devices was based on thyristors used in combination with reactive components. There are a large number of Static var Compensators (SVC) and a few Thyristor Controlled Series Compensation (TCSC) devices in commercial operation. An interesting TCSC project was recently implemented in Brazil. Two TCSC devices are part of the series compensation scheme of a 1000-km, 1000 MW ac interconnection between two large systems. The TCSC devices are primarily used for damping out low frequency electromechanical oscillations appearing during normal operation.

A second generation of FACTS devices is based on forced commutated Voltage Source Inverter (VSI) bridges. The Static Synchronous Compensator (STATCOM) device is a good example of the application of this technology [1]. Unlike SVCs, which use thyristor controlled reactors in parallel with capacitor banks, the STATCOM is an inverter-based device, which uses self-commutated power electronics devices like gate turn-off thyristors (GTO) and dc energy storage capacitors to generate a synchronous voltage. Compared to an SVC, a STATCOM can respond more rapidly to changing system conditions, provides superior low-voltage performance, requires less station space, provides superior harmonic performance to SVCs and can interface real power sources. However, thyristor based FACTS devices, like the TCR have a more proven technology and possibly low cost. Also, there are many examples of actual applications around the world. Therefore, the authors believe that modeling these devices is important for the appropriate design of power system controllers. Furthermore, it is believed that the TCR will survive for some applications, even in the future.

Several other inverter-based devices like the Static Series Synchronous Compensator (SSSC) and the Unified Power Flow Controller (UPFC) are currently being investigated and will probably be available soon to system planners [1]. In most cases, these power electronic controllers have no contribution to short-circuit currents and have a better ability to maintain synchronism than conventional equipment.

FACTS equipments are extremely fast power electronic devices. Therefore, their control design must be coordinated with other fast equipment operating at the same electrical area in order to avoid undesirable control interactions. These devices may interact not only on the electromechanical range of operation, but they may also experience high frequency interactions.

Transient stability and conventional eigenvalue programs available nowadays do not represent the ac network by differential equations. Instead, they represent it by algebraic equations. Therefore, both transient stability simulations and eigenvalue analysis that make use of conventional models can not predict the high frequency self-modes of the several FACTS devices embedded in a large power system network. Consequently, the investigation of high frequency control interactions among the several FACTS devices must be carried out using EMTP type programs or any other analytical tool that captures high frequency phenomena, as will be shown in the paper.

The switching operation of the converter bridges usually adopted in power electronics applications can be represented by a Switching Matrix. The idea of a Switching Matrix was introduced by Guygyi [2] and was further explored by Wood [3]. The mathematical function that defines the sequence of operation of the converter valves is known as a Switching or Existence Function. The Switching Function representation of a power electronic device permits an accurate analysis of both the external and internal voltage and current characteristics of the converter.

The idea of Generalized Switching Functions [4] is a simple natural extension of the theory developed for the conventional Switching Functions. It incorporates analytically the particularities of each type of converter on the conventional Switching Function, allowing for a precise evaluation of the equipment both on the time and frequency domains.

The main purpose of this paper is to describe a Nonlinear Generalized Switching Function Model applied to the representation of SVC and TCSC devices and is a continuation of a previous work presented at IPEC'95 [5]. These models may be used for nonlinear EMTP type time domain simulation of the devices as well as in the frequency domain for the efficient design of the controllers. These models were compared with conventional models presented in the literature [6]. Conventional eigenvalue programs were compared with programs based on the proposed models and it is clearly demonstrated that the conventional programs do not capture high frequency instabilities that are correctly identified by the Generalized Switching Function based models.

2 Analytical Nonlinear Model of TCR

Figure 1 presents a thyristor controlled reactor (TCR) arrangement. As can be seen in the figure, a TCR is composed by two thyristors placed in anti-parallel and in series with a reactor.

Figure 2 depicts that the reactor current (i_L) is regulated by controlling the firing angle (α), which is measured with respect to the natural zero crossing of the voltage applied to the TCR (v). The conduction angle (σ) corresponds to the time in which the valve conducts.

The switching function representation used to model a TCR in this work is based on a previously published paper [5]. The expressions relating the voltage at the reactors with the voltage at the entire TCR are given by the following expression:

$$\begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} = \begin{bmatrix} S_a & 0 & 0 \\ 0 & S_b & 0 \\ 0 & 0 & S_c \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad (1)$$

The components of the switching matrix are the switching functions and are given by the following expressions:

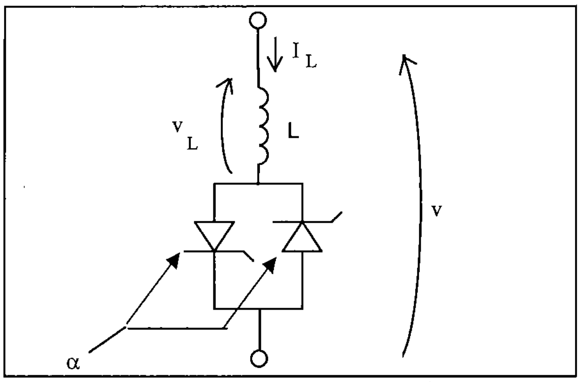

Figure 1: Thyristor Controlled Reactor

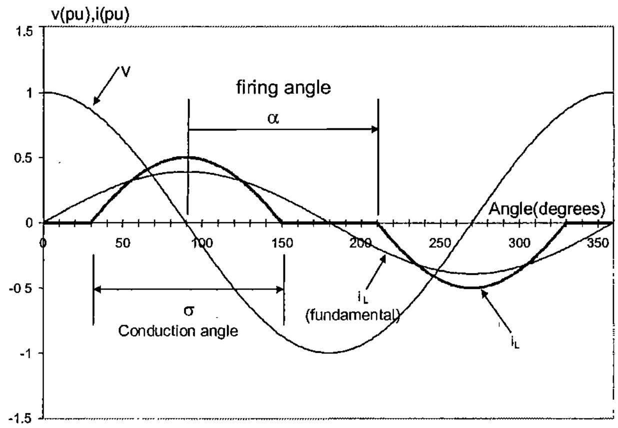

Figure 2: Voltage and Currents in a TCR.

$$Sa = U_0 + \sum_j Uj\cos[2j\omega t + 2j\beta + j\pi]$$

$$Sb = U_0 + \sum_j Uj\cos[2j\omega t + 2j\beta + j\pi - 4j\pi/3]$$

$$Sc = U_0 + \sum_j Uj\cos[2j\omega t + 2j\beta + j\pi + 4j\pi/3]$$

$$U_j = \frac{1}{\pi\gamma j^2}.\{\cos[j\sigma] - \cos[j(\sigma + 2\gamma)]\} \qquad (2)$$

j = 1, 2, 3,... In (2) the maximum value for j is related to the order of the harmonics to be analyzed. The term U_0 is given by

$$U_0 = \frac{\gamma + \sigma}{\pi}.$$

The angle γ is a small ramp angle, used for avoiding Gibbs' phenomenon [5].

Figure 3 shows a graphic representation for (1) considering typical waveforms in a three-phase arrangement. The computational programs suited to analyze electromagnetic transients in electric systems combine the machine representation in the dq0 coordinates and the remaining electric system representation in the abc references. Pilotto [4] modeled the machines in the dq0 frame, as well as the whole electric system including the HVDC converters. This approach allows the analysis of the phenomenon using only one reference frame for the entire system. Applying this concept to TCRs, the corresponding expression for (1) is obtained as

$$v_{l(d,q,0)} = S_{(d,q,0)}\; v_{(d,q,0)}. \qquad (3)$$

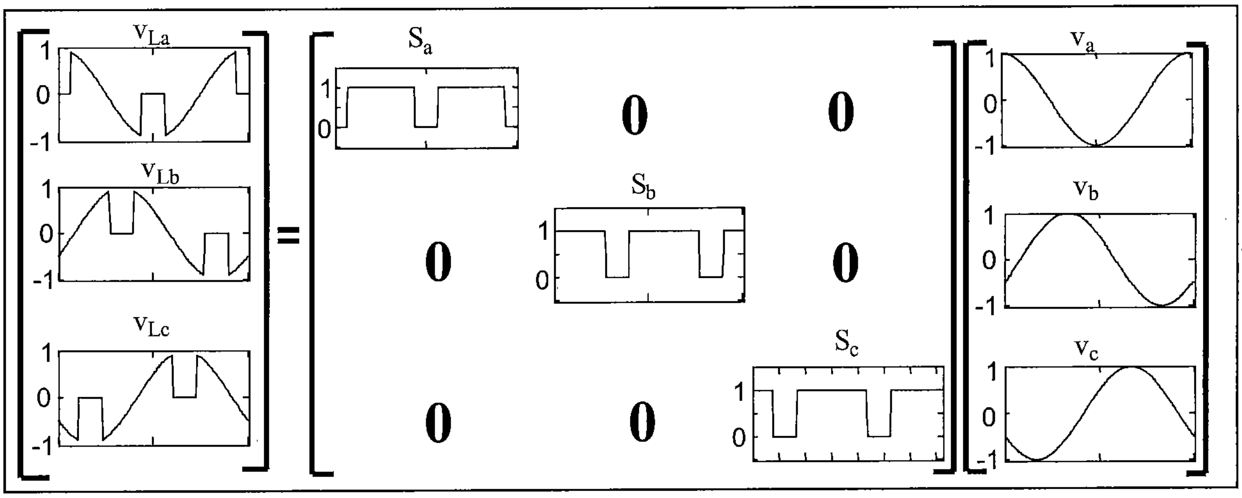

Figure 3: Typical Waveforms of a TCR Switching Matrix in an abc Reference Frame.

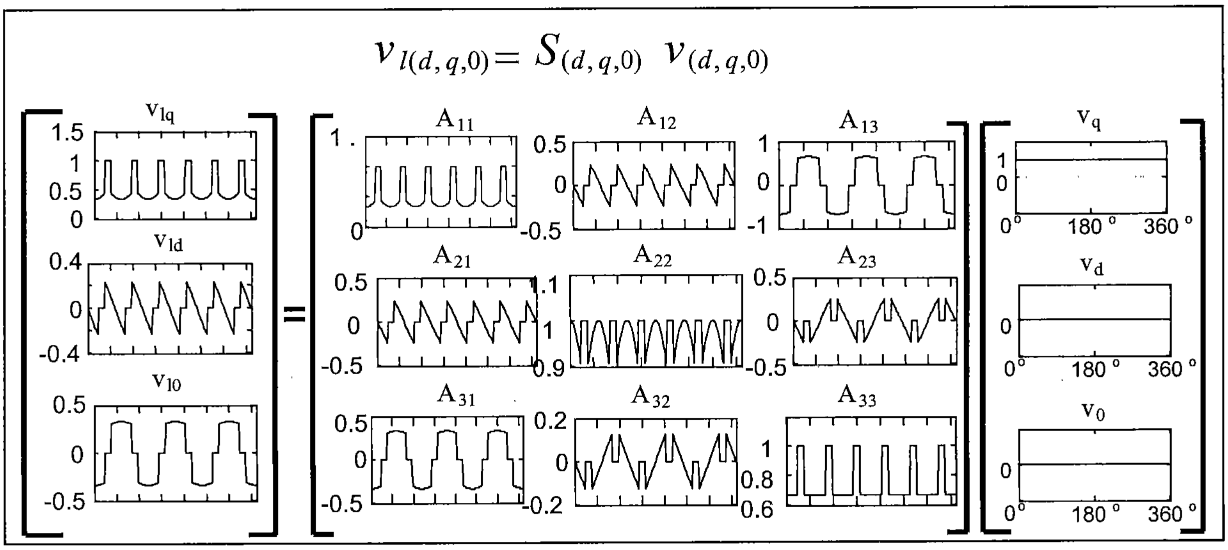

Figure 4: Typical Waveforms of a TCR Switching Matrix in a dq0 Reference Frame.

In eq. (3), $v_{(d,q,0)}$ is the voltage at the busbar of the TCR, $v_{l(d,q,0)}$ is the voltage on the reactors of the TCR and $S_{(d,q,0)}$ is Switching Matrix of the TCR, all terms referred to dq0 coordinates.

Figure 4 shows typical waveforms of the switching functions in a dq0 reference frame.

3 Analytical Linear Modeling of TCRs

To derive a linear model, two steps were performed: (i) elimination of the harmonic components of the nonlinear equations and (ii) linearization of the expressions.

The main purpose of the investigation is to evaluate the fundamental frequency component on an abc reference frame coordinate. This component, for a balanced system, when transformed into a dq0 reference frame, is seen as a continuous and constant component. Therefore, this was adopted as an interesting approach for eliminating all the harmonic components of (3).

In a TCR the variables that directly affect the current are the firing angle α and the voltage v. Therefore, the following expression was obtained:

$$\Delta(S_{dc}\ v_{(d,q)}) = \frac{\partial(S_{dc}\ v_{(d,q)})}{\partial v}\Delta v + \frac{\partial(S_{dc}\ v_{(d,q)})}{\partial \alpha}\Delta\alpha \quad (4)$$

where, S_{dc} is the Switching Matrix of the TCR, without harmonic components.

The first term in the right hand side corresponds to the voltage busbar deviation around an operating point, maintaining the switching functions constant over time. The second term corresponds to the small deviation of the firing angle around an operating point while maintaining constant voltages.

These two transfer functions were validated by comparing its Bode diagrams, obtained using both the EMTP program and expression (4). All the comparisons have shown good agreement between both approaches. To better understand this validation one example is presented.

Consider the system depicted in Fig. 5, with one SVC. A sinusoidal signal of variable frequency is injected at the reference point of the voltage controller of an SVC as depicted in the block diagram of Fig. 6. The modulated output voltage of the static compensator is also calculated. A Bode diagram relating the output voltage signal and the injected signal is obtained for several frequencies. Fig. 7 exhibits discrete points obtained from this "measurement" (magnitude and phase) for several frequencies between 0 and 45 Hertz. The same transfer function was evaluated using the linear model and plotted in Fig. 7 with a continuous line. The obtained results show that the linear model represents with accuracy the dynamics of the system for the frequencies studied. The simulation to validate the Bode diagram obtained from the transfer function was done only up to 45 Hz because for frequencies higher than this the noise is too high, limiting a precise calculation with EMTP. However, the transfer function was plotted up to 60 Hz.

4 Comparison Between Analytical Linear Modeling of TCR and Conventional Model of TCR

Modeling of TCRs aiming at the application in power system studies is described in [6]-[7]. They suggest equation (5) for modeling the dynamics of a TCR. In this expression, T_d is the dead time between the order to change the firing angle and the firing itself. T_b is the delay time due to the sequence of firing in a three-phase arrangement. These values are fixed without an analytical basis and any changing of the operating point may take the model out of tuning.

$$G(s) = \frac{e^{-sT_d}}{1+sT_b} \qquad (5)$$

The traditional model, with fixed parameters represents, normally, the TCR at a fixed operating condition. When the operating point varies the parameters have to be changed empirically. On the other hand, the model proposed here can represent the TCR analytically even when the operating point changes. The system depicted in Figure 5, originally operating with α=114°, had its operating point changed in a way that the firing angle was increased to 141°. As shown in Figure 8, the proposed model presented a different gain for the new conditions.

As another example, a power system with two SVCs, which are physically separated by a 160 km long transmission line, is exhibited in Figure 9. The SVCs are controlling the voltage at buses 1 and 2. Figure 10 shows the transient response of voltage at bus 1 after a 1% step in the voltage reference of SVC 2, simulated with the EMTP program. It can be seen that the system is unstable.

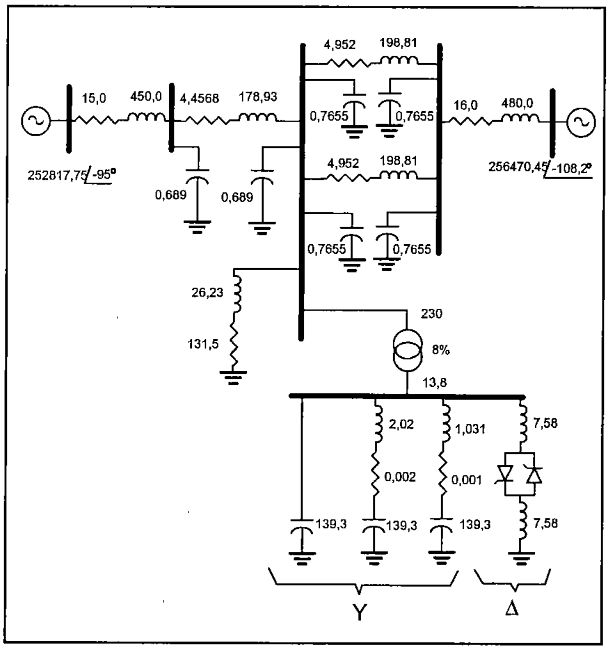

Figure 5: Electric System for Validating the Model

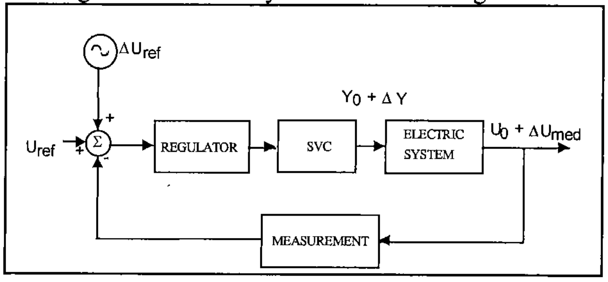

Figure 6: Arrangement for Validating the Transfer Function.

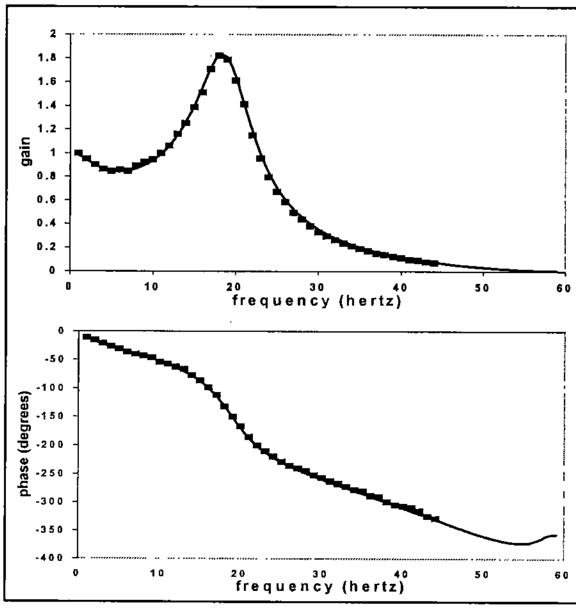

Figure 7: Comparison of Transfer Functions obtained with the EMTP Program (square marks) and the Linear Model (continuous line).

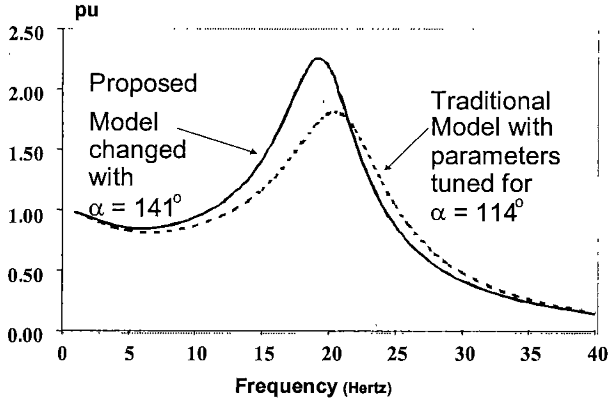

Figure 8 – Transfer Function for Two Different Operating Points.

Figure 11 presents the firing angle of SVC 1 also simulated with the EMTP and the same instability can be observed. The same case was simulated with conventional [6]-[7] linear models of SVCs (expression (5)) and the voltage deviation at bus 1 is presented in Figure 12. This figure shows that the conventional model was not able to indicate the instability observed in the EMTP simulation.

However, this was not the case with the proposed model. Figure 13 shows the voltage deviation of bus 1, simulated with the proposed linear model and it can be seen that the system is unstable, with negative damping, agreeing with the EMTP simulation.

Several other simulations were performed with TCSCs, considering now that the TCR is placed in series with the electrical system. An excellent agreement between these results and the ones obtained with the EMTP was achieved.

Conclusions

This work presented the development of an analytic state-space nonlinear model of thyristor-controlled reactors. It can be applied to fast simulation, in the time domain, of an electric power system containing these equipments. In addition, a linear model was developed, suitable for frequency analysis of these equipments in an enlarged range comprising subsynchronous interactions.

The basis for the proposed model derivation is the switching function concept. Using this technique it is possible to obtain a detailed analysis of power electronics equipment, especially for HVDC converter bridges and TCRs. The approach used, based on generalized switching functions, is described in [5].

The linear model was obtained directly from the nonlinear model by eliminating harmonics and also by linearizing the resulting expressions. The obtained model allows for the identification of important subsynchronous interactions that may occur in an electric power system. In addition, the developed model is highly accurate for any operating point of the TCR.

It was shown in the paper that the proposed model predicts precisely stability problems at higher frequencies, that can not be detected at all with conventional models. The design of the controllers with the proposed model may achieve optimized systems with a good transient response.

The authors believe that both the nonlinear and the linear models proposed in this paper will be very useful for the optimal design of FACTS controllers in future electrical systems.

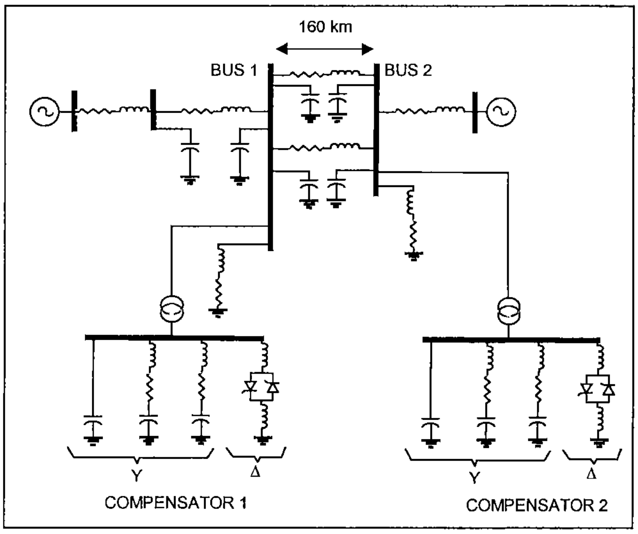

Figure 9: Electric System Studied.

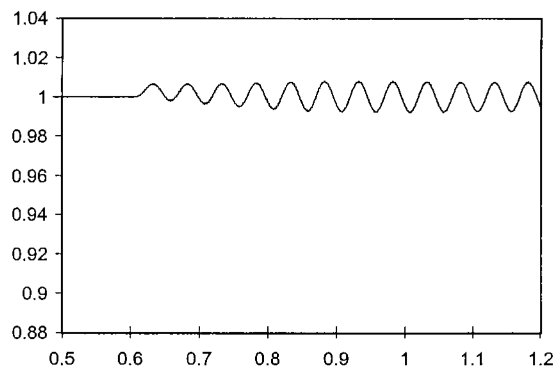

Figure 10: Voltage at bus 1 Simulated with the EMTP Program.

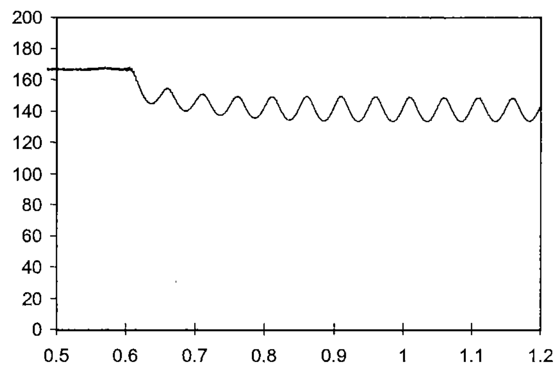

Figure 11: Firing angle of SVC 1 Simulated with the EMTP Program.

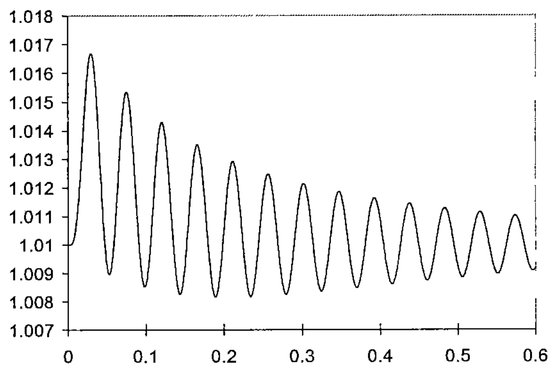

Figure 12: Voltage Deviation at bus 1 Simulated with a Conventional Model.

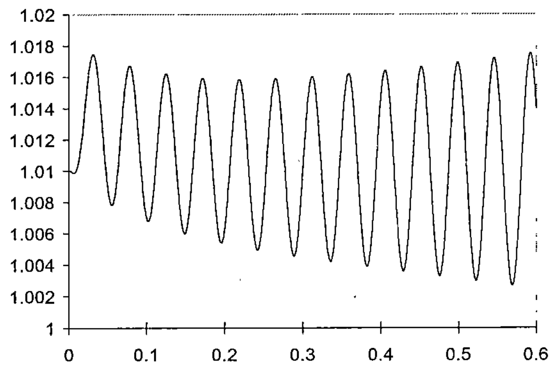

Figure 13: Voltage deviation at bus 1 simulated with the proposed model.

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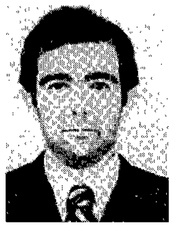

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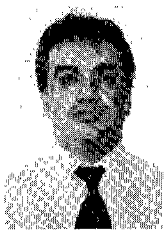

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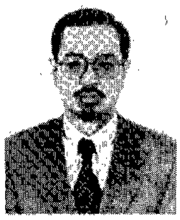

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