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Time-Domain Comparisons of Two Linear Models of a Thyristor-Controlled Series Capacitor

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Abstract – This paper describes a method to construct a linear model of a Thyristor-Controlled Series Capacitor (TCSC) by analyzing its frequency response obtained from time-domain simulations of a detailed model of the device. Such linear model represents the low frequency behavior of the device as needed in power system stability studies.

The linear model is validated comparing the time-domain simulations obtained using the original detailed TCSC-model, the developed linear model and a previously obtained linear model. The latter one has been built by disturbing the TCSC with two events and identified with Matlab's System Identification ToolBox from time-domain simulations.

By using a linear model, the computing time can be reduced significantly compared to simulations with a detailed TCSC-model, maintaining dominant behavior of the TCSC.

All simulations are done with the power system simulation software Simpow.

Keywords: Linearization, TCSC, identification, frequency response

1 INTRODUCTION

POWER system simulations play a major role in power system planning and operation since stability may affect both the design and the operation of a power system. Accuracy and speed of power system simulations are of capital importance to detect the problems and to find the adequate solutions.

This paper deals with simulation models of one of the newest components on the power system market namely the Thyristor-Controlled Series Capacitor (TCSC) and compares two linear (simplified) models of it. The linear models are aimed to be used in simulations where the main goal is to get an overview of the dynamics of the whole power system and in which therefore it is not required to check the performance of a specific variable of the TCSC.

The reader can follow how a linear model of a detailed instantaneous value model of a TCSC is obtained by analyzing its frequency response in time-domain simulations. The detailed representation of the TCSC contains thyristors and control algorithms as shown in figures 1 and 2.

By performing time-domain simulations with a simplified model, the simulation time can be reduced significantly with kept resemblance with the original detailed model.

2 ORGANIZATION OF THE PAPER

The paper is organized as follows. Section 3 contains a short description of the TCSC. Section 4 describes the advantages of linear models. In section 5 the control functions of the TCSC are presented. In section 6 a linear model of the TCSC is developed. Section 7 outlines the interface between the linear model and the power system.

In section 8, a system used for time-domain comparisons is described. Sections 9 – 11 describe three cases considered to show the validity of the linear models in time-domain simulations. Section 12 contains the conclusions of the paper.

3 THE COMPONENTS OF THE THYRISTOR-CONTROLLED SERIES CAPACITOR

For each phase, the TCSC consists of a series capacitor with a shunted reactor and two anti-parallel thyristors in parallel, see figure 1. By varying the start-conducting time for each thyristor, the fundamental reactance between Node A and Node B can be varied which is the main point with the TCSC.

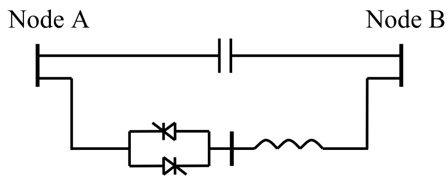

Figure 1: A Thyristor-Controlled Series Capacitor (TCSC).

To each phase, a control algorithm is associated and it calculates the instant when the thyristors should start conducting, see figure 2. The thyristors stop conducting at the following zero-crossing of the phase valve current.

Simulations with a detailed representation of the TCSC, as in figure 1, increases the simulation time significantly since it creates a number of events in every period such as thyristor switchings and events in the control system, see figure 2.

4 LINEAR MODELS OF NON-LINEAR COMPONENTS

As a consequence of that the TCSC creates a large number of events in each period, it switches constantly between different sets of differential equations and therefore it behaves non-linear and demands a detailed simulation. This makes it a big task to simulate the TCSC and therefore it is of great interest to build and include a simplified model in time-domain simulations in cases in which the internal events of the TCSC can be neglected.

In the literature, simplified low-order, non-linear models of TCSCs can be found. In [1] a first-order, symmetric model is documented which is aimed for transient and oscillatory studies and in [2] a TCSC-model assuming a sinusoidal steady-state current and an expression of the equivalent impedance is used.

In [3,4,5] a linear model has been developed by identifying transfer functions with Matlab's System Identification ToolBox from time-domain simulations. That linear model has been identified by disturbing the TCSC with a 10% step change in the *d*- and *q*-component of the current. From those events, four auto-regressive difference equations, ARX-models, have been identified describing the relations for u_d/i_d, u_q/i_d, u_d/i_q, and u_q/i_q. The difference equations have then been translated into a linear model of order 10. A 10th order model was selected since it gives a similar response to the events that were simulated with the original TCSC-model. The pre-disturbance steady-state used in [4,5] is the same as used in section 6.

The linear model developed in this paper will in sections 9 – 11 be compared with the one developed in [4,5]. The linear model is developed within the *dq*-representation. The existing control algorithm, shown in figure 2, is included in the built linear model.

All power system simulations are done with the power system simulation software Simpow [6,7].

5 THE CONTROL OF THE TCSC

The control of the TCSC is following the Synchronous Voltage Reversal-control algorithm developed in [8,9]. Here, that control algorithm is briefly viewed.

The aim of the applied TCSC-control is to create a desired value of the fundamental reactance between the buses on each side of the series capacitor. To do so, the control algorithm calculates the instant at which the thyristors should start conducting phase current through the series reactor, see figure 4. The Synchronous Voltage Reversal-control algorithm consists of three parts:

- Phase Locked Loop, PLL
- Booster, BOO
- Thyristor Pulse Generator, TPG

The Phase Locked Loop (PLL) generates a phase angle from the phase current i_a, see figure 2.

The Booster (BOO) calculates instants when the next two zero-crossings of the series capacitor voltage will occur and the Thyristor Pulse Generator (TPG) calculates the instants when the thyristors should start conducting.

Each phase has a similar control system to the one shown in figure 2. A more comprehensive explanation of the control system can be found in [3,4]. The control system in figure 2 is imbedded in the created linear model, i.e., it is not treated separately but included in the linear model.

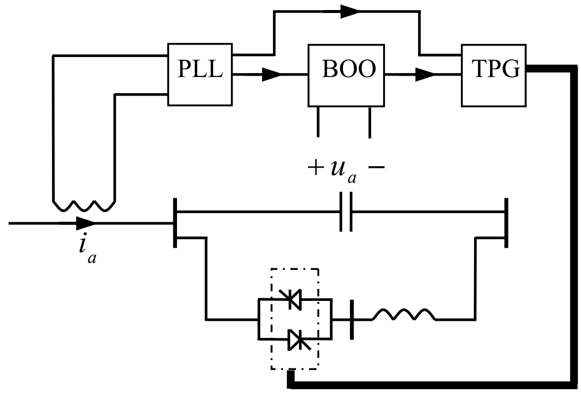

Figure 2: Control system of the TCSC.

6 DEVELOPING THE LINEAR MODEL

To obtain the dynamic response of the TCSC the current into it is disturbed, see *i* in figure 4. The *d*- and *q*-components of the incoming current *i* are disturbed with a frequency-variant sinusoidal signal $g(t)$ as given in equation (1) and shown in figure 3.

$$g(t) = K \cdot \sin(2\pi ft) \quad (1)$$

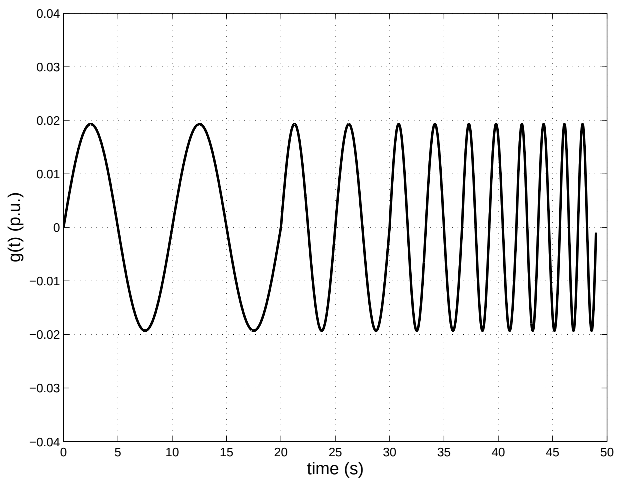

Figure 3: Frequency-variant signal $g(t)$.

The signal $g(t)$ is first added to the *d*-component of the current while the *q*-component remains constant. Later the signal $g(t)$ is added to the *q*-component of the current while the *d*-component remains constant. $g(t)$ is varied in the frequency range $0.1 < f < 70.0$ Hz ($0.628 < \omega < 440$ rad/s) as in figure 3. For every frequency, $g(t)$ is applied until the TCSC reaches a stationary status, see [12], then the TCSC's frequency response in u_d and u_q is calculated using Fast Fourier Transform (FFT). The results are shown in figures 5 – 6.

The signal $g(t)$ is added to the steady-state current i_{d0} = 0.193 p.u. and i_{q0} = 0 p.u. respectively. This current is selected since it is the steady-state current of the TCSC in section 9 and 10 for t < 6 s. K in equation (1) is 10% of the magnitude of the steady-state current, i.e., 0.0193 p.u. Figure 4 describes the actual situation where the current i through the load in Node B is disturbed with $g(t)$ in both its d- and q-component respectively. The current through the load in Node B is the same as the incoming current i to Node A.

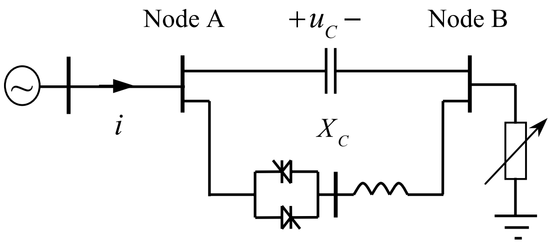

Figure 4: System used for identifying a linear model of the TCSC.

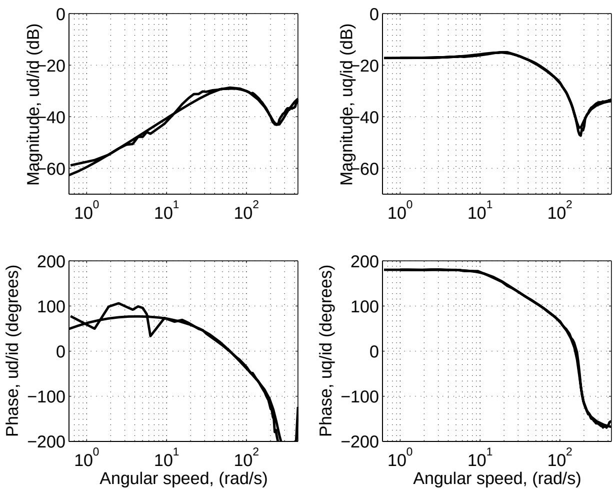

Figure 5: The frequency response of the TCSC and the response from the identified model when i_d is disturbed. $u_d(i_d)$ and $u_q(i_d)$ are shown in this figure.

The frequency response of the d- and q-components of the voltage drop over the TCSC when disturbing the d- and q-components of the current respectively are shown in figures 5 and 6. The 'unsmooth' curve is the recorded response from the original detailed TCSC-model. Also the response from the identified model is shown and that curve is smoother.

In the right-hand diagrams of figure 5 (u_q/i_d), the identified response is so close to the recorded one so that it is hard to see any difference between the two curves. The situation is the same for the left-hand diagram of figure 6.

From the recorded responses in figures 5 – 6, four transfer functions are built by using the automatic Matlab function 'fitsys'. 'fitsys' fits frequency response data with a transfer function of an order suggested by the user.

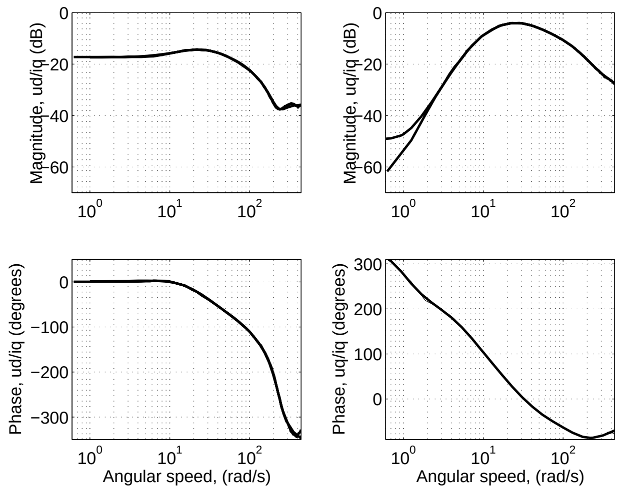

Figure 6: The frequency response of the TCSC and the response from the identified model when i_q is disturbed. $u_d(i_q)$ and $u_q(i_q)$ are shown in this figure.

The magnitude and phase responses are depicted as the 'smooth' curves in figures 5 – 6. The identified responses demand at least a linear model of order 17. For orders lower than 17, the matching between the identified and the recorded response of the TCSC becomes worse. The exact values of the linear model are omitted here.

7 INTERFACE

The input signal to the linear model is the difference between the actual current and its steady-state value. The output signal is the difference between the actual voltage drop over the TCSC and its steady-state value. Figure 7 describes this interface.

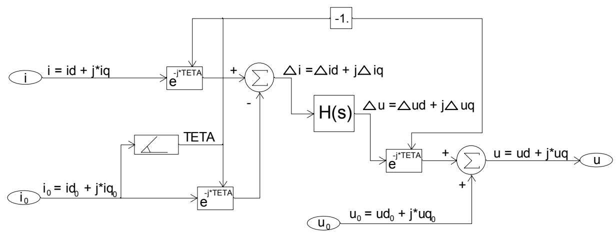

Figure 7: The interface to the linear model $H(s)$ of the TCSC.

To model the deviations in the current from steady-state as an input signal to the linear model of the TCSC, a surrounding reference system has to be built. In figure 7 the deviation Δi from the steady-state current, models the input signal to the linear model, $H(s)$. The signal i_0 is the d- and q-components of the current through the TCSC in steady-state.

u_0 in figure 7 is the d- and q-components of the voltage drop over the TCSC in steady-state. Δu, immediately to the right of the block diagram $H(s)$ in figure 7, is the output signal from the linear model $H(s)$. $H(s)$ was developed earlier in section 6. The same interface is used for the linear models.

8 SYSTEM USED FOR COMPARISONS

A system used for checking the accuracy of the linear models in comparison to the original TCSC-model is presented in figure 8.

The two synchronous machines, S1 and S2, are modeled with realistic ninth-order machine models including saturation, see [11]. Also exciters, governors, and turbines are modeled.

The machines are connected directly to the 500 kV level, i.e., no transformers are included in the system. The impedance of the line between Bus D and E is $R = 17.7\ \Omega$ and $X_L = 266\ \Omega$. It represents a 1000 km long transmission line. The impedance of the line between Bus A and Bus B is $X_L = 0.266\ \Omega$.

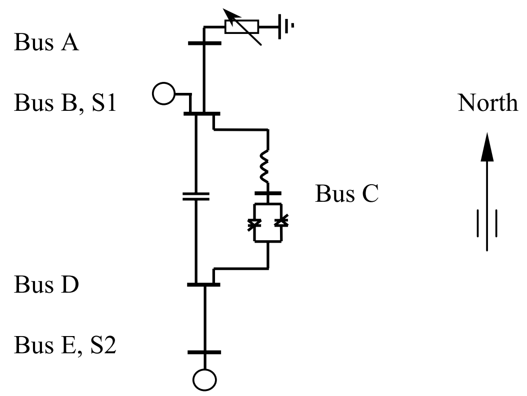

Figure 8: A power system including a TCSC-compensated link.

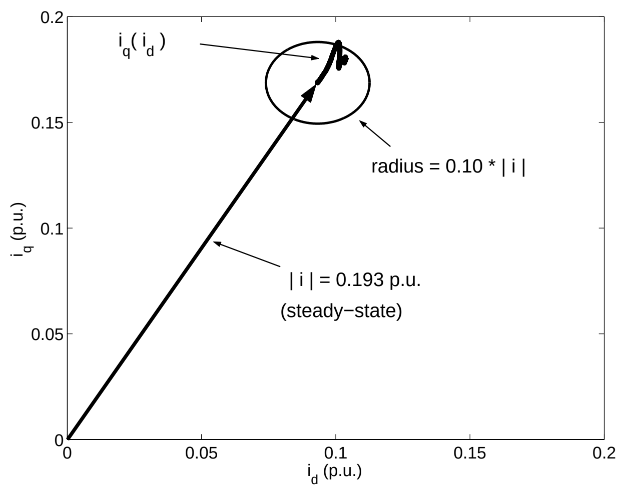

Figure 9: The current i_d and i_q through the TCSC for the three simulations depicted in one diagram for case A.

In the following three test cases the built linear model (indexed as 'Linear model 1') is compared with a linear model (indexed as 'Linear model 2') that has been developed in [4,5]. Every diagram shows three different simulations representing the TCSC as either:

- Original detailed model.
- Model identified with frequency response as in section 6, indexed as 'Linear model 1'.
- Model identified from time-domain simulations as in [4,5], indexed as 'Linear model 2'.

9 CASE A

In case A, the real power at Bus A is P = 500 MW until t = 6 s when it is increased with 50 MW (10%). The disturbance of i_d and i_q is in this case in the same range as when the the linear model was identified in section 6.

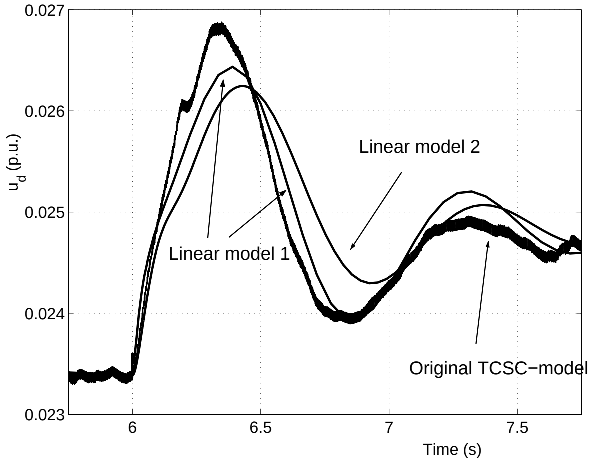

Figure 10: Voltage drop u_d over the TCSC in case A.

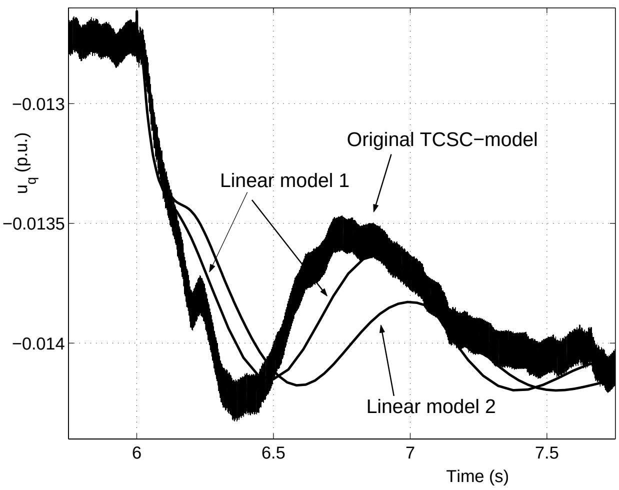

Figure 11: Voltage drop u_q over the TCSC in case A.

In figure 9, i_d and i_q are depicted in the same figure and there we can see that the change of the current is in the same range as when the linear model was identified in section 6, i.e., the current is within the circle of radius $0.10*|i|$. Therefore, the linear models should provide results in close agreement with the original TCSC-model since also 'Linear model 2' was identified with a 10% step in the d- and q-component of the current, see section 4.

For all three simulations the current into the TCSC is very similar and is therefore not shown. In figures 10 – 11 the voltage drop over the TCSC is depicted for the three simulations.

In figures 10 – 11 the output signals from the linear models are compared with the original TCSC-model. We can see that Linear model 1 follows the original model better than Linear model 2.

The simulations with the linear models take 5 seconds to complete. This should be compared with the simulation of the original TCSC-model that takes 2 hours.

10 CASE B

In case B, the real power at Bus A is P = 500 MW until t = 6 s when it is increased with 100 MW. Also the reactive power at Bus A is increased at t = 6 s from 0 Mvar to 100 Mvar. This implies the same initial state as in case A, but the disturbance is larger (22%).

In figures 12 – 13 we can see the same as in case A namely that the voltage drop over Linear model 1 follows the voltage drop of the original TCSC-model better than Linear model 2 does. The figures also proves that the linear models show resemblance for disturbances larger than the signals that were used when the linear models were identified, see sections 4 and 6.

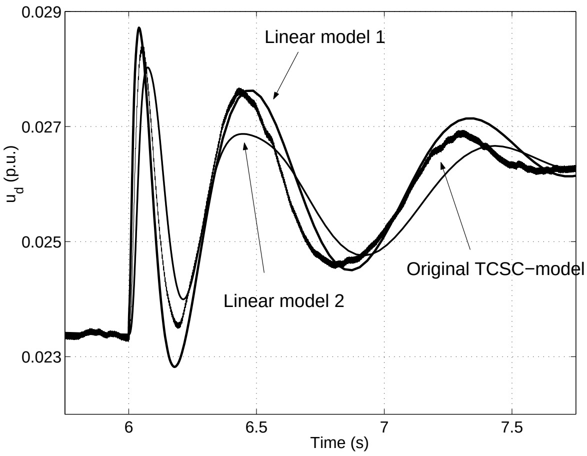

Figure 12: The voltage drop u_d over the TCSC in case B.

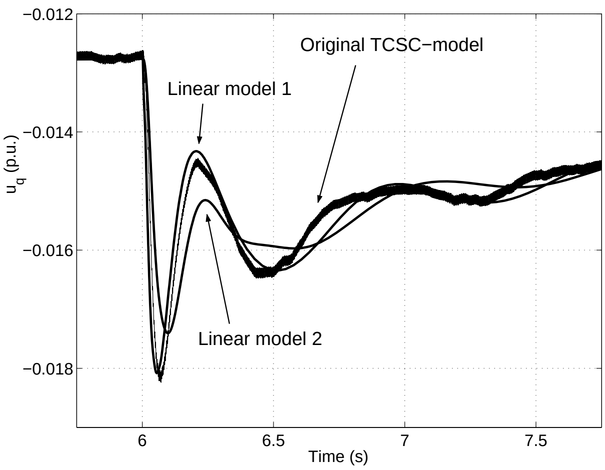

Figure 13: The voltage drop u_q over the TCSC in case B.

11 CASE C

It is important to check if the linear model is valid in another initial steady-state than the one used during the identification in section 6. Therefore in case C, the real power at Bus A is P = 700 MW until t = 6 s when it is increased by 50 MW (7.1%).

The current into the TCSC is, as in case A, very similar in the three simulations and is since then not documented here. Only the voltage drop across the TCSC is plotted in the figures 14 – 15.

The voltage drop of the linear models follow the voltage drop of the original TCSC-model, however, the linear models show worse resemblance than in cases A and B.

12 CONCLUSIONS

A method of identifying a linear model of a non-linear component is described by using its frequency response. The paper makes time-domain comparisons between an original TCSC-model and an identified linear model. Time-domain comparisons show that the linear model is valid for larger disturbances than the disturbance that was used when the linear model was developed.

The two linear models show also resemblance for other steady-states than the one used when the linear model was

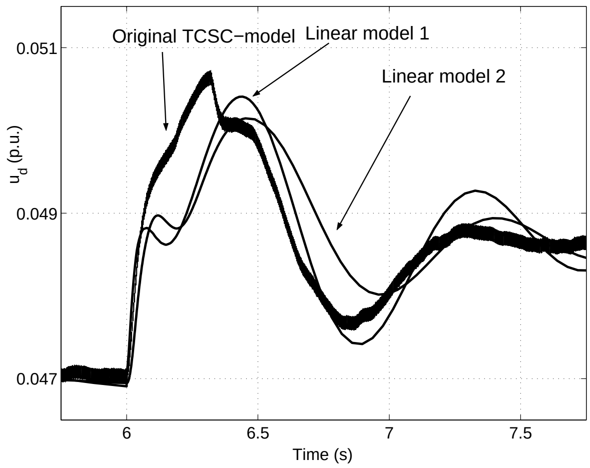

Figure 14: The voltage drop u_d over the TCSC in case C.

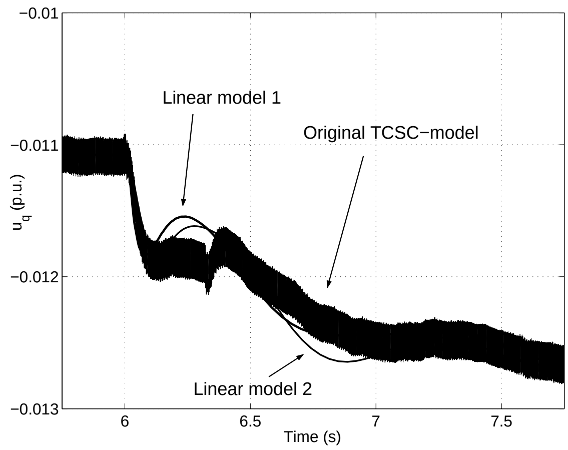

Figure 15: The voltage drop u_q over the TCSC in case C.

identified. However, the linear models show more resemblances with the steady-state that was used when the linear model was identified. It has to be further investigated if this indicates that the TCSC has different dynamic responses in different steady-states.

Simulations with the linear model take seconds to complete. This should be compared with simulations with the original TCSC-model that takes hours to complete.

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Luis Rouco Rodríguez was born in Spain. He obtained his Ingeniero Industrial and Doctor Ingeniero Industrial degrees from Universidad Politécnica de Madrid in 1985 and 1990. He is Professor of the School of Engineering of Universidad Pontificia Comillas in Madrid, Spain. He teaches a course of Electric Machines at undergraduate level and courses of Advance Power System Analysis and Power System Dynamics at graduate level. His areas of interest are modeling, analysis, simulation and identification of electric power systems. He has been visiting researcher at Ontario Hydro, MIT and ABB Power Systems.

Lennart Söder was born in Solna, Sweden in 1956. He received his M.Sc. and Ph.D. degrees in Electrical Engineering from the Royal Institute of Technology, Stockholm, Sweden in 1982 and 1988 respectively. He is currently a professor in Electric Power Systems at the Royal Institute of Technology. He also works with projects concerning deregulated electricity markets and integration of wind power.