

# Detailed Dynamic Modelling of a 50 MVar-STATCOM via Network Simulations in Time Domain

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**Abstract** — Much attention has been focused recently on FACTS (Flexible AC Transmission Systems). A detailed model of a STATCOM (Static Synchronous Compensator) has been developed for time domain simulations using the power system analysis software NETOMAC. The model captures both the control system and the entire three-phase electrical network. The performance of the model is studied, when the STATCOM is inserted into a power system and subjected to different disturbances.

**Index Terms** — Static Synchronous Compensator (STATCOM), Modelling, PQV-Curves, Power Systems.

## I. INTRODUCTION

Flexible AC Transmission Systems (FACTS) are a group of innovative devices based on power electronics used in HV transmission applications. They allow dynamic compensation of electric power transmission systems and improve utilization of existing generation and transmission facilities. Implementation of FACTS devices in conventional power systems leads to an increasing capacity of existing transmission lines, a higher power quality and allows to control power flow within the power system and reduces costs due to less investments [1,3].

The Static Synchronous Compensator (STATCOM) is a shunt connected FACTS device, Fig. 1, that provides a three-phase voltage system and allows generation as well as consumption of reactive power. This FACTS device consists of the following blocks: measuring system, controller, dc-capacitor, inverter circuit and a coupling transformer unit.

Its steady-state  $V-I$  and  $V-Q$  characteristic is shown in Figs. 2a and b, respectively. The reactive current  $I_Q$  can be set within its maximum capacitive and inductive limits even under strongly reduced voltage conditions.

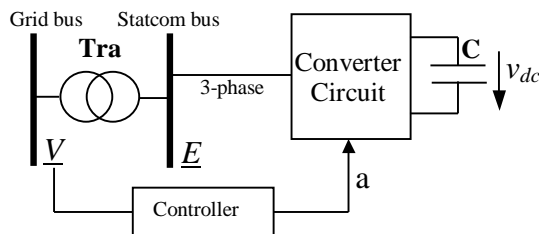


Fig. 1. STATCOM connected to the power system via a coupling transformer

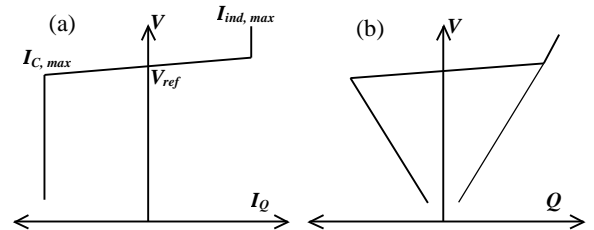


Fig. 2. Steady-State Capability of a STATCOM

(a)  $V-I$ -Characteristic  
(b)  $V-Q$ -Characteristic

The output of reactive current strongly depends on the thyristor firing angle  $a$  that is given by the phase shift between the STATCOM-voltage  $\underline{E}$  and the bus voltage  $\underline{V}$ . Depending on this firing angle  $a$ , the charging state of the dc-capacitor is changed and therefore the amplitude of the STATCOM bus voltage  $\underline{E}$  changes. The amplitude difference of the STATCOM bus voltage and the grid voltage together with the transformer leakage reactance  $X_T$  determines the amplitude of reactive current that is injected into the power system as given in (1).

$$I = \frac{V - E}{X_T} \quad (1)$$

The influence of the STATCOM on the steady-state voltage profile is summarized in part II of the paper with the concept of the  $PQV$ -curves.

In this project, a detailed 3-phase STATCOM model is presented and its dynamic behaviour is investigated when subjected to changing system conditions. The dynamic performance of the STATCOM is significantly influenced by the suggested controller of part IV.

## II. THE $PQV$ -CURVES

The influence of a shunt-connected STATCOM on the load bus voltage profile can be visualised using the concept of the  $PQV$ -curves, where  $P_{Load}$  and  $Q_{Load}$  are the active and reactive power drawn by a load and  $V$  is the according voltage on the load bus. The influence of a STATCOM connected to the load bus is shown in Figs. 3 and 4. Without a STATCOM, the voltage drops, if the active power drawn by the load is increased or if the load becomes more inductive.

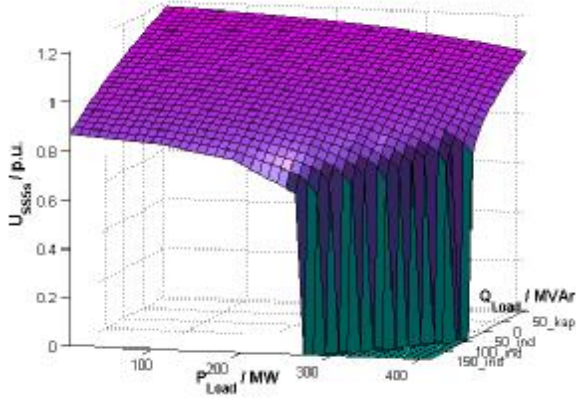


Fig. 3. PQV-curve on bus SS5 without a STATCOM.

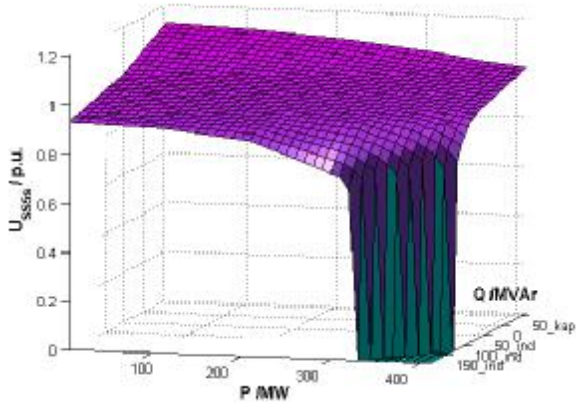


Fig. 4. PQV-curve on bus SS5 with a STATCOM applied.

With a STATCOM applied, the voltage profile is flattened, since there is capacitive power support if the voltage is lower than the reference voltage and inductive support, if the voltage is higher than the reference voltage due to a low load demand. On the other hand, higher power transfer to the load can be achieved due to the capacitive power support of the device. From the view of the time-varying load, a flattened profile and increased reactive generation margins are convenient to ensure a voltage stable system [1, 5]. The PQV-curves are used to determine the STATCOM model's initial conditions prior to the dynamic simulation and are generated with a static model suitable for load flow studies based on the  $V$ - $I_Q$ -relationship of Fig. 2.

### III. DETAILED STATCOM MODEL

The STATCOM is connected to the power system as shown schematically in Fig. 1. The dynamic model is implemented into the power system software Netomac [6]. However, the critical parts of the model in the sense of numerical stability are the converter circuit and the controller that relates the voltage difference, measured on the bus, to the ignition pattern of the thyristors.

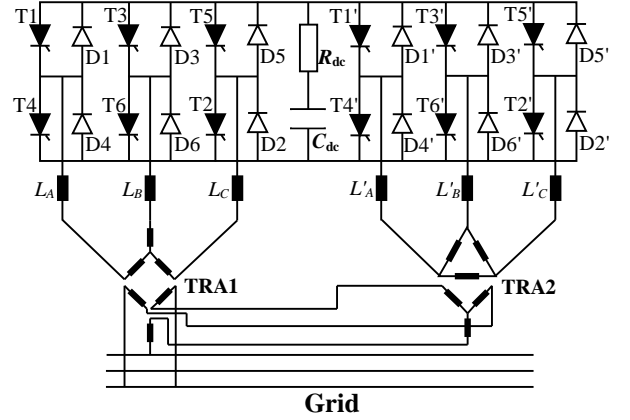


Fig. 5. STATCOM 12-pulse inverter circuit and connection to the grid via two coupling transformers.

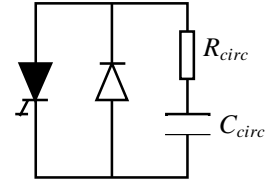


Fig. 6. Model of one valve of the voltage-sourced inverter.

The total converter circuit consists of two six-pulse inverters with a common dc-bus [7]. The voltage sourced inverter valves are made up of an asymmetric turn off device (GTO) with a parallel diode connected in reverse. The triggering of the thyristors takes place with fundamental frequency. The inverter circuits are connected to the power system via two separate transformers, Fig. 5. It is necessary to employ separate transformers because otherwise phase shift in the non-12-pulse harmonics, i.e. 5<sup>th</sup>, 7<sup>th</sup>, 17<sup>th</sup>, 19<sup>th</sup>, ... in the secondary windings will result in a large circulating current due to common core flux. The 100-MVA-transformers are equipped with wye- and delta-secondaries, respectively. Due to that, the secondary voltages are 30° out of phase. The harmonics that will be emitted to the grid are of the order  $12n \pm 1$ , e.g. 11<sup>th</sup>, 13<sup>th</sup>, 23<sup>rd</sup>, 25<sup>th</sup>, etc.[4].

$C_{dc}$  is the common capacitor of the two inverter circuits and  $R_{dc}$  represents the inverter losses of the device. Modelling of the thyristors was carried out using a time-varying resistor model to describe the conducting and non-conducting state. The ignition was controlled by an external controller circuit assuring a defined phase delay of  $\alpha$  in reference to the grid voltage. The non-linear resistor was chosen to be 0.1 mΩ and 20 kΩ for the two states, respectively. Due to the high gradients of turn-on and turn-off currents, numerical stability was not achieved. To solve this problem, an external circuit for the individual valves was composed, Fig. 6.

TABLE I  
PARAMETERS OF THE STATCOM MODEL

$C_{dc}$	500 $\mu$ F
$R_{dc}$	0.1 $\Omega$
$L_{ABC}$	0.01 mH
$L'_{ABC}$	0.01 mH
$R_{Thyristor}$	0.1 m $\Omega$ / 20 k $\Omega$
$R_{Diode}$	0.1 m $\Omega$ / 20 k $\Omega$
TRA <sub>1</sub> :	110 kV / 13.8 kV ; Yy0
TRA <sub>1</sub> : $u_r$	0.5 p.u.
TRA <sub>1</sub> : $u_k$	12 p.u.
TRA <sub>2</sub> :	110 kV / 13.8 kV ; Yd1
TRA <sub>2</sub> : $u_r$	0.5 p.u.
TRA <sub>2</sub> : $u_k$	12 p.u.

Those circuits permit fast transient oscillations as occurring in devices with distributed parameters. Supplementary, the STATCOM network nodes were connected to ground with a high impedance as suggested in [2]. Those remedial actions eliminated numerical problems and lead to accurate performance of the electrical circuit.

The values chosen for the circuit elements are given in table I.

The limits of  $I_{Qref}$  for maximum capacitive power and maximum inductive power ( $Q = \pm 50$  MVar) in steady-state are set to an equivalent power of +52 MVar and -46 MVar, respectively. However, during the transient state-change, overshoots of inductive power can occur when the bus voltage changes suddenly since the reactive current  $I_Q$  strongly depends on the voltage amplitude.

The capacitor was chosen according to the following boundaries: If the capacitor is too small, a small time constant allows a fast discharge during the commutation, hence the dc-voltage is subjected to distortion and the generated STATCOM output voltage  $E$  has not a sinusoidal shape due to harmonics. A too large capacitor leads to a long time constant for a change of dc-voltage and increases the overall inertia of the STATCOM.

#### IV. CONTROL LOOP

The controller is designed that the ignition angle  $a$  is equal to zero in steady state if there is no input of reactive power. The reference voltage is the result of the power-flow calculation without the STATCOM. The difference of actual bus voltage and reference voltage allows the calculation of the desired reactive current  $I_{Qref}$ . This current is limited and compared to the actual  $q$ -component of the STATCOM line current.

Both direct and quadrature currents are calculated but only the reactive portion is input of the PI-controller that leads to the calculation of leading or lagging ignition of the thyristors. There is no limitation of  $a$  needed.

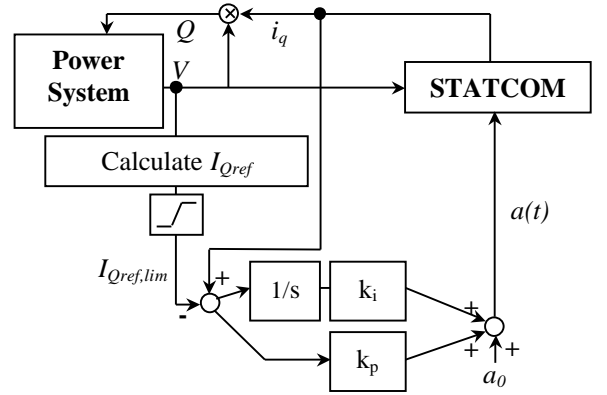


Fig. 7. Controller.

This detailed STATCOM model has not necessarily to be connected to a slack bus since it can handle varying bus voltage amplitudes and frequency deviations.

#### V. SIMULATION RESULTS

For all the investigations, the STATCOM is implemented into a 2-bus power system with generation on one side and power transfer to the load bus via parallel transmission lines. Voltage deviations on the load bus can be generated by dropping one of the parallel transmission lines. A 3-phase model is used in order to allow investigations on symmetrical and unsymmetrical disturbances.

If the STATCOM is driven in the capacitive mode, the amplitude of the output line-line voltage  $e(t)$  exceeds the amplitude of the grid voltage  $u(t)$  and contains the harmonics as shown in Fig.8.

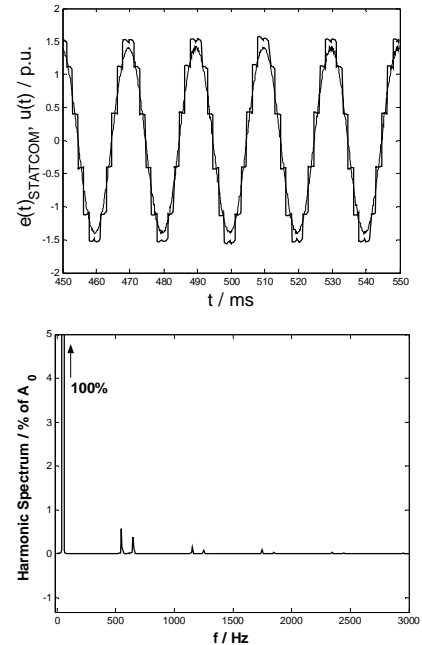


Fig. 8. Grid voltage  $u(t)$ ; STATCOM output voltage  $e(t)$  and harmonics in  $e(t)$ .

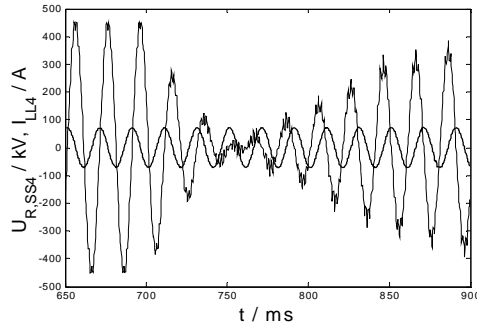


Fig. 9. STATCOM line current and phase voltage as simulated with the detailed model.

#### A. Change of thyristor ignition angle $\alpha$

In a first investigation, the ignition angles are set manually and the PI-controller is deactivated. A step function for  $\alpha$  is applied changing the STATCOM from fully inductive to fully capacitive mode. The line current has the characteristic distortions due to converter switching actions, Fig.9 and the phase shift between current and voltage of  $p$  takes place within a few cycles only.

#### B. STATCOM Response to a voltage step

A load bus without a STATCOM applied has an initial voltage of 0.95 p.u. and is subjected to a voltage drop of 0.1 p.u. of 0.5 s duration due to a disturbance. The system's dynamic response with a STATCOM applied is shown for this case in Fig. 10.

The STATCOM is able to support the voltage to the new steady-state value of 0.945 p.u. The response time is mainly limited by the gains  $k_I$  and  $k_p$  of the PI-controller and overshoots of reactive current and hence bus voltage can be observed. There is no sag of load power due to the system disturbance. The dynamic behaviour of the STATCOM model was also investigated for load changes and unsymmetrical faults and the results will be presented.

## VI. CONCLUSIONS

In this paper a detailed network model of a 12-pulse STATCOM is presented using NETOMAC. The steady-state behaviour is investigated using  $PQV$ -curves and the harmonic contents of output voltage and current are presented. The dynamic behaviour of the model is investigated applying sudden changes of ignition angle and severe disturbances. Using PI-control, the model was subjected to a voltage drop due to loss of a transmission line and it was shown that the STATCOM is able to fully compensate the load demand by insertion of required reactive power. Further investigations will include non-linear control techniques in order to avoid oscillation problems considering dynamic load models.

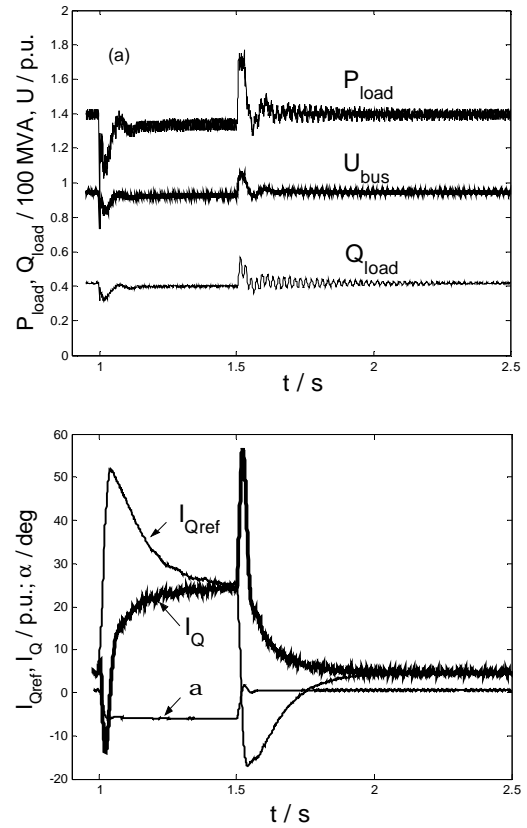


Fig. 10. Response of STATCOM and load when subjected to load bus voltage drop.

- (a) Bus Voltage  $U$ , Load power  $P_{load}$  and  $Q_{load}$ .
- (b) STATCOM values  $I_Q(t)$ ,  $I_{Qref}$  and  $\alpha(t)$ .

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