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Analysis and Control Design of Statcom in Distribution Network Voltage Control Mode

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Abstract – **This paper proposes and validates model which represent Static Synchronous Compensator (STATCOM) in voltage stability studies of distribution systems. The design of voltage controller, analysis of STATCOM dynamic behaviour and computer simulation are presented. Network voltage controller comprises "inner loop" for current control and "outer loop" for tight control of voltage. The control design was done using decoupling method in *d-q* rotational reference frame.**

Keywords – **STATCOM, FACTS, modelling, voltage control, controller design.**

I. INTRODUCTION

The concept of FACTS (Flexible AC Transmission Systems) uses the advent of modern semiconductor switching devices to achieve flexibility of system operation with fast and reliable control. STATCOM (Static Synchronous Compensator) is a representative of the FACTS devices based on voltage source converter which can be used for shunt reactive power compensation and dynamic voltage regulation [1]. STATCOM regulates the grid voltage u_{GRID} by injecting/absorbing reactive current i_{STAT} that will provide the source current i_S perpendicular to the phasor representing the voltage drop across the distribution line inductance x_S [1].

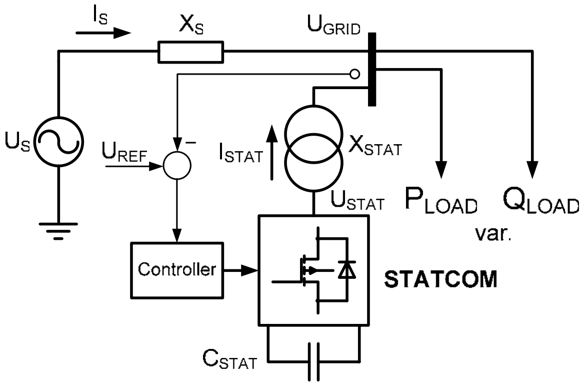

Fig. 1. System under study.

The reactive current i_{STAT} injected or absorbed by the STATCOM can be varied by varying the magnitude of the converter output voltage u_{STAT}, which is ideally in phase with respect to the voltage at the point of common coupling u_{GRID} (Fig. 1). This paper will first present a simple distribution network model with the STATCOM connected. Switching and averaged model of the STATCOM is given, which enables study of dynamic behaviour of considered system. Than, it focuses on the control of the STATCOM converter in order to achieve stable grid voltage level.

II. MODEL OF THE SYSTEM

Distribution network in most cases has radial structure with, in normal operation, week coupling between the network legs. Thus simple model from Fig. 2 can be used for its analysis, where the grid is modelled as voltage source u_S and series inductance l_S and resistance r_S, load comprising active power p_{LOAD} and reactive power part q_{LOAD}, while the STATCOM is modelled as voltage source u_{STAT} and series inductance l_{STAT} and resistance r_{STAT}. The load is modelled by the variable resistance r and variable inductance l [2].

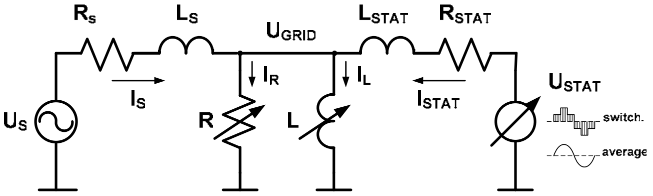

Fig. 2. Simplified model of the system.

Equations that describe the system from Fig. 2, in α-β stationary reference frame are:

$$\frac{d}{dt}\begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} = \frac{1}{\tau_S}\left(\begin{bmatrix} u_{S\alpha} \\ u_{S\beta} \end{bmatrix} - \begin{bmatrix} u_{GRID\alpha} \\ u_{GRID\beta} \end{bmatrix} - r_S \cdot \begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix}\right) \quad (1)$$

$$\frac{d}{dt}\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \frac{1}{\tau_L} \cdot \begin{bmatrix} u_{GRID\alpha} \\ u_{GRID\beta} \end{bmatrix} \quad (2)$$

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$$\begin{bmatrix} u_{GRID\alpha} \\ u_{GRID\beta} \end{bmatrix} = r \cdot \left(\begin{bmatrix} i_{S\alpha} \\ i_{S\beta} \end{bmatrix} + \begin{bmatrix} i_{STAT\alpha} \\ i_{STAT\beta} \end{bmatrix} - \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \right) \tag{3}$$

$$\frac{d}{dt}\begin{bmatrix} i_{STAT\alpha} \\ i_{STAT\beta} \end{bmatrix} = \frac{1}{\tau_{STAT}} \cdot \left(\begin{matrix} \begin{bmatrix} u_{STAT\alpha} \\ u_{STAT\beta} \end{bmatrix} - \begin{bmatrix} u_{GRID\alpha} \\ u_{GRID\beta} \end{bmatrix} \\ - r_{STAT} \cdot \begin{bmatrix} i_{STAT\alpha} \\ i_{STAT\beta} \end{bmatrix} \end{matrix} \right) \tag{4}$$

where are:

$$\tau_S = \frac{L_S}{Z_B}, \tau_L = \frac{L}{Z_B}, \tau_{STAT} = \frac{L_{STAT}}{Z_B}, r = \frac{R}{Z_B}, r_{STAT} = \frac{R_{STAT}}{Z_B} \tag{5}$$

In general, output voltage of the STATCOM voltage source converter, u_{STAT}, can be expressed by defining a switching functions for each phase of the converter - S_{aN}, S_{bN} *and* S_{cN}. Line-to-neutral output voltages of the STATCOM converter can be expressed as:

$$\begin{bmatrix} u_{STAT\_aN} \\ u_{STAT\_bN} \\ u_{STAT\_cN} \end{bmatrix} = \begin{bmatrix} S_{aN} \\ S_{bN} \\ S_{cN} \end{bmatrix} \cdot u_{DC} \tag{6}$$

where u_{DC} represent dc voltage across capacitor C_{STAT}. Sequence of switching functions, S_{aN}, S_{bN}, and S_{cN}, in order to achieve 3-phase voltage waveforms that are devoid of low-frequency harmonic content, is determined by space-vector modulation strategy (SVM) [3].

III. CONTROLLER DESIGN

It is convenient to perform control design in *d-q* rotational reference frame [4], where alternating variables become constants in steady state. Linking *d-q* rotational reference frame with voltage of common coupling, u_{GRID} ($u_{GRIDq} = 0$), reactive power flow between STATCOM and network is determined with STATCOM current in *q*-axis, i_{STATq}, and active power flow is determined with STATCOM current in *d*-axis, i_{STATd} (Eqs. (7) and (8)).

$$q_{STAT} = u_{GRIDd} \cdot i_{STATq} - u_{GRIDq} \cdot i_{STATd} = u_{GRIDd} \cdot i_{STATq} \tag{7}$$

$$p_{STAT} = u_{GRIDd} \cdot i_{STATd} + u_{GRIDq} \cdot i_{STATq} = u_{GRIDd} \cdot i_{STATd} \tag{8}$$

In such way, STATCOM current in *q*-axis, i_{STATq}, controls magnitude of voltage u_{GRID}, and STATCOM current in *d*-axis covers STATCOM losses and controls magnitude of dc voltage u_{DC}. Corresponding controller structures, based on those circumstances, are shown in Fig. 3.

Loop equation which describe STATCOM dynamic behaviour in *d*- and *q*- axis, which is Eq. (4) transformed to the rotational reference frame, can be expressed as:

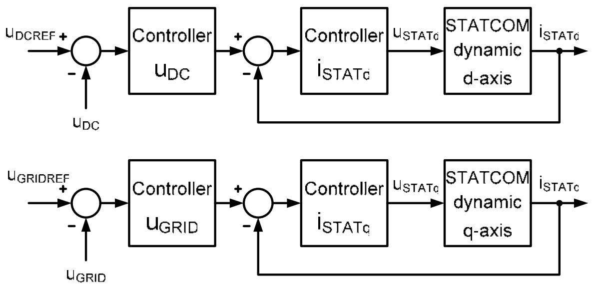

Fig. 3. Controller structure.

$$\tau_{STAT} \cdot \frac{d}{dt}\begin{bmatrix} i_{STATd} \\ i_{STATq} \end{bmatrix} = \begin{bmatrix} d_d \\ d_q \end{bmatrix} \cdot u_{DC} - \begin{bmatrix} u_{GRIDd} \\ 0 \end{bmatrix} - r_{STAT} \cdot \begin{bmatrix} i_{STATd} \\ i_{STATq} \end{bmatrix} + \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix} \cdot \begin{bmatrix} i_{STATd} \\ i_{STATq} \end{bmatrix} \tag{9}$$

d- and *q*-axis modulation indexes, d_d and d_q, which are input commands for SVM modulation strategy, are obtained as:

$$d_d = \frac{u_{STATd}}{u_{DC}}, d_q = \frac{u_{STATq}}{u_{DC}} \tag{10}$$

where u_{STATd} and u_{STATq} represent outputs from corresponding controllers (Fig. 3). In *d-q* domain there is a coupling between axis, i.e. in Eq. (9) term with i_{STATq} existing in equation for i_{STATd}, and reverse, term with i_{STATd} existing in equation for i_{STATq}. That circumstance protracts design of current controllers in Fig. 3.

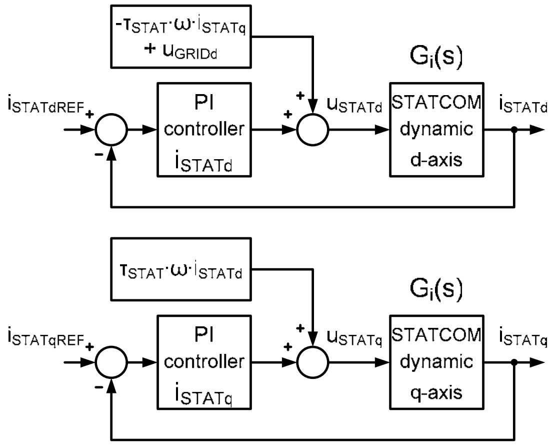

Fig. 4. Decoupling between d- and q- axis.

By including feed-forward terms as part of current controllers, as shown in Fig. 4, controllers perceives STATCOM dynamic as process that can be describe by following first-order model:

$$G_i(s) = \frac{\dfrac{1}{r_{STAT}}}{1 + s \cdot \dfrac{\tau_{STAT}}{r_{STAT}}} = \frac{k_{ekvi}}{1 + s \cdot T_{ekvi}} \tag{11}$$

By controlling this process with the PI controller,

$$G_{Ri}(s) = K_{Pi}\cdot\left(1+\frac{1}{s\cdot T_{Ii}}\right) \tag{12}$$

a characteristic equation, for the second-order closed-loop system, becomes:

$$s^2 + s\cdot\left(\frac{1}{T_{ekvi}} + \frac{k_{ekvi}\cdot K_{Pi}}{T_{ekvi}}\right) + \frac{k_{ekvi}\cdot K_{Pi}}{T_{ekvi}\cdot T_{Ii}} = 0 \tag{13}$$

If desired closed-loop poles are characterized by their relative damping, ξ_i, and their natural frequency, ω_i, equations determining K_{Pi} and T_{Ii}, are given by [5]:

$$K_{Pi} = \frac{2\cdot\xi_i\cdot\omega_i\cdot T_{ekvi} - 1}{k_{ekvi}}, T_{Ii} = \frac{2\cdot\xi_i\cdot\omega_i\cdot T_{ekvi} - 1}{\omega_i^2\cdot T_{ekvi}} \tag{14}$$

From Eq. (3) it is obvious that STATCOM current dynamic will fully determine dynamic of regulated voltage u_{GRID}. Thus, by proper selection of parameters ξ_i and ω_i, i.e. K_{Pi} and T_{Ii}, dynamics of process perceived by voltage controller u_{GRID}, can be characterized as:

$$G_u(s) = \frac{k_{ekvu}}{1+s\cdot T_{ekvu}} \tag{15}$$

In order to have $G_u(s)$ as in Eq. (15) relative damping ξ_i must be equal or greater then 1. The parameter ω_i can be viewed as a design parameter that determines the response speed and is related with T_{ekvu} as follows:

$$T_{ekvu} = \frac{1}{\xi_i\cdot\omega_i} \tag{16}$$

By controlling voltage u_{GRID} with the PI controller,

$$G_{Ru}(s) = K_{Pu}\cdot\left(1+\frac{1}{s\cdot T_{Iu}}\right) \tag{17}$$

and supposing that desired closed-loop poles are characterized by their relative damping ξ_u and their natural frequency ω_u, the following PI parameters are obtained:

$$K_{Pu} = \frac{2\cdot\xi_u\cdot\omega_u\cdot T_{ekvu} - 1}{k_{ekvu}}, T_{Iu} = \frac{2\cdot\xi_u\cdot\omega_u\cdot T_{ekvu} - 1}{\omega_u^2\cdot T_{ekvu}} \tag{18}$$

If control requirements are given in form of overshoot δ_u and setting time T_{Su}, damping ξ_u and frequency ω_u, are given by:

$$\xi_u = \frac{1}{\sqrt{1+(\pi/ln\,\delta_u)^2}}, \omega_u = \frac{3}{\xi_u\cdot T_{Su}} \tag{19}$$

The goal set for the voltage, u_{GRID}, controller is to obtain minimum overshoot $\delta_u < 4\%$ and fast setting time T_{Su} in order of period of grid frequency ($T_{Su} \approx 20$ ms).

IV. SIMULATION RESULTS

System parameters and based values used in the model are given in Table I.

TABLE I
SYSTEM PARAMETERS

Parameter	Label	Value
Network inductance	L_S	3.73 mH
Network resistance	R_S	1.17 Ω
Network voltage	U_S	10 kV
Active load power	(related to R)	150 kW
Reactive load power	(related to L)	50 kVAr
Statcom inductance	L_{STAT}	15.91 mH
Statcom resistance	R_{STAT}	1,0 Ω
Based voltage	U_B	10 kV
Based current	I_B	1000 A

Following instructions for designing current PI controllers and taking $\xi_i = 1.0$ and $\omega_i = 60$ rad/s (which correspond to settling time 50 ms), yield $K_{Pi} = 9.1\cdot 10^{-2}$ and $T_{Ii} = 1.59\cdot 10^{-2}$. Simulation was firstly done using averaged model of STATCOM converter. Step response of the system with current controllers is shown in Fig. 5.

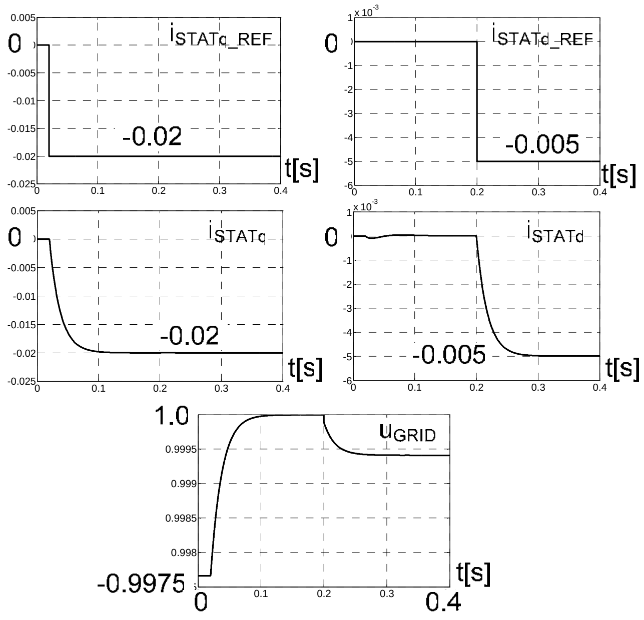

Fig. 5. Step response of system to current references.

From Fig. 5 it can be seen that decoupling method performed well and that actual system response agrees with desired, given by parameters ξ_i and ω_i. From step response of voltage u_{GRID}, it can be find that for the voltage control loop the gain is $k_{ekvu} = 0.115$ and loop time constant is $T_{ekvu} = 16.67$ ms. Settling time is approximately $3\cdot T_{ekvu} = 50$ ms. Real expectations from voltage controller is to speed up response 3-4 times. Following instructions for designing voltage PI controller and taking overshoot $\delta_u = 0\%$ and settling time $T_{Su} = 20$ ms, yields voltage controller parameters $K_{Pu} = 34.78$ and $K_{Iu} = 1.07\cdot 10^{-2}$. Step response of system with voltage controller using detailed switching model is shown in Fig. 6. Response of voltage u_{GRID} is considered for following disturbances: connecting STATCOM to point of common coupling with voltage reference 1.0 p.u. at 0.01 s, step change of active load power from 0.015 p.u. to 0.02 p.u. at 0.1 s, step change of reactive load power form 0.005 p.u. to 0.01 p.u. at 0.15 s, step change of source voltage u_S from 1.0 p.u. to 0.99 p.u. at 0.2 s, and step change of d-axis current reference form 0 p.u. to -0.025 p.u. at 0.25 s.

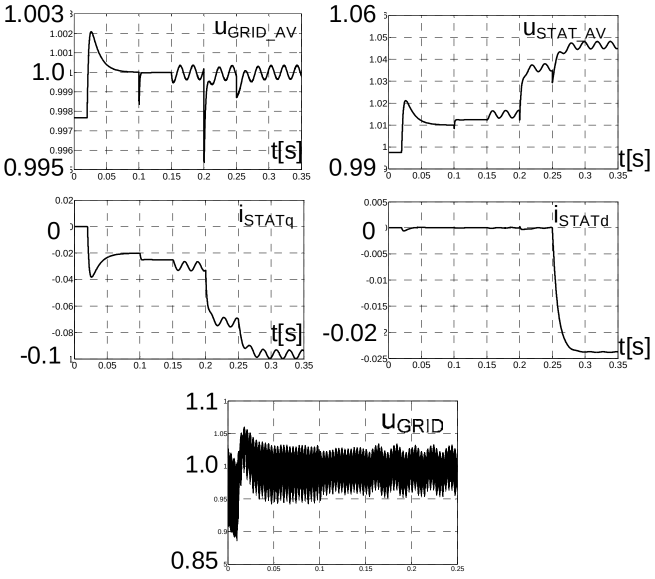

Fig. 6. Step response of system to different disturbances.

Fig. 6 shows averaged values of voltages u_{GRID} and u_{STAT}, averaged values of currents i_{STATq} and i_{STATd}, and also actual voltage waveform of u_{GRID}. From Fig. 6 it can be seen that response of system is close to desired. The voltage controller performs better to load disturbance than to change of voltage reference, which usually the case when the controller is designed based on pole placement method [5]. Only q-axis component of current i_{STAT} assists in supporting voltage u_{GRID}, which agree with STATCOM functionality.

V. CONCLUSION

The paper proposes and validates model which represent STATCOM in voltage stability studies of distribution systems. The model discussed here is based on switching strategy using SVM. Design of controllers was done using average model and then verified with switching model of STATCOM converter. Grid voltage controller comprises inner loop for current control and outer loop for voltage control. Design of current controllers was done in d-q rotational reference frame using decoupling method between d- and q-axis by introducing feed-forward terms as part of current controllers. It simplifies tuning of PI gains in current controllers. Design of grid voltage controller was done by identifying process of grid voltage response to STATCOM current reference. Detailed switching model shows satisfactory response to different disturbances such as change of voltage reference, change of load power, and change of network voltage (u_S). Response could be improved by using multilevel inverter.

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