IMPROVEMENT OF DISTRIBUTION SYSTEM VOLTAGE STABILITY BY USE OF STATCOM – STATIONARY AND DYNAMIC ANALYSIS

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INTRODUCTION

The rapid development of power electronics technology enabled development of new power equipment that can improve the performance of the existing transmission and distribution power system. During last decade, new control devices called „Flexibile AC Transmission Systems“ (FACTS), have been proposed and designed. With the advent of modern semiconductor switching devices, such as gate turn-off thyristors (GTO) and insulated gate bipolar transistors (IGBT), a new generation of power electronic equipment, STATCOM (Static Synchronous Compensator) a representative of the FACTS devices, shows great promise for application in the power systems.
The primary functions of the STATCOM are power flow control and dynamic voltage regulation in AC transmission and distribution systems, but it can be also used to improve transient stability and to damp power oscillations. The concept is based on voltage sourced inverter shunt connected to the grid, shown in Fig. 1.

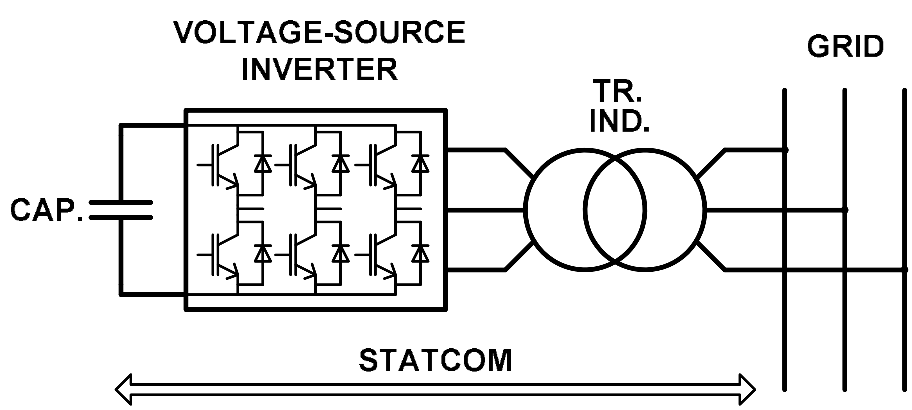

Fig. 1. Basic block diagram of STATCOM connected to the grid.

The paper will first present a basic study of STATCOM operation with the aim to provide grid voltage regulation. After that, applying simple model of the system, the static analysis is performed to obtain the level of the device impact and to specify the guidelines for its sizing. Finally, dynamic analysis of the modelled system will be applied to evaluate the requirements for the STATCOM dynamic characteristics, which will enable control design.

OPERATIONAL PRINCIPLE

The basic electronic building block for a STATCOM is a voltage-source inverter that converts the DC voltage at its input terminals into a three-phase set of variable AC output voltages. The power inverter is connected to the line through a coupling transformer and/or coupling reactors. The simplest implementation of such an inverter source is illustrated in Fig. 1.

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 modeled as voltage source u_S and series reactance x_S, load comprising active power p_{LOAD} and reactive power part q_{LOAD}, while the STATCOM is modeled as additional voltage source u_{STAT} in series with coupling reactance x_{STAT}. A fixed capacitor with reactance x_C is provided near the load to supply fixed reactive power.

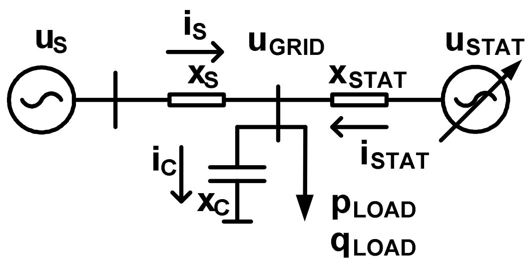

Fig. 2. Simplified model of the system.

STATCOM injects reactive current i_{STAT}, whose phase is 90^0 shifted with respect to the voltage at the point of common coupling u_{GRID} [1]. It can be operated in two control modes: reactive power control mode, where the STATCOM reactive power output is adjusted based on the system demands, and voltage regulation mode, where the device holds voltage constant, i.e. provide 1.0 p.u. voltage support. The focus here is on the voltage regulation mode of STATCOM, illustrated with Fig. 3, using circuit currents and voltages phasor diagram.

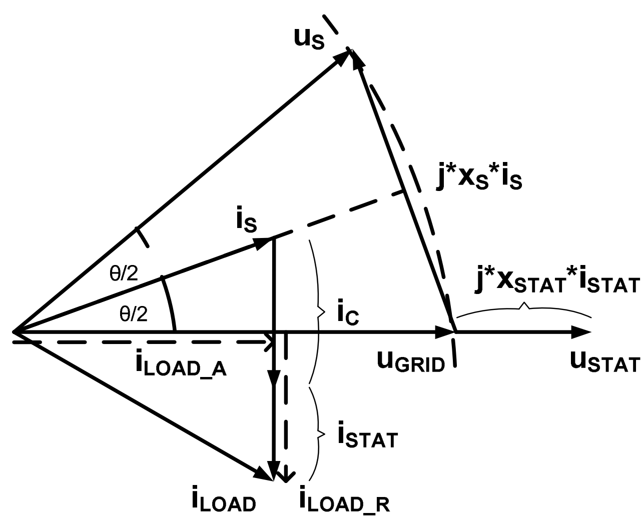

Fig. 3. Phasor diagram of the model from Fig. 2 with STATCOM injecting reactive current i_{STAT}.

There θ is load angle, i_S grid current, and i_C fixed capacitor current. Load current is represented by its active and reactive component, $i_{LOAD} = i_{LOAD\_A}+i_{LOAD\_R}$. To accomplish the goal $u_S = u_{GRID} = 1$, the source current i_S must be perpendicular to the phasor representing the voltage drop across the distribution line inductance. So, the STATCOM must provide current equal to $i_{STAT} = i_{LOAD} - i_S - i_C$. It can be observed that changes in both active and reactive load power, influence required STATCOM current, i_{STAT}.

STATIC ANALYSIS

This part analyses STATCOM's impact on the grid voltage [2]. The following equations, in normalized form, are valid for power flows from Fig. 2:

$$p_{LOAD} = \frac{u_S \cdot u_{GRID}}{x_S} \cdot \sin\theta \tag{1}$$

$$q_{LOAD} = \frac{u_S \cdot u_{GRID} \cdot \cos\theta - u_{GRID}^2}{x_S} + \frac{u_{GRID}^2}{x_C} + q_{STAT} \tag{2}$$

where q_{STAT} is the STATCOM generated reactive power. Load dependences on the grid voltage can be formulated with [3]:

$$p_{LOAD} = p_{LOAD}^0 \cdot u_{GRID}^{mp} \tag{3}$$

$$q_{LOAD} = q_{LOAD}^0 \cdot u_{GRID}^{mq} \tag{4}$$

where are: p^0_{LOAD}, q^0_{LOAD} – load active and reactive powers at nominal voltage $u^0_{GRID}=1$, and mp, mq – factors of their dependences on grid voltage u_{GRID}. mp and mq take the values in the range 0-2 depending on the load type. Eliminating the angle θ, it yields following non-linear equation for calculating the grid voltage:

$$\left(p_{LOAD}^0 \cdot u_{GRID}^{mp} \cdot x_S\right)^2 + \left(q_{LOAD}^0 \cdot u_{GRID}^{mq} \cdot x_S + \left(1 - \frac{x_S}{x_C}\right) \cdot u_{GRID}^2 - q_{STAT} \cdot x_S\right)^2 = \left(u_S \cdot u_{GRID}\right)^2 \tag{5}$$

With provided grid voltage support $u_{GRID}=1$ p.u. and for certain load power, equation (5) and Fig. 4 gives STATCOM reactive power demand as a function of p_{LOAD} and q_{LOAD} :

$$q_{STAT} = \frac{q_{LOAD}^0 \cdot x_S + \left(1 - \frac{x_S}{x_C}\right) - \sqrt{u_S^2 - \left(p_{LOAD}^0 \cdot x_S\right)^2}}{x_S} \tag{6}$$

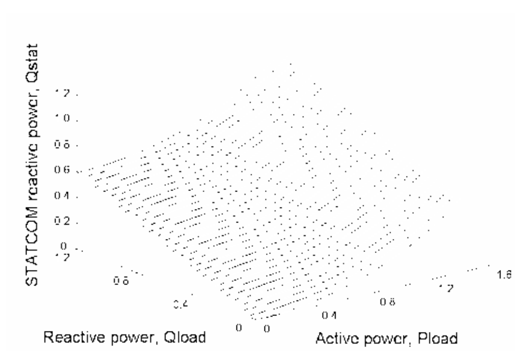

Fig. 4. STATCOM reactive power values for given p_{LOAD} and q_{LOAD} ranges, with provided voltage regulation u_{GRID}=1.0 p.u.

In practice STATCOM usually implements the *u-i* characteristic illustrated in Fig. 5 [4]. Instead of maintaining the u_{GRID} at fixed value, voltage slope is added, between 1% and 4%, to compensate voltage drops down the network legs.

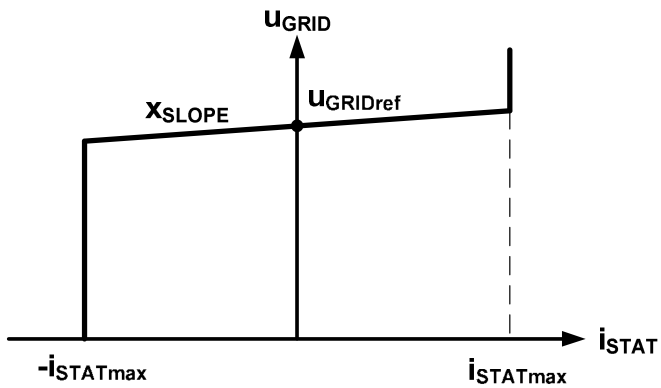

Fig. 5. STATCOM *u-i* characteristic.

With voltage droop added, the *u-i* static control characteristic is described by the following equation:

$$u_{GRID} = u_{GRIDref} + x_{SLOPE} \cdot i_{STAT} \quad (7)$$

DYNAMIC ANALYSIS

The system from Fig. 2. in slightly different form suitable for dynamic analysis is shown in Fig. 6. The load is modeled by the variable resistance and variable inductance where according to the equations (3) and (4) is:

$$r = r_0 \cdot \left(\frac{u^0_{GRID}}{u_{GRID}} \right)^{mp-2} \quad (8)$$

$$l = l_0 \cdot \left(\frac{u^0_{GRID}}{u_{GRID}} \right)^{mq-2} \quad (9)$$

where are:

$$r_0 = \frac{{u^0_{GRID}}^2}{p^0_{LOAD}} \quad \text{and} \quad l_0 = \frac{{u^0_{GRID}}^2}{\omega \cdot q^0_{LOAD}} \quad (10)$$

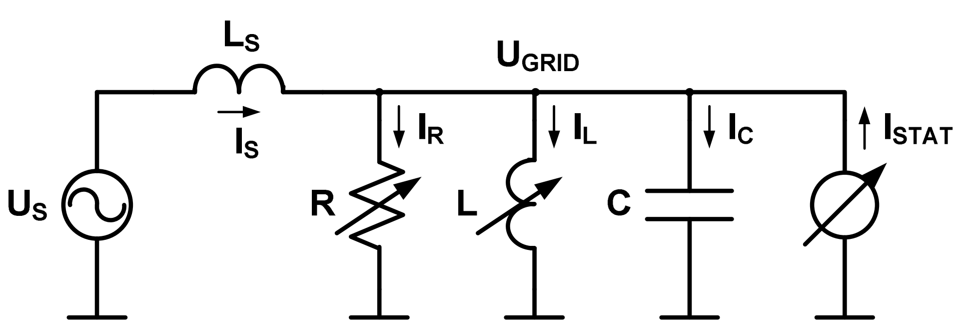

Fig. 6. System under study for dynamic analysis.

State-space equations that describe the system from Fig. 6, in α-β stationary reference frame are:

$$\tau_1 \cdot \frac{du_{GRID\_\alpha\beta}}{dt} = -\frac{1}{r_0} \cdot u_{GRID}^{mp-2} \cdot u_{GRID\_\alpha\beta} + i_{S\_\alpha\beta} - i_{L\_\alpha\beta} + i_{STAT\_\alpha\beta} \tag{11}$$

$$\tau_2 \cdot \frac{di_{S\_\alpha\beta}}{dt} = -u_{GRID\_\alpha\beta} + u_{S\_\alpha\beta} \tag{12}$$

$$\tau_3 \cdot \frac{di_{L\_\alpha\beta}}{dt} = u_{GRID}^{mq-2} \cdot u_{GRID\_\alpha\beta} \tag{13}$$

Constants τ_1, τ_2, τ_3 and r_0 are given in the Appendix. Linearized around operating point $u_{GRID}=1.0$, non-linear set of equations (12-14) became:

$$\frac{du_{GRID\_\alpha\beta}}{dt} = -\frac{1}{r_0 \cdot \tau_1} \cdot (mp-1) \cdot \Delta u_{GRID\_\alpha\beta} + \frac{1}{\tau_1} \cdot \Delta i_{S\_\alpha\beta} - \frac{1}{\tau_1} \cdot \Delta i_{L\_\alpha\beta} + \frac{1}{\tau_1} \cdot \Delta i_{STAT\_\alpha\beta} \tag{14}$$

$$\frac{di_{S\_\alpha\beta}}{dt} = -\frac{1}{\tau_2} \cdot \Delta u_{GRID\_\alpha\beta} + \frac{1}{\tau_2} \cdot \Delta u_{S\_\alpha\beta} \tag{15}$$

$$\frac{di_{L\_\alpha\beta}}{dt} = \frac{1}{\tau_3} \cdot (mq-1) \cdot \Delta u_{GRID\_\alpha\beta} \tag{16}$$

In dynamic analysis and control design, it is more convenient to formulate the system of state-space differential equations in the *d-q* rotational reference frame:

$$\frac{dx_{dq}}{dt} = [A] \cdot x_{dq} + [B] \cdot u_{dq} \tag{17}$$

where $x_{dq} = [u_{GRID\_d} \quad u_{GRID\_q} \quad i_{S\_d} \quad i_{S\_q} \quad i_{L\_d} \quad i_{L\_q}]^T$ are the state variables associated with the network elements, and $u_{dq} = [i_{STAT\_d} \quad i_{STAT\_q} \quad u_{S\_d} \quad u_{S\_q}]^T$ are the input variables associated with the STATCOM injected currents (i_{STAT_d}, i_{STAT_q}) and the grid voltages (u_{S_d}, u_{S_q}). Matrix A determines behaviour of the system and matrix B determines impact of the STATCOM and u_S and they are given in the Appendix.
The dynamic properties of the system are determined by eigenvalues of matrix A, i.e. poles location shown in the Fig. 7a, expressed in stationary *α-β* reference frame, and in the Fig. 7b, expressed in rotational *d-q* reference frame [5]. From the corresponding poles location, it follows that the pole pairs in stationary *α-β* reference frame has became pole pairs in the rotational *d-q* reference frame with the same real parts, but with imaginary parts displaced with ± ω_{GRID}. This is consequence of applying transformation of rotation. In particular, in stationary *α-β* reference frame poles of the system are given by:

$$s_{1/2} = 0 \qquad s_{3/6} = -\frac{mp-1}{2 \cdot r_0 \cdot \tau_1} + j \cdot \sqrt{\left(\frac{1}{\tau_1 \cdot \tau_2} + \frac{mq-1}{\tau_1 \cdot \tau_3}\right) - \left(\frac{mp-1}{2 \cdot r_0 \cdot \tau_1}\right)^2} = -\frac{mp-1}{2 \cdot r_0 \cdot \tau_1} \pm j \cdot \omega_{RES} \tag{18}$$

After *d-q* transformation, poles of the system are displaced at:

$$s_{1/2} = \pm\omega_{GRID} \qquad s_{3/4} = -\frac{mp-1}{2 \cdot r_0 \cdot \tau_1} \pm j \cdot (\omega_{RES} + \omega_{GRID}) \qquad s_{5/6} = -\frac{mp-1}{2 \cdot r_0 \cdot \tau_1} \pm j \cdot (\omega_{RES} - \omega_{GRID}) \tag{19}$$

Based on the obtained system poles location it can be observed that the pole pair $s_{1/2}$ on the imaginary axis stay fixed irrespective of the changes in the load power. On the other hand, pairs $s_{3/4}$ and $s_{5/6}$ will change their position depending on the load active and reactive power consumption. By increasing active load mainly real part of the poles changes, moving away from imaginary axis. By increasing reactive load, imaginary part of the poles changes, moving away from the real axis. Knowing dynamic properties of the system under study will, in the future work, enable selection of STATCOM controller structure and setting up its parameters.

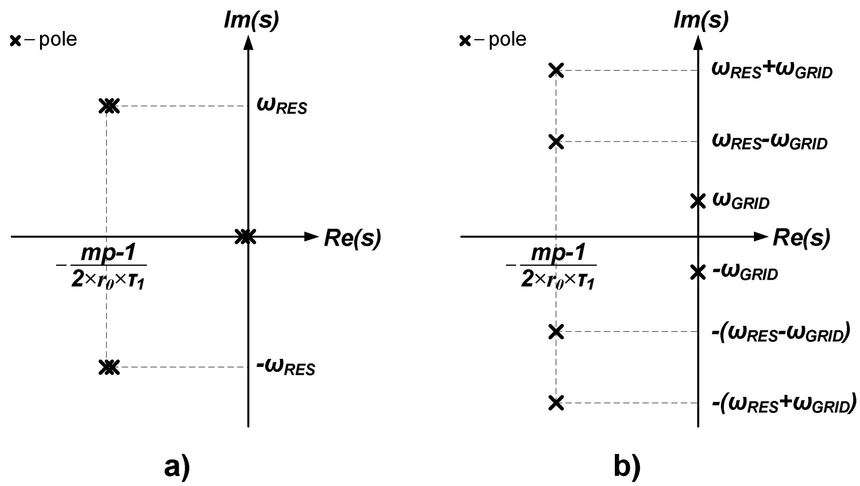

Fig. 7. Poles location of the model from Fig. 6 expressed in a) stationary *α-β* reference frame and b) in rotational *d-q* reference frame.

CONCLUSION

The paper deals with STATCOM application in distribution power grid system to provide active grid voltage regulation. It presents introductionary study of, first, its principle of operation in voltage regulation mode where the voltage is subject to changes in load active and reactive power. The distribution grid, usually of radial topology, is analysed using simplified model of one leg of the network. Based on this static analysis is performed in order to determine the level of influence of STATCOM on the system and to acquire the guidelines for its sizing. Finally, employing linearized model of the system, its dynamic properties are obtained and discussed as it will in the future work enable design of the control structure and setting up its parameters.

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APPENDIX

Constants τ_1, τ_2, τ_3 and r_0 are defined by:

$$\tau_1 = C \cdot Z_B \qquad \tau_2 = \frac{L_S}{Z_B} \qquad \tau_3 = \frac{L_0}{Z_B} \qquad r_0 = \frac{R_0}{Z_B}$$

where are: $U_B=U^0_{GRID}$ – based voltage, S_B – based power, and $Z_B=U_B^2/S_B$ – based impedance.
Matrix A, which represent behaviour of the system (normalized and linearized model in rotational reference frame) is given by:

$$A = \begin{bmatrix} -\frac{1}{r_0 \cdot \tau_1}\cdot(mp-1) & \omega_{GRID} & \frac{1}{\tau_1} & 0 & -\frac{1}{\tau_1} & 0 \\ -\omega_{GRID} & -\frac{1}{r_0 \cdot \tau_1}\cdot(mp-1) & 0 & \frac{1}{\tau_1} & 0 & -\frac{1}{\tau_1} \\ -\frac{1}{\tau_2} & 0 & 0 & \omega_{GRID} & 0 & 0 \\ 0 & -\frac{1}{\tau_2} & -\omega_{GRID} & 0 & 0 & 0 \\ \frac{1}{\tau_3}\cdot(mq-1) & 0 & 0 & 0 & 0 & \omega_{GRID} \\ 0 & \frac{1}{\tau_3}\cdot(mq-1) & 0 & 0 & -\omega_{GRID} & 0 \end{bmatrix}$$

Matrix B, which determine impact of the STATCOM and the generator on the system is given by:

$$B = \begin{bmatrix} \frac{1}{\tau_1} & 0 & 0 & 0 \\ 0 & \frac{1}{\tau_1} & 0 & 0 \\ 0 & 0 & \frac{1}{\tau_2} & 0 \\ 0 & 0 & 0 & \frac{1}{\tau_2} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Key words: STATCOM, FACTS devices, static analysis, dynamic analysis, grid voltage regulation, STATCOM modelling.

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