Tuning of Voltage Controller Gain for Multiple STATCOM Systems

Steinkohl, Joachim; Wang, Xiongfei

Published in:
Proceedings of 2018 IEEE 19th Workshop on Control and Modeling for Power Electronics (COMPEL)

DOI (link to publication from Publisher):
10.1109/COMPEL.2018.8460094

Publication date:
2018

Document Version
Accepted author manuscript, peer reviewed version

Tuning of Voltage Controller Gain for Multiple STATCOM Systems

Joachim Steinkohl* and Xiongfei Wang†
Department of Energy Technology
Aalborg University
Aalborg, Denmark
*joa@et.aau.dk, †xwa@et.aau.dk

***Abstract*—STATCOMs with voltage control are known for their fast reaction time to stabilize the grid voltage. For optimal dynamic performance it is essential to use the correct gain settings for the PI voltage regulation controller, adapted for different states of operation. This paper shows the equation to calculate the accurate value for the gain setting in the voltage controller. The inner control behavior with enabled droop control is considered as well as the strength of the grid. After this the influences between STATCOMs installed in parallel in one bus is shown and the adaption of the gain to take this into account is calculated. The equations are validated by analytic aspects as well as by simulations. This enhances the existing control solution in industry and allows constant dynamic performance under various system changes in future grids.**

***Index Terms*—FACTS, STATCOM, Voltage Control**

I. Introduction

A Static Compensator (STATCOM) is a device for advanced reactive power compensation to vontrol the voltage in the power grid [1]. It can be used to control power factor, regulate voltage, stabilize power flow, and improve the dynamic performance of power systems. It has been well understood that the voltage control of a STATCOM is highly dependent on the conditions in the grid it is connected to, especially to system strength [2] and to other dynamical voltage controlling devices. Without adapting to these conditions control instabilities occur [3]. Other research has focused on adaptive controller settings [4]–[6] or fuzzy control [7]. All these control techniques lack on the calculated adjustment of the voltage controller gain to the influences of other STATCOMs.

To prevent instabilities and to maintain optimal dynamic performances, communications between the FACTS devices are installed to reduce the gain of the voltage controllers by a constant factor [3]. But this control adaption does not guarantee constant dynamic performances. This paper shows the calculation for the optimal gain adaption for the voltage controller in a multiple STATCOM system. This allows to have constant dynamic performances for different system conditions.

II. STATCOM Gain Calculation

The gain calculation for a single STATCOM installation is determined at first. For this, the needed reactive output of a STATCOM due to a voltage deviation is calculated. Then the influences of other STATCOMs are taken into account as well.

A. Single STATCOM installation

The control scheme of the STATCOM voltage controller with droop control is shown in Fig. 1. The inner current control is not shown, it can be neglected for this analysis, due to the slower dynamics. The reactive output of the STATCOM is fed back to change the voltage reference value. This is beneficial for keeping dynamic reserve in the system and to avoid instabilities with multiple voltage controlling devices.

The proportional-integral (PI) controller of the voltage controller has the form

$$Gain \cdot \left(1 + \frac{1}{T_{\mathrm{N}} \cdot s}\right) \tag{1}$$

With this form of the PI controller is it possible to adapt to changes in the grid strength and the Droop control. $\mathrm{T_N}$ has to be set according to internal time constants such as the measurement delays. The Droop control is used to allow load sharing between multiple units. This allows the operators to reduce the impact of the STATCOMs under normal operating conditions [8].

The controlled positive phase sequence grid voltage in steady state is expressed in (2). This shows the deviation from the reference voltage due to the Droop control.

$$V_{\mathrm{GRID}} = V_{\mathrm{REF}} - Q_{\mathrm{STATCOM}} \cdot \frac{Droop}{Q_{\mathrm{NOM}}} \tag{2}$$

Fig. 2 shows the crossing of the Grid Line (determined by the grid strength) and the Control Line (determined by the Droop control) in a single STATCOM system. The point of crossing determines the operating point of the STATCOM under steady state conditions.

The Droop control has to be taken into account for the gain calculation, because it has a severe impact on the needed reactive power output due to a change in the grid voltage. It therefore changes the point of operation in the steady state. If it is not taken into account, the step response time and settling time of the STATCOM do not forfill the specifications for the voltage controlling dynamics [2]. The equation for the reactive power flow can be used to express the impact of the reactive output power of a STATCOM to the voltage difference, that is caused by this output.

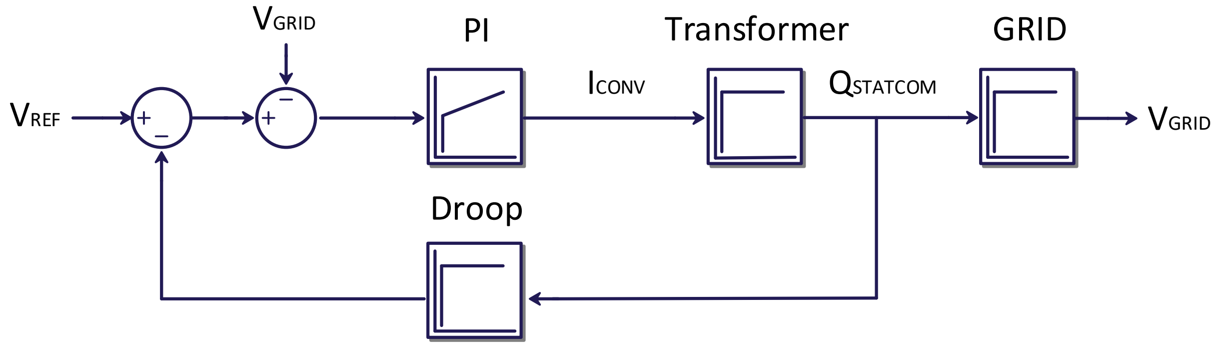

Fig. 1. STATCOM control scheme with Droop control.

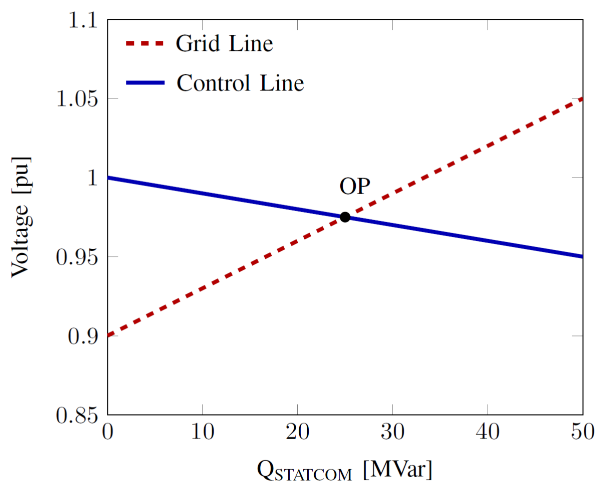

Fig. 2. Single STATCOM System.

$$Q = \frac{E \cdot V \cdot \cos\theta - V^2}{X} \tag{3}$$

Assumed, that the angle θ is small, the equation can be rewritten as

$$Q = \frac{E - V}{X} \cdot V \tag{4}$$

This can be rewritten so that the strength of the grid is an expression of the grid reactance X. (4) can be linearized around a stable operating point and the gain of the PI voltage controller can then be calculated using (5). This equation shows the relationship between a voltage drop in the grid and the needed reactive output change to compensate it.

$$Gain = \frac{\Delta Q_{\text{STATCOM}}}{\Delta V_0} \tag{5}$$

The needed change of reactive output for a voltage deviation with Droop control consists of two terms as can seen in (6). The first term represents the reactive output that is needed to fully compensate a voltage deviation. The second term represents the change of the voltage reference setpoint due to the Droop control.

$$\Delta Q_{\text{STATCOM}} = \Delta V_0 \cdot SCL - \Delta Q_{\text{STATCOM}} \cdot \frac{Droop}{Q_{\text{NOM}}} \cdot SCL \tag{6}$$

After solving (6) to ΔV_0 and setting it into (5) leads to:

$$Gain = \frac{1}{\frac{1}{SCL} + \frac{Droop}{Q_{\text{NOM}}}} \tag{7}$$

With (7) it is possible to adapt the gain of the controller to keep the optimal dynamic performance of the STATCOM even with changes in the control parameters or changes in the grid strength.

B. Multiple STATCOM Installation

This section describes the adaption of the gain to the influence of other STATCOMs.

The equation used in the industry [3] is shown in (8).

$$Gain = \frac{1}{\frac{1}{SCL} + \frac{Droop}{Q_{\text{NOM}}}} \cdot 0.55 \tag{8}$$

The reduction of the controller gain is done, by multiplying a constant factor to the previously calculated gain as in the single STATCOM system.

The voltage change due to the other STATCOM affects the reactive output, that is needed to control a voltage deviation.

$$\Delta Q_{\text{STATCOM 1}} = \left(\Delta V_0 - \frac{\Delta Q_{\text{STATCOM 2}}}{SCL}\right) \cdot SCL -$$

$$\Delta Q_{\text{STATCOM 1}} \cdot \frac{Droop_1}{Q_{\text{NOM 1}}} \cdot SCL \tag{9}$$

(9) can also be done for the second STATCOM. By solving the equations to the outputs of the separate STATCOMs leads to the following two equations

$$\Delta Q_{\text{STATCOM 1}} = \frac{\Delta V_0 - \frac{\Delta Q_{\text{STATCOM 2}}}{SCL}}{\frac{1}{SCL} + \frac{Droop_1}{Q_{\text{NOM 1}}}} \tag{10}$$

$$\Delta Q_{\text{STATCOM 2}} = \frac{\Delta V_0 - \frac{\Delta Q_{\text{STATCOM 1}}}{SCL}}{\frac{1}{SCL} + \frac{Droop_2}{Q_{\text{NOM 2}}}} \tag{11}$$

With these equations it is possible to determine the optimal change of reactive output of the two STATCOMs depending on the voltage deviation in the grid even with unequal ratings and control settings. Solving the two equations (10) and (11) with the same STATCOM ratings (Q_{NOM}) and control settings (Droop) entered in (5) leads to (12) as a gain for both STATCOM units.

$$Gain = \frac{1}{\frac{2}{SCL} + \frac{Droop}{Q_{NOM}}} \tag{12}$$

Therefore a second STATCOM changes the gradient of the grid line shown in Fig. 3 following (12).

For this, the diagram for the STATCOM effect on the system voltage has been redrawn to take the effect of a second STATCOM into account. This is done by changing the slope of the grid line.

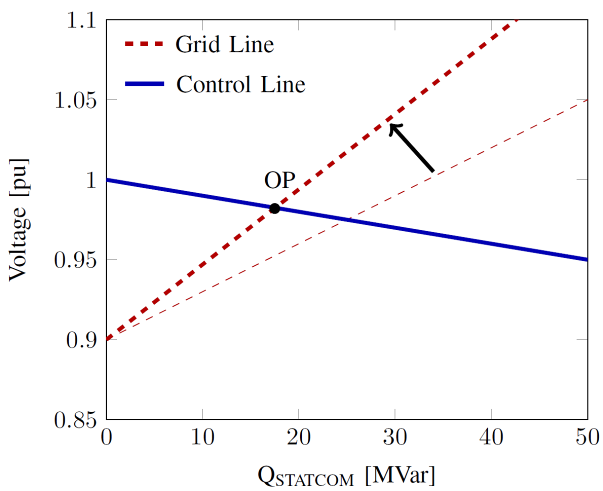

Fig. 3. Multiple STATCOM System.

The influence of a second STATCOM is taken into account in (6). The other STATCOM changes the voltage in the grid, but not the reactive output that is taken into consideration in the Droop control term. This can be seen also in [3], where the time constant of the control system is changed according to the droop, the grid strength and the existence of other voltage controlling devices.

This equation is not exactly the equation, that is used in the industry, both solutions are further analyzed in Section IV.

The gain can now be calculated for all values of the SCL and Droop settings. The proposed equation allows constant dynamic performances even with changed control parameters and grid conditions. This is shown in simulations in Section IV.

C. Not equally sized STATCOMs

If there are STATCOMs installed close to each other with different reactive output ratings, then the equation has to change according to the nominal reactive power to the sum of all nominal reactive powers together.

$$Gain_1 = \frac{1}{\frac{1}{SCL} \cdot \frac{Q_{NOM\,1}+Q_{NOM\,2}}{Q_{NOM\,1}} + \frac{Droop}{Q_{NOM}}} \tag{13}$$

and

$$Gain_2 = \frac{1}{\frac{1}{SCL} \cdot \frac{Q_{NOM\,1}+Q_{NOM\,2}}{Q_{NOM\,2}} + \frac{Droop}{Q_{NOM}}} \tag{14}$$

The calculated gains in (13) and (14), that can be calculated from (10) and (11) allow the correct control of STATCOMs with different ratings in the same power grid. It is assumed that the Droop control is the same in both units, because they are installed in one power system with the same grid code. If the Droop control set points are different, it is still possible to calculate the optimal gain following the equations from above.

D. Multiple STATCOM Installation

With more than two STATCOMs installed at one bus, the influence of these STATCOMs can also be taken into account for the gain calculation. The voltage deviation that has to be controlled by the different STATCOMs can be calculated to get an expression for the influences of all other STATCOMs to the individual ones. (15) demonstrates the influence of all other STATCOMs to one STATCOM.

$$\Delta Q_{STATCOM\,1} = \left(\Delta V_0 - \sum_{i=2}^{N} \frac{\Delta Q_{STATCOM\,i}}{SCL} \right) \cdot SCL - \Delta Q_{STATCOM\,1} \cdot \frac{Droop_1}{Q_{NOM\,1}} \cdot SCL \tag{15}$$

The gain of the voltage controllers can be calculated following the same calculations as for (12). Solving these equations again with the same ratings and controller settings leads to (16).

$$Gain = \frac{1}{\frac{N}{SCL} + \frac{Droop}{Q_{NOM}}} \tag{16}$$

With N in (16) being defined as the total number of identical STATCOMs in one bus. This formula is only applicable with the same Droop control settings and ratings of all STATCOMs installed in one bus. Different STATCOM ratings can also be expressed and calculated with respect to (17).

$$Gain_i = \frac{1}{\frac{1}{SCL} \cdot \frac{\sum_{i=1}^{N} Q_{NOM\,i}}{Q_{NOM\,i}} + \frac{Droop}{Q_{NOM\,i}}} \tag{17}$$

This allows the constant dynamic performance of a wide variety of possible STATCOM configurations.

III. Analysis

To determine the impact of the different gain calculation methods, an analytic approach is needed. For this, the control system from Fig. 1 is analyzed. The filter for the measurement of the reactive output and also for the grid voltage is simplified to a first order low-pass filter. This slows down the control in such a way, that the step response of the closed loop control meets the dynamics as in a modern transmission STATCOM installation.

The bode diagrams of the closed-loop system with the gain reduction method as in (8), used in industry, are shown. For this, the system is analyzed with a droop of $10\,\%$ (in Fig. 4) and $4\,\%$ (in Fig. 5). The strength of the power system is changed in 5 GVA steps from 0.5 GVA to 20.5 GVA in both cases.

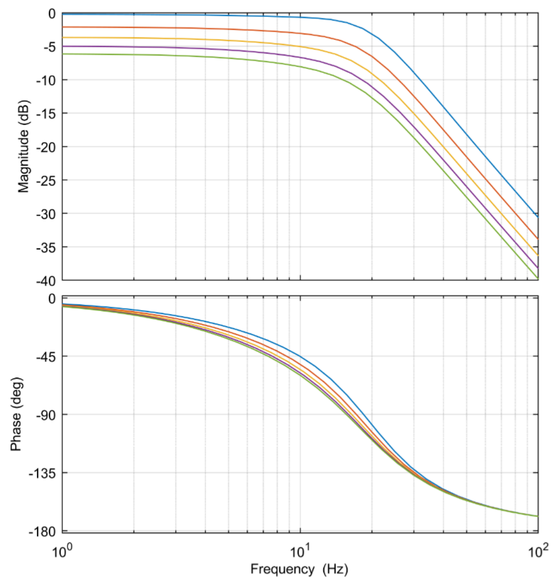

Fig. 4. Bode plot with SCL variations with fixed reduction factor with 10 % Droop.

It can be seen in the lower graphs in Fig. 4 that the time response of the system is not constant with the variation of the grid strength. This causes unwanted dynamics in the operation of the STATCOM system in a wide variety of grid conditions, if there are other voltage controlling devices nearby. The droop control affects the steady state operation point as one can see by the deviation of 0 db in the upper graph.

With reduced droop control setpoint the system variations in steady state are smaller than with 10 % droop. Nevertheless, the dynamic variations are still visible and the dynamics of the system are not constant under changing grid conditions.

Afterwards, the closed-loop behavior with the proposed gain reduction as in (12) is analyzed. Fig. 6 and Fig. 7 show the bode plots of the closed-loop system with the proposed gain tuning equation. The SCL variations are the same as in the previous analysis.

The time response of the system shown in Fig. 6 is constant and does not change with the SCL variations. The steady state operation point is still varying due to the different effects of the STATCOM output to the grid voltage under droop control. The deviations under steady state are exactly the same as in Fig. 4, because the gain control adaption only affects the dynamics of the control system.

Fig. 7 proves also the constant dynamic behavior of the system under changed grid and control conditions. The steady state operation points are again the same as in Fig. 5.

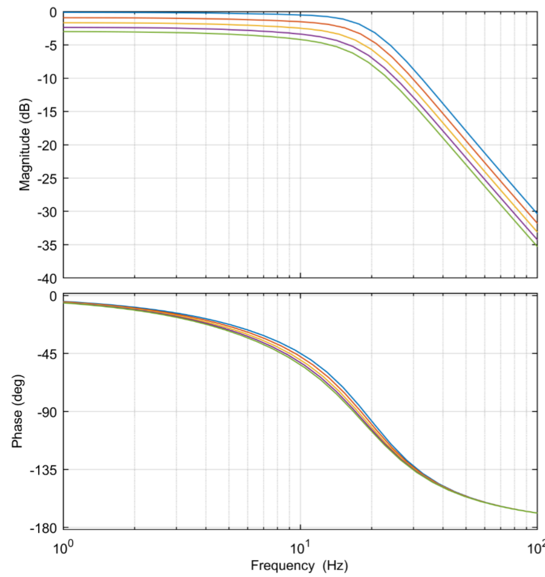

Fig. 5. Bode plot with SCL variations with fixed reduction factor with 4 % Droop.

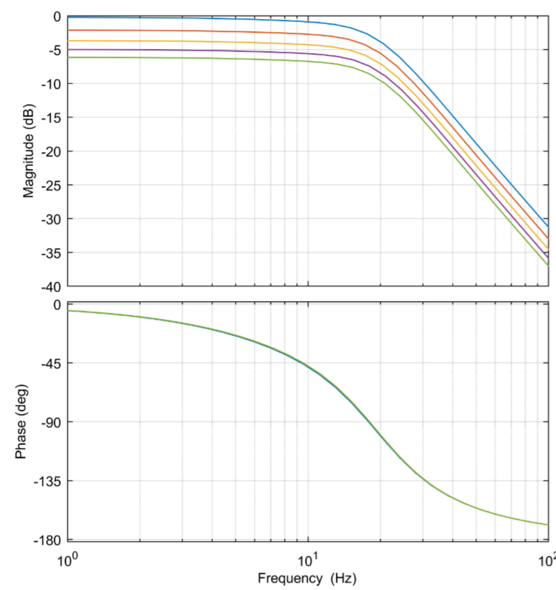

Fig. 6. Bode plot with SCL variations with proposed gain tuning with 10 % Droop.

The proposed gain tuning is therefore enhancing the dynamic behavior of the voltage in the power grid. This system behavior is also tested with step response tests in simulations, to further verify the performance under more detailed conditions.

IV. Simulation

The theoretical results have been verified with simulations to see if the equations for the gain calculation are correct and that they improve the dynamic response of the STATCOM

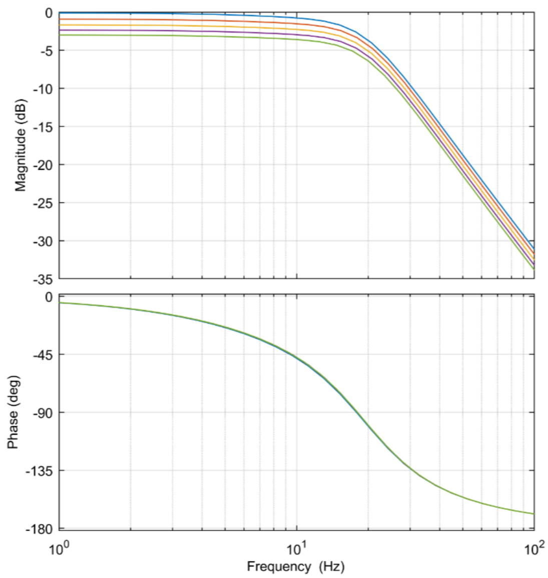

Fig. 7. Bode plot with SCL variations with proposed gain tuning with 4 % Droop.

compared to the adaption that is used in the industry. The dynamic response of the STATCOM control has been tested with step response tests. For this test the reference voltage setpoint is changed at the time 4 sec in the simulation for all STATCOMs. All STATCOMs have identical ratings of 50 MVar and the Droop value is always set to $4\,\%$.

The simulation is performed with EMTDS / PSCAD. The STATCOMs are simulated with a controlled voltage source as the converter in a delta configuration. The model includes synchronization and current control. Also the positive sequence voltage is filtered and measured for the voltage control to get a more realistic system behavior.

The PI controller of the voltage control is tuned in a single STATCOM condition and afterwards also tested with the influence of a second STATCOM at the same bus.

A. Single STATCOM installation

In the first simulations the gain adjustment for a single STATCOM installation is tested to verify (7). For this, the STATCOM is installed with a fixed Droop setting of $4\,\%$ in different grids.

Fig. 8 and Fig. 9 show the adaption of the voltage controller gain to a change in the grid strength with droop control. The dynamic response to the changed reference value is constant. Further simulations are performed with varying control and system conditions. The results are shown in Table I.

The simulation results in Table I show that a single STATCOM unit can be adapted to changes in future system strength and droop control conditions with constant voltage control dynamics.

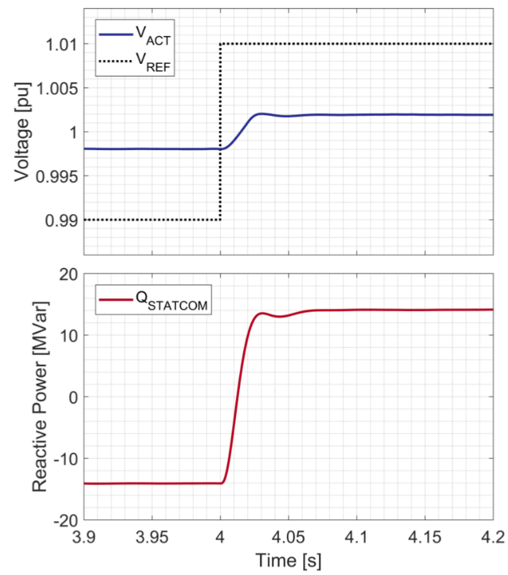

Fig. 8. Single STATCOM in 5 GVA grid.

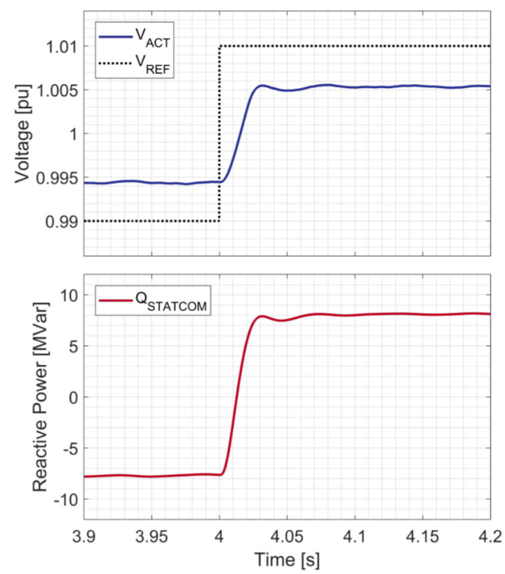

Fig. 9. Single STATCOM in 1 GVA grid.

B. 2 STATCOM installation with fixed reduction

In these simulations two STATCOMs are installed in the same bus. The gain is reduced as proposed in industry by 45 % compared to the single STATCOM simulations, as shown in [3].

The simulation results in Fig. 11 prove, that with a fixed gain reduction factor it is possible to achieve good dynamic results with some constellations of SCL and Droop control. But the system dynamics shown in Fig. 10 do not have a sufficient dynamic behavior. In this case the system response is too slow. This proves incorrect controller settings, if the gain is reduced with a constant factor. A pure change of the reduction factor can not be applied with respect to the other simulations results shown in Table II. A reduced reduction factor can speed up the

TABLE I
Simulation Results with single STATCOM installation

	Droop	Rise Time	Overshoot
1 GVA	1 %	25 ms	2 %
	2 %	25 ms	3 %
	4 %	26 ms	2 %
5 GVA	1 %	27 ms	1 %
	2 %	25 ms	2 %
	4 %	26 ms	2 %
10 GVA	1 %	26 ms	2 %
	2 %	27 ms	1 %
	4 %	25 ms	3 %

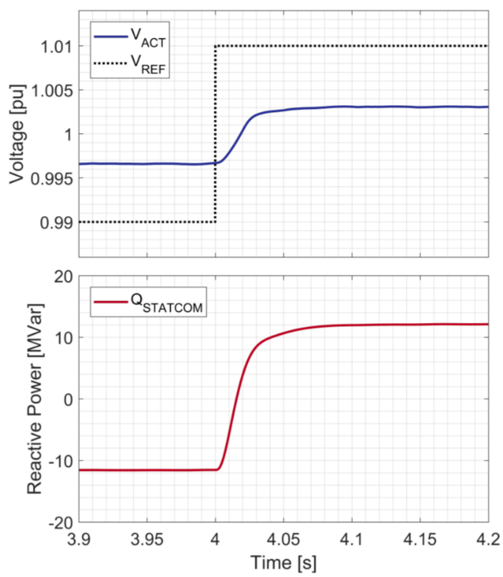

Fig. 10. 2 STATCOMs in 5 GVA grid.
With fixed Gain adaption as used in industry.

control in some grid conditions, other conditions in the grid will then lead to high overshoots that are not allowed for a stable grid operation (as in the first test result in Table II).

Table II shows the dynamic behavior of the tested setup with the constant gain reduction of 45%. This adaption is not sufficient under all conditions. The overshoots are in the specified limits, due to the value of the reduction. But the rise time increases to very high values (up to 44 ms in the performed simulations). This method will therefore limit the optimal dynamic operation range of the STATCOM voltage control.

C. 2 STATCOM installation with proposed calculation

In the following simulations the proposed gain reduction is used.

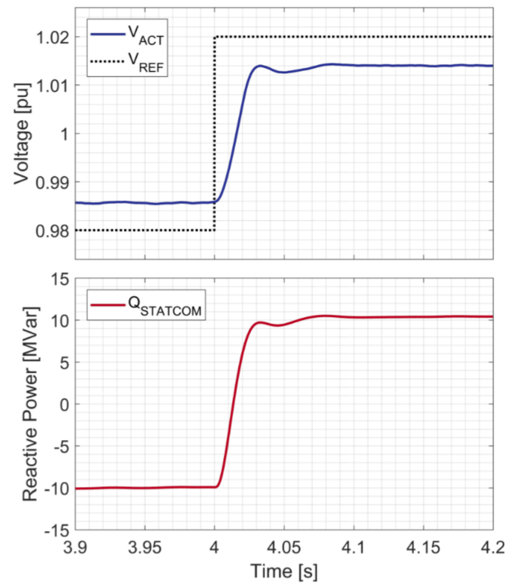

Fig. 11. 2 STATCOMs in 1 GVA grid.
With fixed Gain adaption as used in industry.

TABLE II
Simulation Results with double STATCOM installation with fixed Gain Reduction as used in industry

	Droop	Rise Time	Overshoot
1 GVA	1 %	25 ms	4 %
	2 %	26 ms	3 %
	4 %	27 ms	1 %
5 GVA	1 %	26 ms	1 %
	2 %	31 ms	0 %
	4 %	38 ms	0 %
10 GVA	1 %	29 ms	0 %
	2 %	37 ms	0 %
	4 %	44 ms	0 %

The simulation results shown in Fig. 12 and Fig. 13 prove the correct adaption of the STATCOM controller to the influence of a second STATCOM installed in the same bus with the proposed gain tuning. The time to reach the new steady state operation is constant and the overshoots of the controller are always low enough to fulfill the requirements for stable grid operation.

The results of the dynamic analysis are shown in Table III. It can be seen, that the proposed gain tuning method allows to keep a constant dynamic performance, even with the installation of a second STATCOM unit close nearby.

Also simulations are performed with different STATCOM nominal reactive outputs. This leads to the conclusion, that (13) and (14) are valid and enable constant system dynamics.

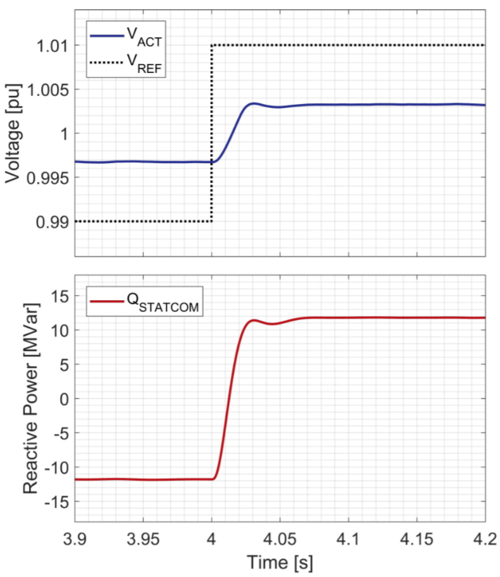

Fig. 12. 2 STATCOMs in 5 GVA grid.
With proposed Gain adaption.

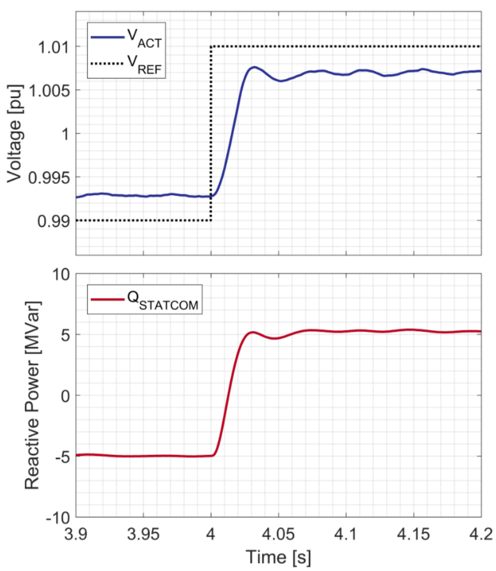

Fig. 13. 2 STATCOMs in 1 GVA grid.
With proposed Gain adaption.

The used nominal reactive outputs used for the simulations are 50 MVar in one STATCOM and then variations in the second STATCOMs nominal reactive power (50 MVar, 25 MVar and 10 MVar). The simulation results are not shown here, they correspond almost to the results shown in Table III.

TABLE III
Simulation Results with double STATCOM installation with proposed Gain Reduction

	Droop	Rise Time	Overshoot
1 GVA	1 %	25 ms	2 %
	2 %	25 ms	3 %
	4 %	26 ms	2 %
5 GVA	1 %	27 ms	1 %
	2 %	25 ms	2 %
	4 %	26 ms	2 %
10 GVA	1 %	26 ms	3 %
	2 %	27 ms	2 %
	4 %	27 ms	2 %

V. Conclusion

The simulations performed in this paper proves the correctness of the equation for adapting the controller gain. So it is possible to achieve optimal dynamic response to voltage deviations from the STATCOM in all analyzed system conditions with the proposed gain adaption method. The equation used in the industry right now is not sufficient to adapt to multiple STATCOMs in a correct way. This can lead to unwanted behavior during severe grid events.

Further investigation is needed to the influence of distances and therefore impedance between different STATCOM units. This changes the impact of the reactive power of one STATCOM to the measured voltage on the other STATCOM. Therefore it affects the optimal gain that is needed for constant dynamics. Due to the high number of possible grid configurations has it not been included.

References

[1] N. G. Hingorani, L. Gyugyi, and M. El-Hawary, *Understanding FACTS: concepts and technology of flexible AC transmission systems*. Wiley Online Library, 2000, vol. 2.

[2] G. Romegialli and H. Beeler, "Reactive compensation. Problems and concepts of static compensator control," in *IEE Proceedings C (Generation, Transmission and Distribution)*, vol. 128, no. 6. IET, 1981, pp. 382–388.

[3] *Coordination of Controls of Multiple FACTS/HVDC Links in the Same System*, ser. Brochures thématiques: International Conference on Large High Voltage Electric Systems. CIGRE, 1999.

[4] Y. Xu and F. Li, "Adaptive PI Control of STATCOM for Voltage Regulation," *IEEE Transactions on Power Delivery*, vol. 29, no. 3, pp. 1002–1011, June 2014.

[5] J.-x. Xu, L.-c. Xiu, C.-c. Hang, C. Li, Q.-r. Jiang, and Z.-h. Wang, "PI control of STATCOM using fuzzy set and auto-tuning techniques," *IFAC Proceedings Volumes*, vol. 32, no. 2, pp. 7340–7345, july 1999.

[6] Y. Xu, F. Li, Z. Jin, and C. Huang, "Flatness-based adaptive control (FBAC) for STATCOM," *Electric Power Systems Research*, vol. 122, pp. 76–85, 2015.

[7] S. A. Al-Mawsawi, M. Qader, and G. Ali, "Dynamic controllers design for STATCOM," *Iranian journal of electrical and computer engineering*, vol. 3, no. 1, pp. 16–22, 2004.

[8] L. Gyugyi, "Power electronics in electric utilities: static VAR compensators," *Proceedings of the IEEE*, vol. 76, no. 4, pp. 483–494, Apr 1988.