Modular STATCOM for compensation of reactive power and voltage asymmetry in medium-voltage distribution power grids

Josef Štengl, Tomáš Kormska, Jakub Talla, Zdeněk Peroutka
UNIVERSITY OF WEST BOHEMIA
Univerzitní 2732/8, 301 00
Pilsen, Czech Republic
jstengl@fel.zcu.cz

Acknowledgements

This research has been supported by the Ministry of Education, Youth and Sports of the Czech Republic under the project No. SGS-2021-021 and by the Technology Agency of the Czech Republic under the project No. TN01000007.

Keywords

«Static Synchronous Compensator (STATCOM)», «Medium voltage», «Grid-connected converter», «Zero sequence voltage», «Reactive power»

Abstract

A cost-effective STATCOM is proposed and discussed in this paper. Its modular topology enables to scale the power to target systems. Besides reactive power, the proposed STATCOM enables to generate a zero-sequence component and compensate the voltage asymmetry, e.g., in widely spread medium-voltage distribution power grids with resonant grounding.

Introduction

Power consumption is constantly growing which brings several problems; many power grids are operated close to the limit of their transmission or distribution capacity. To ensure stable and reliable power supply, it is necessary to increase the robustness of power grids. In the case of medium-voltage distribution power grids, there is increasing pressure on the power quality. Reactive power (inductive or capacitive) is to be compensated within the distribution power grid. Its transmission to a superior power system might expose the operator to financial penalty. Also, a voltage symmetry is an issue.
A lot of distribution power grids are operated as resonant-grounded systems [1]. In these systems, arc suppression coils are tuned in resonance with stray capacitance to ground to effectively compensate earth faults. However, tuning the coil in the resonance point or nearby causes significant voltage asymmetry [2].

Modern systems based on power semiconductor converters enable to solve problems mentioned above. Reactive power can be effectively compensated by STATCOM systems. However, these systems operate with positive sequence component only [3-7]. This is enough for the reactive power compensation, but not for the compensation of the voltage asymmetry. Moreover, their design is often based on multilevel converters, which, on one hand, generate a high-quality voltage waveform, on the other hand, their design is rather complicated and may suffer by high costs and unreliability [3-5].

This paper deals with a modular STATCOM designed for medium-voltage distribution power grids. Its design pursues two main goals: i. compensation of both, reactive power, and voltage asymmetry, ii. robustness, cost effective design and modularity for power scaling.

System topology

The topology of the proposed STATCOM is depicted in Fig. 1. The whole system is connected to a three-phase distribution power grid of 22 kV using a three-phase transformer 22/0.4 kV with star-connected primary winding. The star point (the neutral) is earthed which enables to operate with the zero-sequence component. Secondary windings are connected to the power converter. The modular design of the converter is based on unified basic power units of 150 kVA. Each unit is a air-cooled single-phase voltage-source inverter (full bridge, see Fig. 2), based on inexpensive IGBT modules with blocking voltage of 1200 V. These basic power units are connected in parallel via filtering inductors (see Fig. 1) and all are interconnected via a common dc link. Its voltage is controlled to 730 V.

In our installation, there are altogether 9 power units of 150 kVA and the total power of the whole installation is 1,35 MVA. However, the total power can be easily scaled by adding or removing power units and the installation can be adapted to the final power system.

To achieve a high-quality voltage and current, the converter is connected to the transformer via an LCL filter, where the installed components L_f and C_f are completed by the transformer leakage inductance L_σ (see Fig. 1 and 2).
The start procedure of the STATCOM includes precharging from the additional precharge circuit consisting of a conventional diode rectifier, while the power converter is disconnected from the grid (the contactor K_1 is switched off, see Fig. 1). Once the precharging is completed, the contactor K_2 is switched off, and the power converter starts to generate three-phase voltage on the filter capacitor C_f. Once this voltage is synchronized to the transformer secondary, the contactor K_1 is switched on and the power converter is connected to the grid voltage.

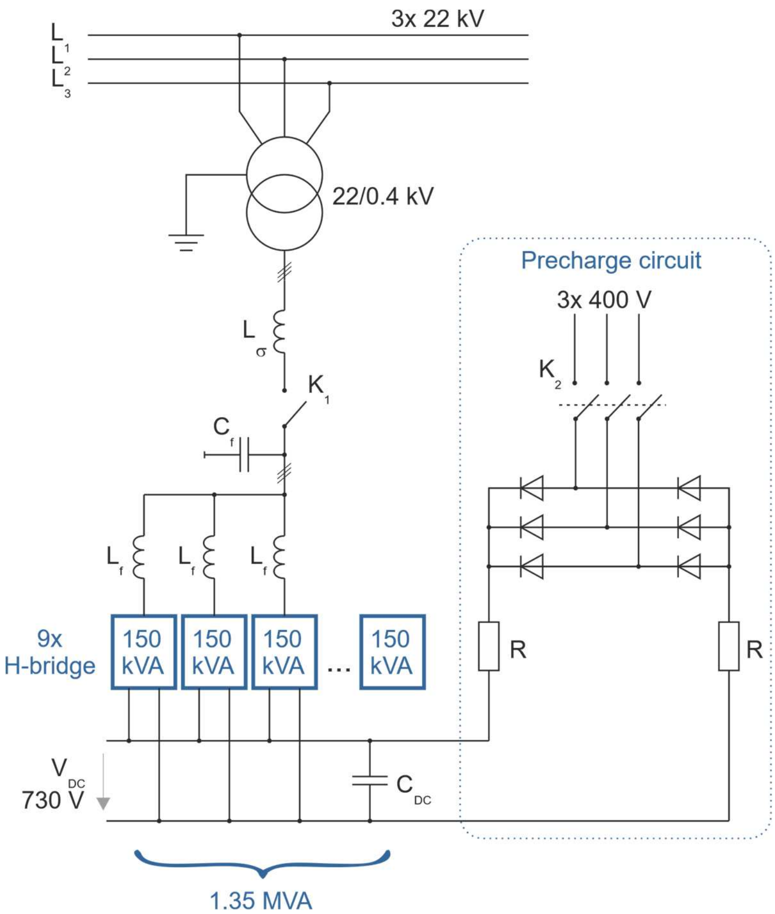


Fig. 1: Topology of the proposed air-cooled modular STATCOM controlling both, positive sequence and zero sequence component

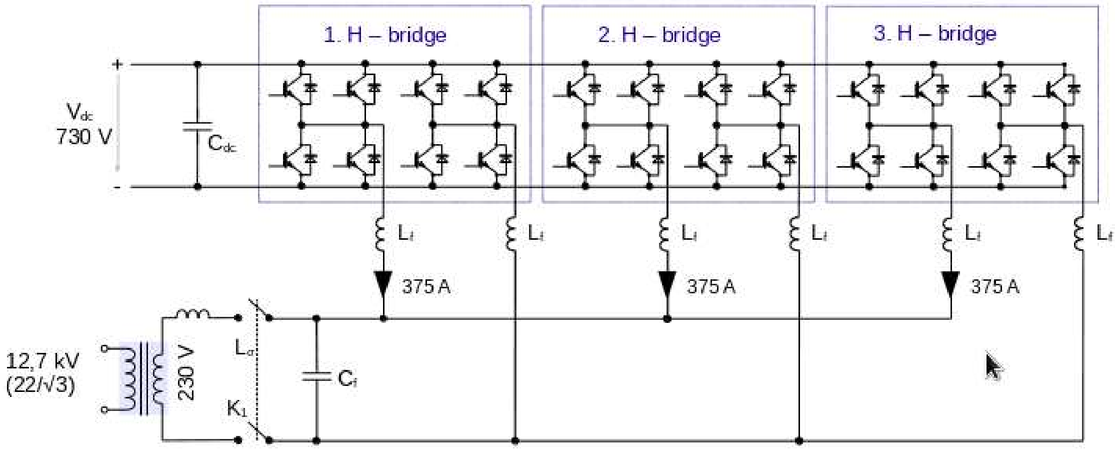


Fig. 2: Detail of the secondary: Three or more power units (single-phase bridge inverters) supplying one phase of transformer

Control algorithm

The employed control algorithm of the whole STATCOM is depicted in Fig. 3. It controls all power units in the same time; the carriers of the PWMs are shifted to minimize the current ripple.

The control algorithm consists of two main loops, one for positive and one for zero sequence component. Two PI controllers control the positive sequence component using the currents I_d, I_q in the rotating reference frame d-q. The I_d control loop is employed to control active power which is necessary to keep the dc-link voltage at the required constant value of 730 V. To linearize the system, the error related to energy ($\frac{1}{2}C_{dc}V_{dc}^{w\,2} - \frac{1}{2}C_{dc}V_{dc}^2$) is employed instead the direct voltage error (see Fig. 3). If necessary, the positive sequence component can be utilized to supply some load connected to the dc-link voltage.

The compensation of the reactive power of the grid is controlled using the I_q current component. Thus, the converter can generate either inductive or capacitive reactive power. Since the installation includes the LCL filter, the derivative feedback ($k_d(I_m - I_s) = k_d I_{Cf}$) is employed to stabilize the control loop and to avoid oscillations.

The second part of the algorithm is designed for the zero sequence component (see Fig. 3, bottom part), which in fact is a single-phase current control problem. Therefore, it is advantageous to use a resonant controller operating directly in the stationary reference frame, and thus no coordinate transformation is required. This control loop is employed to compensate the voltage asymmetry in the power grid.

In the final step, all required voltage components (V_d^w, V_q^w and V_0^w) are transformed back to the *abc* coordinates and the carrier-based PWM is used to generate the required phase voltage by the converter (see Fig. 3).

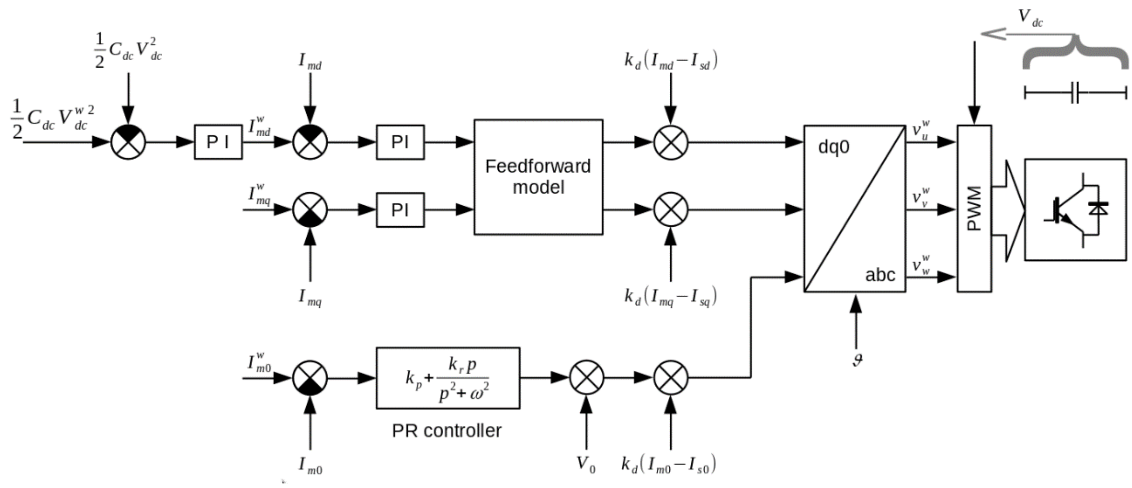


Fig. 3: Control algorithm of the STATCOM consisting of two control loops, one for positive sequence and one for zero sequence current component

Synchronization with power grid voltage

Grid connected converters must be usually synchronized to the grid voltage. Although the phase locked loop (PLL) is probably the most common solution, a computationally simple "sliding" discrete Fourier transform (DFT) algorithm is adopted for this system. This method extracts a single spectral component, namely the fundamental harmonic of 50 Hz, from the voltage waveform, sampled in a sliding window (single period of the fundamental). In principle, the voltage phasor of the fundamental $\bar{S}^1 = |\bar{S}^1|e^{j\omega t}$ rotating in the complex plane is shifted by an angle of $\frac{2\pi}{N}$ in every sampling period:

$$\overline{S}(k) = \overline{S}(k-1)e^{\frac{2\pi}{N}}, \tag{1}$$

where *k* is sampling time and *N* number of samples of the fundamental. For the real and imaginary part, we can write

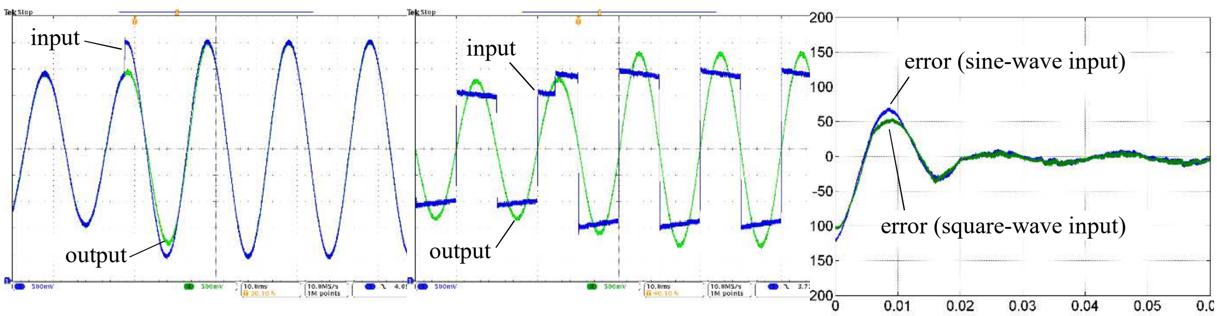
$$S_{re}(k) = S_{re}(k-1)\cos\left(\frac{2\pi}{N}\right) - S_{im}(k-1)\sin\left(\frac{2\pi}{N}\right) - x(k-N) + x(k), \tag{2}$$

$$S_{im}(k) = S_{re}(k-1)\sin\left(\frac{2\pi}{N}\right) + S_{im}(k-1)\cos\left(\frac{2\pi}{N}\right), \tag{3}$$

where $x(k)$ is the actual voltage sample and $x(k-N)$ is the oldest sample in the sliding window. From (2) and (3), the actual angle ϑ can be calculated, which is crucial for the synchronization with the grid (see Fig. 3).

$$\vartheta(k) = \arctan\left(\frac{S_{im}(k)}{S_{re}(k)}\right)$$

Fig. 4 shows the performance of the DFT-based synchronization in a test bed using the sine-wave (Fig. 4a) and square-wave inputs (Fig. 4b) with amplitude step change.



(a) (b) (c)

Fig. 4: Synchronization to the input signal using the DFT method: (a) Sine-wave input, (b) Square-wave input, (c) Error related to the fundamental component.

As can be seen from Fig. 4, the DFT method provides a pure sine wave on its output. Since the length of the sampling window corresponds to the single period of the fundamental (50 Hz), the transient takes 20 ms when a change of the input signal occurs. As the main advantages of this synchronization method, we can mention low computational complexity, robustness to the input distortion level resulting from the principle of spectral analysis and the absence of parameter tuning which is necessary for PLL-based and other methods.

In resonant-grounded distribution power grids [1], the phase to ground voltage may differ from the phase voltage of the grid transformer (related to the neutral) and the zero-sequence component v_0 is usually present. This leads to asymmetry of the phase to ground voltage. Fig. 6 shows the voltage phasor diagram based on measurements taken in the medium-voltage distribution power grid of 22 kV with resonant grounding. Due to this reason, it is preferable to synchronize the converter to the phase-phase voltage, which is stable, rather than to phase to ground voltage, which is directly measured. However, for the synchronization, the V_α component can be used (see Fig. 5):

$$V_\alpha = \frac{2}{3}\left(v_u - \frac{1}{2}v_v - \frac{1}{2}v_w\right). \tag{4}$$

As shown in (4), its computation is based on the phase voltage difference. Thus, the V_α is related to phase-phase voltage and stable.

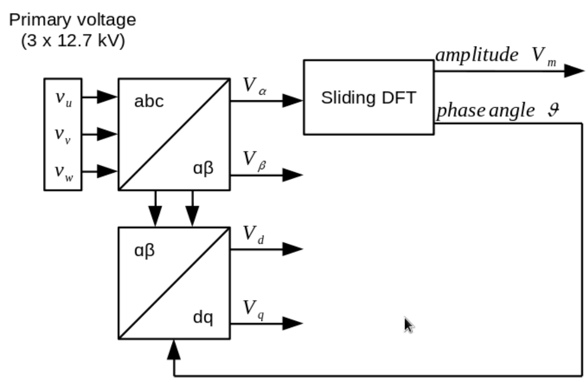


Fig. 5: Synchronization to the V_α component of the grid voltage using the sliding DFT method

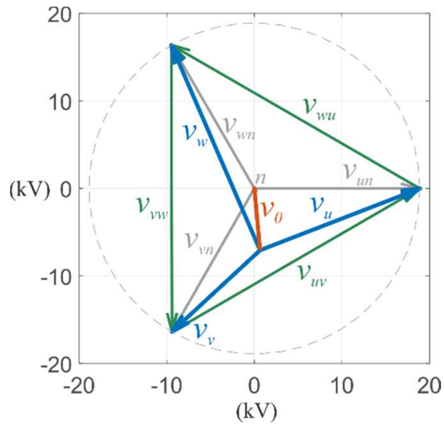


Fig. 6: Experimental results: Voltage asymmetry in resonant-grounded distribution power grid of 22 kV

For safety reasons, the sliding DFT discussed above is applied to the V_β component as well. It is used for faster and more reliable detection of the power outage of the grid.

$$V_\beta = \frac{2}{3}\left(\frac{\sqrt{3}}{2}v_v - \frac{\sqrt{3}}{2}v_w\right) \tag{4}$$

Experimental results

Fig. 7 and 8 show the start-up sequence of the STATCOM. Once the precharging is finished and the contactor K_2 is disconnected (see Fig. 1), the converter starts to generate ac voltage (see Fig. 8, bottom, time sequence *c*) synchronized to the voltage on the transformer secondary (see Fig. 8, top). The dc-link voltage is slightly decreasing (see Fig. 7, time sequence *c*). Next, the contactor K_1 is switched on and the power converter is connected to the transformer secondary. The connection time corresponds to the border between time sequence *c* and *d* in Fig. 7 and 8. Finally, control algorithm is activated; the active current component I_d is increased, and the dc-link voltage converges to the required level of 730 V (see Fig. 7, time sequence *d*).

Fig. 9 illustrates the STATCOM operation in the resonant-grounded medium-voltage distribution power grid. For better readability, the waveforms of phase *v* and *w* are not displayed. It can be seen that the STATCOM generates inductive or capacitive reactive power.

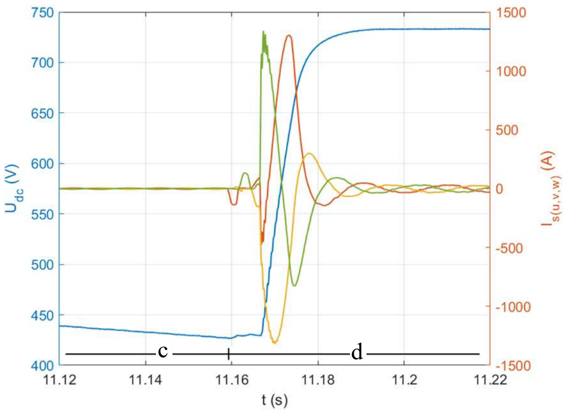


Fig. 7: Experimental results, start-up sequence: Activation of the control algorithm and convergence of the dc-link voltage to its required level (blue: dc-link voltage, green, orange and yellow: three-phase currents generated by converter on secondary side of transformer)

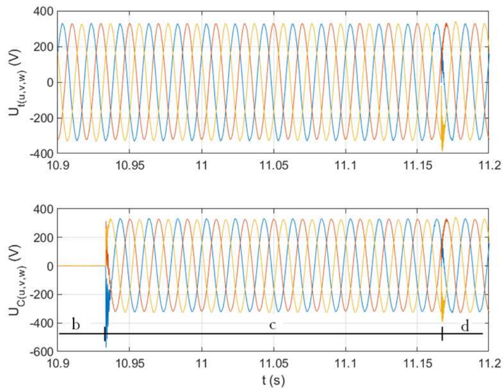
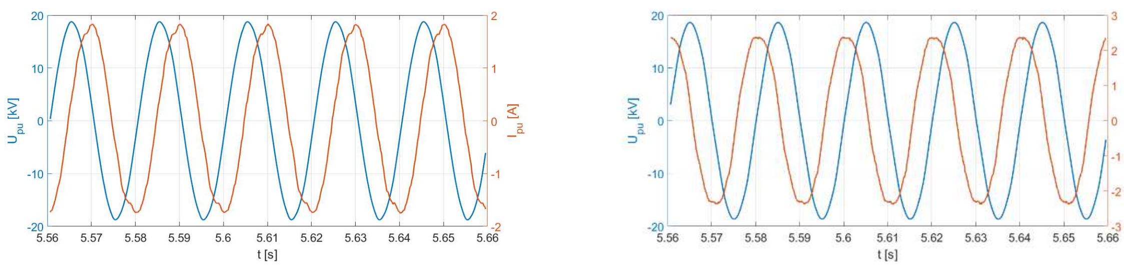


Fig. 8: Experimental results, start-up sequence: Generation of three-phase voltage (v_{cu}, v_{cv}, v_{cw}, bottom figure) synchronized with voltage on secondary side of transformer (top figure) and converter connection to the transformer (K_1 switched on in t =11.16 s)



(a) (b)

Fig. 9: Experimental results, operation in power grid of 22 kV: Compensation of reactive power in (a) inductive and (b) capacitive mode (voltage (blue) and current (orange) of phase *u*).

The final installation in the distribution substation of 110/22 kV is shown in Fig. 10.

Fig. 10: Final installation of proposed STATCOM of 1.35 MVA in distribution substation of 110/22 kV

Conclusion

A STATCOM of 1.35 MVA designed for widely spread resonant-grounded medium-voltage distribution power grids is discussed in the paper. The proposed cost-effective air-cooled modular topology of the power converter enables to simply scale the total power to a target power system. Besides reactive power, the STATCOM enables to generate zero sequence component and compensate the grid voltage asymmetry as well. For the operation with both components, the proposed control algorithm includes two current control loops based on two PI controllers operating in rotating the reference frame and single PR controller operating in the stationary coordinates. To achieve robustness and high reliability, the sliding DFT is employed to synchronize the control algorithm to the grid voltage without undesired parameter tuning. Since the proposed STATCOM design avoids complicated structures of multilevel converters, it saves costs, it is robust and suitable for operation in medium-voltage power grids, demanding on reliability.

References

[1] "IEEE Guide for Protective Relay Applications to Distribution Lines," *IEEE Std C37.230-2020* pp. 1-106, 2021.
[2] G. Kaufmann and R. Vaitkevičius, "Sensitive ground fault detection in compensated systems (arc suppression coil). What is influencing the sensitivity?," *The Journal of Engineering,* vol. 2018, no. 15, pp. 971-977, 2018.
[3] V. Spudić and T. Geyer, "Model Predictive Control Based on Optimized Pulse Patterns for Modular Multilevel Converter STATCOM," *IEEE Transactions on Industry Applications,* vol. 55, no. 6, pp. 6137-6149, 2019.
[4] H. A. Pereira, M. R. Haddioui, L. O. M. d. Oliveira, L. Mathe, M. Bongiorno, and R. Teodorescu, "Circulating current suppression strategies for D-STATCOM based on modular multilevel converters," *2015 IEEE 13th Brazilian Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC),* pp. 1-6, 2015.
[5] Y. Jin *et al.*, "A Dual-Layer Back-Stepping Control Method for Lyapunov Stability in Modular Multilevel Converter based STATCOM," *IEEE Transactions on Industrial Electronics,* pp. 1-1, 2021.
[6] R. K. Varma and R. Salehi, "SSR Mitigation With a New Control of PV Solar Farm as STATCOM (PV-STATCOM)," *IEEE Transactions on Sustainable Energy,* vol. 8, no. 4, pp. 1473-1483, 2017.
[7] R. K. Varma and H. Maleki, "PV Solar System Control as STATCOM (PV-STATCOM) for Power Oscillation Damping," *IEEE Transactions on Sustainable Energy,* vol. 10, no. 4, pp. 1793-1803, 2019.