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Investigation of Modular Multilevel Converters for E-STATCOM Applications

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***Abstract*—The power quality in electrical grids can be improved by static synchronous compensators (STATCOM), classically realized by low voltage inverters and conventional transformers. One of the main challenges for current and future STATCOM solution is the increase of flexibility for optimized power quality management by not only exchanging reactive power but also active power. For active power supply energy storage systems need to be integrated, classically at the dc link of the low voltage inverter. However, by the usage of classical low-voltage inverters, the power is quite limited even by parallel connection and bulky transformers are needed. Instead this paper suggests an E-STATCOM based on the modular multilevel converter (MMC) with integration of batteries at the dc link by isolated dc-dc conversion state. In this way, very high energy capacities can be installed and very high active and reactive power can be provided at very high efficiencies for safe and reliable grid operation.**

***Index Terms*—Modular Multilevel Converter, STATCOM, Battery Energy Storage System, Smart Transformer**

I. Introduction

The integration of decentralized energy systems from renewable sources (e.g. wind and photovoltaics) is linked with high challenges for stable and safe operation of medium voltage distribution grids. Fluctuating power generation and changing load conditions can cause undesired conditions as voltage and frequency instability [1],[2]. Strict grid codes need to be followed to ensure safe and stable operation of the grid [2].

Changes in the reactive power typically affect the voltage regulation and can lead to undesired voltage fluctuations and even to voltage dips within the grid. With the help of static synchronous compensators (STATCOM) the grid operation and stability can be improved by reactive power exchange, maintaining the grid voltage [1], [3]. This is particularly important for the support of weak grids, already being sensitive to smaller changes from generation and load side.

With the purpose of more flexible support of the grid, the integration of energy storage systems (ESS) in STATCOM applications is becoming more and more relevant. In this way, not only reactive power can be exchanged with the grid but also active power, providing more flexibility to the grid [4]. Depending on the grid characteristics, the ESS specifications and the grid conditions, the voltage and frequency can be regulated for safe and reliable grid operation [2], [3], [4], [5], [6]. With the help of the stored energy, a wide range of grid services can be provided for improved power management, including load shifting and peak shaving [2], [4], [7]. Common low-frequency oscillations and flickers can be compensated for improved integration of renewable energy systems [4], [7], [8].

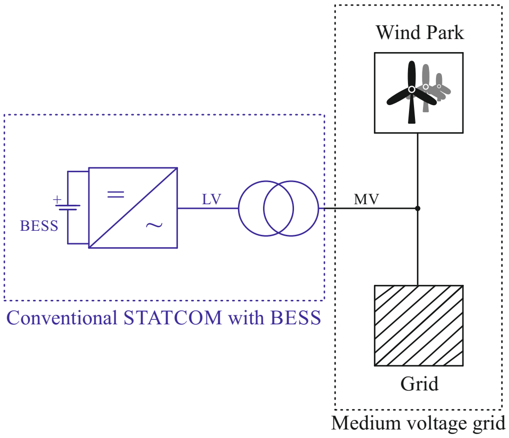
Different kind of ESS are available with various characteristics, including flywheels, supercaps, batteries and pumped storage systems [4]. Flywheels and supercaps can be used to compensate small and fast power variations. Pumped storage systems can compensate very high power variations with slow response time, their potential is strongly affected by geographical conditions. Battery systems (lead-acid, lithium ion) can fill the gap to provide high energies with relatively fast response. Especially the relevance of lithium ion batteries is more and more growing due to high power density and low maintenance cost. STATCOM applications with integrated ESS, so called E-STATCOM [6], are becoming more and more attraction in literature [9]. Different systems already have been realized, e.g. in UK [10].

II. Classical Solution

An E-STATCOM for connection to the medium voltage grid can be realized on various ways. The classical realization is illustrated in Fig. 1a. A battery energy storage system (BESS) is integrated at the dc link of a low voltage inverter, e.g. a classical two-level inverter [11]. In addition, a transformer is required to step up the voltage for connection to the medium voltage grid. For an increase of the rated power, several inverter and transformer units can be connected in parallel. However, the increase of power is limited since the high currents at low voltage side require very big passive components (wires, filters etc.). Additionally the switching losses are becoming very high due to limited number of voltage levels.

III. Advanced Solution

With the help of advanced modular power converters much higher powers can be transferred to the medium voltage grid. Due to direct connection to the grid, the usage of bulky low-frequency transformers can be avoided. The scheme of such a smart transformer (ST) solution is depicted in Fig. 1b.



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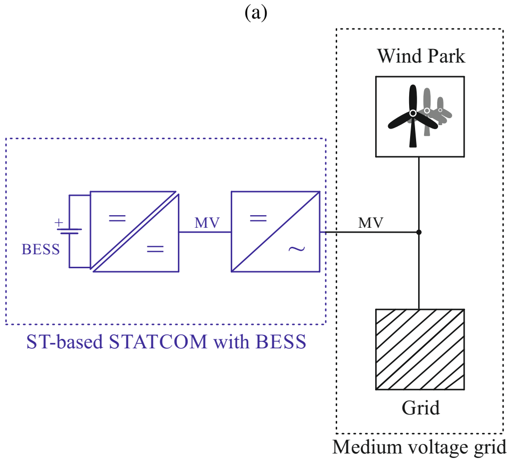

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Fig. 1: STATCOM with integrated BESS: a) Classical solution, b) ST-based solution.

The BESS is connected to an isolated dc-dc conversion stage. The cells of such a modular converter can be connected in parallel to increase the current and in series to fulfill voltage requirements [12]. The system profits by a high degree of modularity and can be flexibly configured for different BESS specifications. Compared to classical solutions, the redundancy in the system is significantly increased, leading to a high fault tolerance. Furthermore, a medium voltage dc connectivity is created.

For the dc-ac conversion state, the modular multilevel converter can be seen as the preferred solution [13], [14]. With the help of modular multilevel converters much higher powers can be achieved compared to classical solutions. Furthermore, the converter profits by very high efficiencies, excellent waveform generation and scalability to different power levels.

IV. MMC-Based E-STATCOM

STATCOM solutions based on the MMC are already at the market and well suited to achieve high power ratings. For conventional STATCOM application, providing reactive power, the power losses can be fed from the medium voltage grid. For E-STATCOM, active power is stored in the BESS.

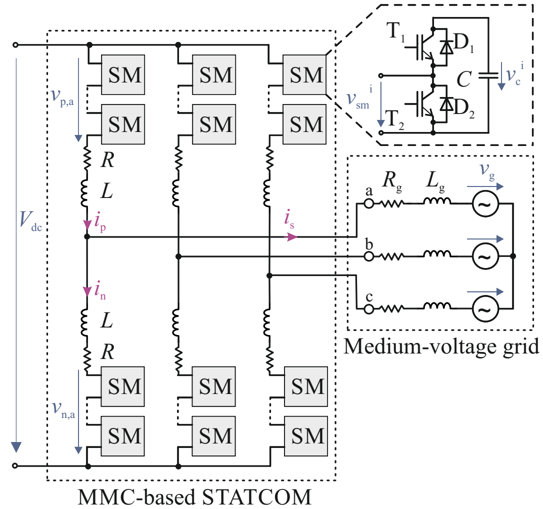


Fig. 2: MMC-based STATCOM.

One possible solution would be the battery integration in all or in some of the SMs. However, for safety issues a galvanic isolation would be preferred to handle large stored energies. The integration of batteries by dual active bridges in a high number of SMs would be linked to a very high hardware effort. Due to the aforementioned practical reasons, the integration of the batteries at the dc link of the MMC is considered. The dc-dc conversion state is setting a constant dc voltage for optimal MMC operation.

The electrical circuit of the MMC-based STATCOM is depicted in Fig. 2, composed by N submodules (SMs) and one inductor per arm. The SMs are realized as half-bridge cells, the voltage at the i^{th} SM terminal can be 0 ($S^i = 0$) or v_{c}^i ($S^i = 1$) by switching on the IGBT T_2 or T_1, respectively. Accordingly, the upper (p) and lower (n) arm voltages can be calculated as follows:

$$v_{\mathrm{p|n}} = \sum_{i=1}^{N} S_{\mathrm{p|n}}^i \cdot v_{c,p|n}^i \quad (1)$$

The ac grid current can be controlled by the converter voltage v_{conv}, defined in (2).

$$v_{\mathrm{conv}} = \frac{v_{\mathrm{n}} - v_{\mathrm{p}}}{2} \quad (2)$$

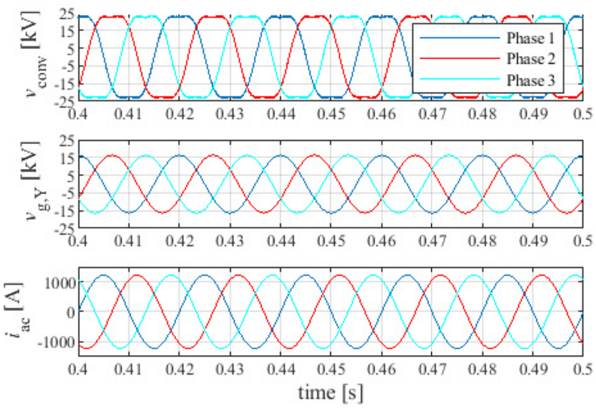
The arm inductors are required to limit the circulating currents from the dc side. The circulating currents can be controlled by the voltage v_{diff} across the inductors in (3).

$$v_{\mathrm{diff}} = V_{\mathrm{dc}} - (v_{\mathrm{p}} + v_{\mathrm{n}}) \quad (3)$$

The MMC can operate in a wide operation range. In Table I, the specifications of a STATCOM for a nominal power of 30 MVA are summarized. Due to high availability at the market 1.7 kV IGBT modules are considered. The MMC is realized by 56 SMs (half-bridge cells) per arm. The capacitor voltages are controlled to 966 V and limited to 1062.5 V for proper operation.

Description	Parameter	Value	Description	Parameter	Value
Nominal Power	S_{nom}	30 MVA	Arm inductance	L	50 mH
SMs per arm	N	56	SM capacitance	C	30 mF
Capacitor voltage reference	$v_{\mathrm{c,ref}}$	966 V	Capacitor voltage limitation	$v_{\mathrm{c,lim}}$	1062.5 V
dc voltage (terminal)	V_{dc}	54090 V	Grid voltage	v_{g}	20 kV
Grid inductance	L_{g}	1.1 mH	Water Temperature	T_{a}	$40°C$

TABLE I: MMC Parameters.



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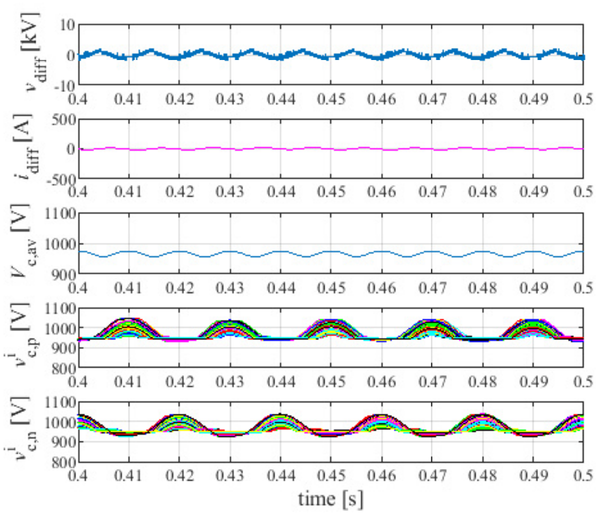

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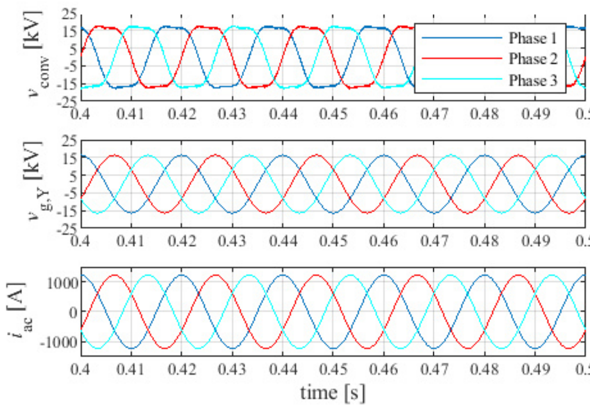
Fig. 3: Reactive power supply ($Q = 30\,\mathrm{Mvar}$): a) ac-side behavior, b) dc-side behavior (phase 1).



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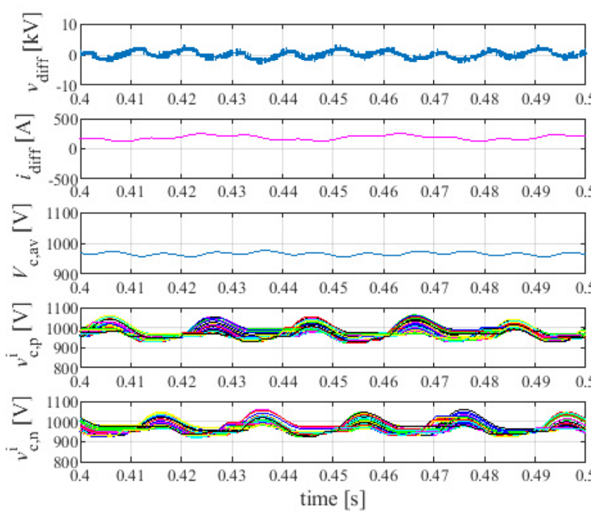
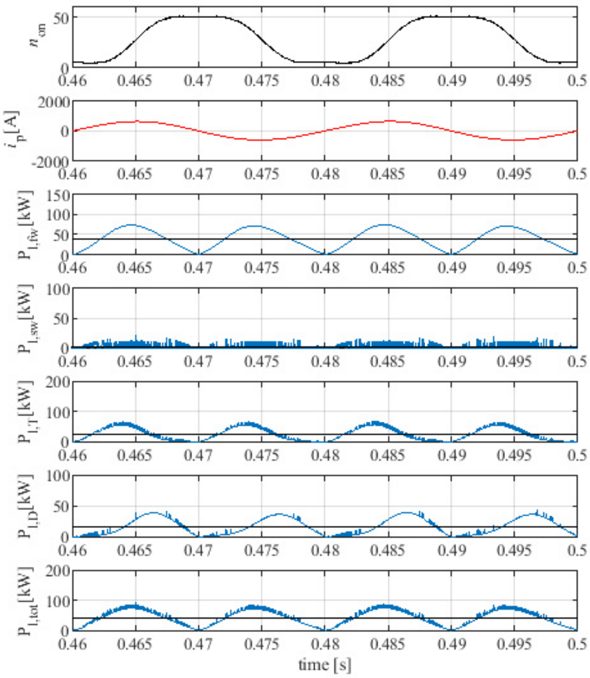


(b)

Fig. 4: Active power injection ($P = 30\,\mathrm{MW}$): a) ac-side behavior, b) dc-side behavior (phase 1).

The electrical behavior of the MMC is simulated in MATLAB. Fig. 3 shows that the grid currents are properly controlled for reactive power injection of $Q = 30\,\mathrm{Mvar}$. For maximum efficiency a nearest level modulation is applied [15]. Both, the circulating current ripples and the capacitor voltage ripples are limited for safe operation. The waveform quality is excellent without any additional filters. The system is also able to provide an active power of $P = 30\,\mathrm{MW}$. The electrical behavior is shown in Fig. 4. The power transfer from the BESS to the medium voltage grid becomes visible in the dc part of the circulating current.

The power module FF450R17IE4 from Infineon is considered. The power losses of each semiconductor are calculated for both operation points according to [16]. The thermal model is applied according to [15]. The power losses and the temperatures of one arm are depicted in Fig. 5 and Fig. 6 for both operation points. At low power factor the power losses and the thermal stress are rather shifted to the diodes. At high power factor IGBTs T_2 are the most stressed devices for inverter operation. The junction temperatures are kept in a range up to $100\,°\mathrm{C}$ for safe operation. For reactive power supply the overall semiconductor power losses are around 251.61 kW and for active power supply around 304.53 kW, corresponding to an efficiency of 98.98 %.



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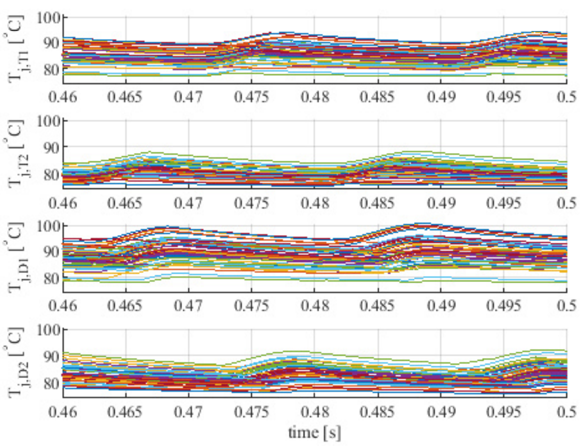
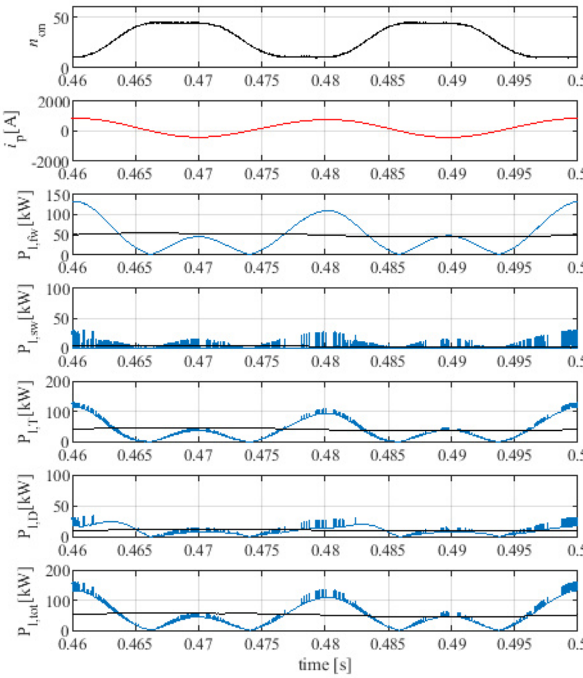


(b)

Fig. 5: Reactive power supply ($Q = 30\,\mathrm{Mvar}$): a) Power losses, b) Junction temperatures (one arm).



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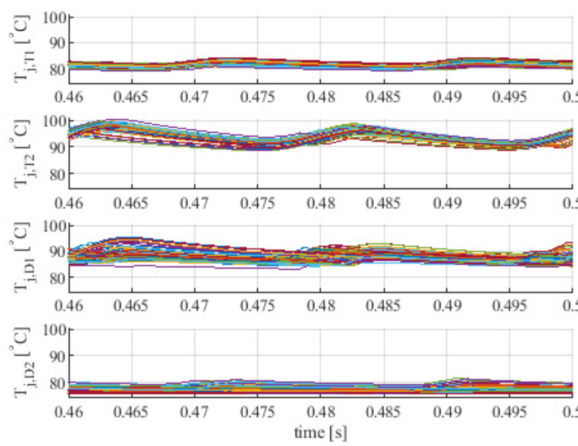

(b)

Fig. 6: Active power injection ($P = 30\,\mathrm{MW}$): a) Power losses, b) Junction temperatures (one arm).

V. Experimental Setup

An experimental setup for the MMC has been realized, depicted in Fig. 7. The control is implemented on a Zynq-700 board (zc702 evaluation kit) from Xilinx which combines a microcontroller based ARM processor and an FPGA unit on a single chip. The control signals are converted and transmitted by optic fiber connections to the 24 SMs. Each of the SMs are configured as half-bridge cells with a SM capacitance of 2 mF. Each arm inductor is dimensioned with 4 mH.

In Fig. 8 the MMC operation is demonstrated where a dc voltage of 200 V is applied. Active power is being transmitted to the ac side where a resistive-inductive load is connected to block 230 V rms voltage (50 Hz). Taking into account the reduced number of SMs, a phase-shifted pwm is applied for voltage generation [17]. The number of voltage levels is defined by $N+1$ in each arm, following equation (1) and assuming that the capacitor voltages are kept constant. All available voltage levels are used in the study case with a modulation index of 0.8. The capacitor voltages are properly balanced, leading to the recorded staircase waveforms. The converter voltage is properly generated by the arm voltages, driving the ac current for proper power transfer.

(a) (b)

Fig. 7: MMC Prototype: a) Cabinet (24 SMs), b) SM board.

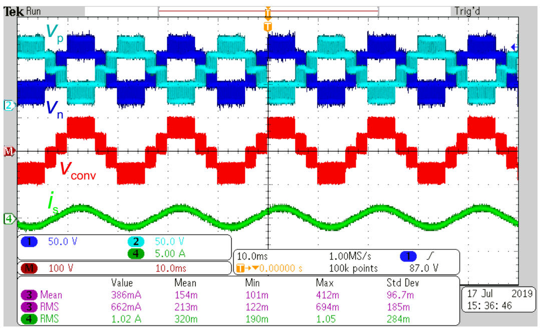

Fig. 8: Experimental results (active power transfer from dc to ac side): arm voltages, converter voltage, converter current.

VI. Conclusion

In this paper an MMC-based E-STATCOM has been investigated where the BESS is integrated at the dc link by an isolated dc-dc conversion stage. With this solution the usage of low frequency transformers can be avoided and the maximum power strongly increased compared to classical STATCOM solutions. The MMC performance has been demonstrated for active and reactive power supply (30 MVA) with excellent waveform generation, achieving converter efficiencies of around 99 %.

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