A New Modular Multilevel Converter with Integrated Energy Storage

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***Abstract*-This paper introduces a new modular converter with integrated energy storage based on the cascaded half-bridge modular multilevel converter with common DC bus. It represents a complete modular solution with power electronics and energy storage building blocks, for medium and high voltage applications. Furthermore, this solution can interconnect a DC and AC grid with bidirectional power flow, where both of them can receive or generate excess power to the third source integrated in each converter sub-module. This particularity enables the converter usage as a high voltage UPS system in the future HVDC meshed grids. Its functionality and flexibility makes the converter independent on the energy storage unit characteristic. The converter concept with its basic functions and control schemes are described and evaluated in this paper.**

I. Introduction

The necessity to reduce the harmful emissions from the conventional electric power systems leads to a transition towards dispersed generation production based on renewable energy sources. Wind power and photovoltaic installations are the most important renewables with important worldwide installed capacities and high annual growth rate. The drawback of renewables is the high fluctuation on daily and seasonal basis. This fact makes their integration with high percentage into the grid a well-known challenge, since the security of supply is a high priority [1]. One way to overcome this drawback is to install distributed energy storage units. With the possibility to communicate between generators, loads and storage systems, the advanced control under the smart-grid concept can define microgrids or virtual power plants [2]. As an energy storage solution with timing for few seconds up to several hours, with capacities up to 100MWh and fast response, batteries are a suitable and efficient solution [3]. Even if the storage in batteries is still an expensive solution nowadays, the outlook of the future vehicle-to-grid opens new perspectives for centralized storage systems such as the reuse of electric cars batteries with reduced capacity before recycling. Thus the development of centralized storage systems is a need for the future grids.

The connection of storage systems can be done at different voltage levels, depending on the application scenario. For increased power and energy ratings, it is natural to increase also the connection point voltage and reduce battery and converter current ratings. Medium voltage is an appropriate level where both transmission and distribution networks can take support from the storage system. At this level, multilevel converters are employed as grid interface, making use of conventional power electronic devices.

Development of multilevel converters started in 1970's when the first concept was the cascaded H-bridge (CHB) converter [4]. Using staircase modulation, with cells supplied from isolated batteries, this was the first modular converter concept. Neutral point clamped converter (NPC) was the next concept to be derived, using diodes to clamp the DC voltage to a half with respect to the midpoint, topology firstly investigated in [5]. By replacing the clamping diodes with a capacitor, the Flying Capacitor (FC) converter cell was developed as a basis for the second modular converter topology [6]. To overcome the unequal loss distribution of the NPC devices the Active NPC (ANPC) converter was developed at the expense of two additional active devices [7], this allowing an increased converter power density. Additional gains are the increased switching states redundancy and partial modular construction based on half-bridge cells. Based on the four basic converters topologies, hybrid converters based on the combination of these concepts were proposed. One of the most important hybrid concept is the combination of the CHB and FC converters, in the so-called concept Modular Multilevel Converter (M2C) [8, 9]. Due to its modular construction based on half-bridge cells, this topology is optimal for medium and high voltage [10].

Considering a centralized storage system, based on battery building blocks, with a power rating in the range of MW and energy in the range of MWh which is connected to medium voltage the converter solutions can be classified into:

- High voltage battery with NPC/ANPC converter [11]
- Low voltage modular batteries with series connected dual active bridges [12] and NPC/ANPC converter
- Low voltage modular batteries with CHB converter

Having a controlled ambient temperature, batteries voltage variation depends mainly on their state of charge (SOC). The typical variations from 5% to 95% SOC for different batteries technologies are shown in Table I. Thus, for the direct conversion with NPC centralized converter or modular CHB converter the battery nominal voltage and the converters nominal DC-Link voltage needs to be oversized to enable the required grid power transfer. In the solution with modular batteries and dual active bridges, only the DC side is modular but not the grid interface which is a centralized NPC/ANPC converter. This is a disadvantage which imposes restrictions in the system scalability on both storage units and converter.

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TABLE I
BATTERIES TECHNOLOGIES VOLTAGE VARIATION

Storage Technology	Voltage Range			Ratio
	U_{max}	U_{nom}	U_{min}	DC-DC
Li-Ion / $LiFePO_4$	3.60 V	3.30 V	3.20 V	1.13
Li-Ion / $LiMn_2O_4$	4.20 V	3.70 V	3.50 V	1.20
Sodium-Sulfur	2.20 V	2.00 V	1.70 V	1.29
Nickel-Cadmium	1.50 V	1.20 V	1.10 V	1.36
Lead-Acid	2.50 V	2.00 V	1.75 V	1.48

This paper introduces a complete modular concept to interface low or medium voltage batteries to the medium or high voltage grids. This enables a flexible scaling of converter modules with integrated energy storage and power electronics to a wide range of operating voltages, output power and stored energy. Having the modular construction with controllable sub-module, the converter topology is not dependent on the used storage technology. The converter control structures are applied in this paper, to validate the possible power flows.

II. CONCEPT OF THE NEW MODULAR CONVERTER WITH INTEGRATED ENERGY STORAGE

To achieve a modular converter structure with building blocks constructed from batteries and power electronics, the M2C topology was considered as a host for this purpose. With the highest degree of modularity, the converter structure from Fig. 1 is moving the centralized stored energy from the conventional main DC-link to distributed smaller voltage rating DC-links [8, 9]. This fact allows in the converter design to eliminate the leakage inductance locally for the used semiconductors. However, this improvement comes up with price paid in increased total installed capacitors and the inherent circulating current between phases required to charge the capacitors with the lowest voltages and discharge the ones with the highest voltages.

Fig. 2 shows three of the possible converter cells structures, as power electronics and energy storage building blocks. The basic converter cell from Fig. 2a is the solution with the reduced number of active components. The half-bridge switches (S_1 and S_2) with the DC-link capacitor from the host configuration are in charged to transfer the power in or out from the converter cell. The second half bridge switches (S_3 and S_4) form a bidirectional boost converter with its inductor, as additional components to charge or discharge the energy storage unit integrated in the cell. Depending on the energy storage unit characteristic, and the chosen control bandwidths, this can be used to control the voltage of the cell capacitor C. If the pulsating currents has a negative effect on the storage unit lifetime, the bridge must be current controlled at a constant DC level. In this case, the capacitor will be in charge to absorb the in-out pulsating energy.

An extended solution is shown in Fig. 2b, where the interleaved boost converter will reduce the inductor current ripple and thus its core size. Sharing the operating current the losses are distributed to the two legs and this is suitable for increased transfer power with the storage unit.

Based on the dual active bridge (DAB) converter [12], the optimized converter cell for high efficiency and high boost ratios is shown in Fig. 2c. The half bridges on the higher voltage side of the DC-DC converter is a voltage doubler and must be designed with higher voltage and smaller current rated devices while the full bridge on the low voltage side designed with lower voltage and higher current rating. With the disadvantage of increased number of components, the advantages are obvious, such as: usage of significant lower voltage energy storage units compared with the total DC-AC output voltages, reduced switching losses between the soft switching boundaries, and the galvanic isolation with medium or high frequency transformer reduces the isolation requirements for leakage current reduction due to ground coupling capacitances.

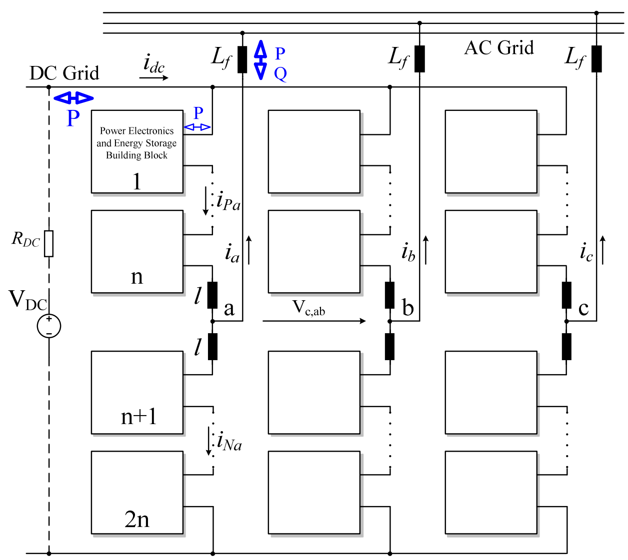

Fig. 1. Modular multilevel converter structure

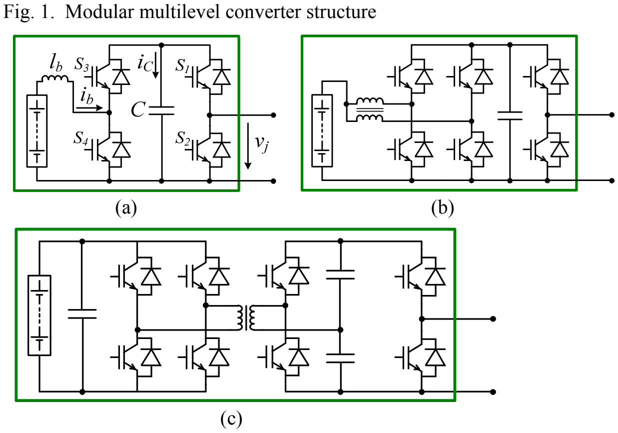

Fig. 2. Converter cell structures: (a) Basic converter cell; (b) Interleaved boost based cell; (c) Voltage doubler DAB based cell.

Having the described cells, it is possible to transfer power between any of the three main power sources namely: the higher voltage DC (e.g. DC grid or wind turbine DC-link), the AC grid and the distributed energy storage units from the converter cells. The basic converter cell from Fig. 2a is considered in the followings, for reduced number of active devices and control simplicity.

III. Converter Operation and Control Methods

The converter with the circuit from Fig. 1 and cell structure from Fig. 2(a) will always respect the following equation, applied for any of the *a*, *b* or *c* phase legs:

$$V_{DC} = \sum_{j=1}^{2n} v_j + l\frac{d}{dt}(i_P + i_N) \tag{1}$$

Here, the V_{DC} is the main DC bus voltage, v_j is the cell output voltage, l is the arm inductor, and i_P and i_N are the arm currents. When the switch S_1 is turned *on* and S_2 is *off* the cell is inserted and the output voltage equal with the capacitor voltage while in complementary when S_2 is *on* and S_1 *off* the cell is bypassed and the output voltage is nearly zero. The converter switching states must always assure that the number of inserted cells must be equal with the number of bypassed cells and equal with n. The output AC current i_{AC}, is equal with the sum of the arm currents (2), while a circulating current i_z between DC buses or between phases is given in (3).

$$i_{AC} = i_P - i_N \tag{2}$$

$$i_z = \frac{1}{2}(i_P + i_N) \tag{3}$$

The circulating current, charges the cells with the lowest voltages and discharges the cells with the highest voltages. Therefore, one method to balance the capacitors voltages is to control this current [10]. On the basis of equations (2), (3) the capacitive energy storage balance between the upper and lower arms can be achieved by controlling independently the voltage contributions on each [13].

A. Modulation Strategies

1. Space Vector Modulation

The universal concept of the space vector representation of converter output voltage levels can be applied for any multilevel converter with theoretical expansion to any number of levels. The complexity increases with high number of levels, where number of the redundant vectors increases [4]. The state transition can be controlled to reduce the line voltage ripple, and therefore the current ripple. For the present converter it is possible to implement a switching state sorting algorithm for capacitors voltage balancing [14]. The decisions are taken by choosing cells with the extreme deviation from their nominal set point depending on the current direction, to charge or discharge them [8]. The result is an $n+1$ level in the phase voltage and $2n-1$ in the line.

2. Level Shift Pulse Width Modulation

For converter configurations with n number of cells per arm, there are necessary $n-1$ carrier signals where half are level shifted up and half down with respect to zero which are compared with reference signal [15]. The result is an $n+1$ level phase output voltage. The disadvantage is that the conduction times are normally uneven distributed per cells. Therefore the capacitors voltage balancing can be achieved rotating cells from one carrier to another and can only be applied successfully at high switching frequencies.

3. Phase Shift Pulse Width Modulation

For converter configurations with n number of cells per arm, one possibility is to use $2n$ carrier signals with $360°/2n$ phase shift. The reference for the positive arm is negative and the reference for the negative arm is positive when the power flow is from the DC to AC, similar to the unipolar modulation. In this way the number of voltage levels in the phase voltage is $2n+1$ and $4n+1$ in the line voltage, with the first switching harmonics centred at $2n{\cdot}f_{SW}$, where f_{SW} is the chosen switching frequency. Two proportional integrator (PI) controllers are required for each phase to control the average voltage through the circulating current, while a proportional controller for each cell balancing must be used [10]. This result in a difficult implementation, and brings limitations in the chosen switching and sampling frequencies.

An alternative solution is presented in Fig. 3, and used in this paper. The reference signals are used as previously with the particularity that $n/2$ carriers with $(360°/n){\cdot}2$ phase shift are used for both the positive and negative arms duty cycles generation. Grouping cells from positive and negative arms to the same carrier leads the achievement of even duty cycle distribution and therefore a simpler voltage balancing is required over the fundamental frequency similar to the flying capacitor converter [6]. This advantage comes up with the drawback of reduced number of levels to $n+1$ for phase and $2n+1$ for the line voltages, with the first switching harmonics at $2{\cdot}f_{SW}$.

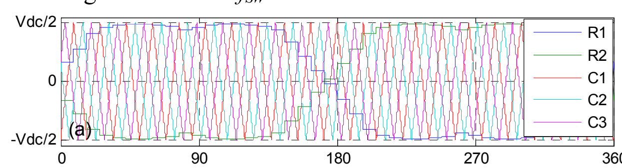

Fig. 3. References and carrier signal for the Phase Shift PWM alternative

B. Current Control

The AC current control dynamics is described by (4) for any of the converter phase, where the R_{ech} and L_{ech} are the equivalent resistance and inductances for the output filter and grid, V_g and V_c are the grid voltage and respectively the converter phase voltages, with V_c reference imposed in (5).

$$\frac{d}{dt}i_g(t) = -\frac{R_{ech}}{L_{ech}}i_g(t) + \frac{1}{L_{ech}}(V_c(t) - V_g(t)) \tag{4}$$

$$V_{C,ref} = \frac{V_{dc}}{2} + m\frac{V_{dc}}{2}[\sin(\omega t + \phi) - \frac{\max(V_{C,ref,abc}) + \min(V_{C,ref,abc})}{2}] \tag{5}$$

Having this, with the modulation strategy that makes sure the cells voltages are balanced, theoretically any of the current control strategies can be used with particular features and dynamics [16]. In this paper, the *abc* current control structure is used [17], which makes use of proportional resonant controllers, see Fig. 4. The control is performed on two of the three phase currents while the third one is indirectly deduced. When the grid unbalanced condition is a concern, a third controller can be employed.

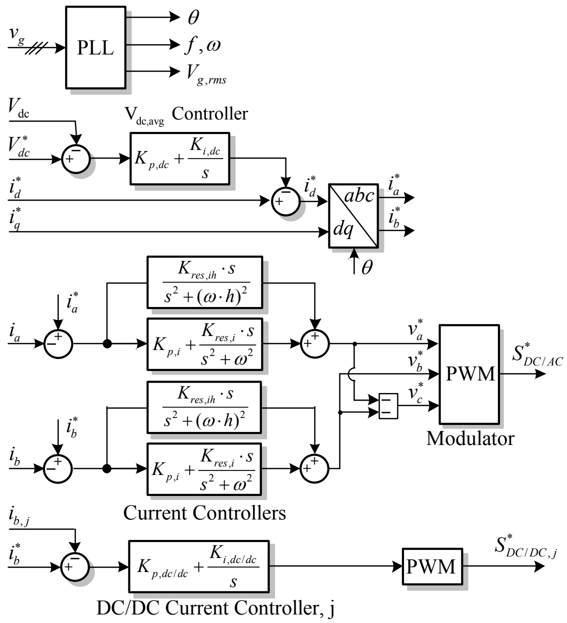

Fig. 4. Grid converter control structure

C. DC Voltage Control

A PI controller is normally employed to control the average voltage regulation at a decoupled smaller bandwidth than the inner current control loop. The current references are calculated using the *dq/abc* transformation with the rotation angle given by a phase-locked-loop algorithm. Depending on the required transfer power, the DC voltage reference must be adapted to keep the energy stored in the converter to a minimum, fact that will enhance the efficiency for various operating points. When connected to a DC grid controlled by other means, the voltage reference is given by [2]:

$$V_{dc}^{*} = V_{DC} + R_{DC} \cdot i_{DC} \tag{6}$$

D. Bidirectional boost DC-DC control

The switches S_3 and S_4 are used to control the energy storage charging/discharging current. Since the storage units may be sensitive to low frequency ripple currents, depending on the used technology, the voltage mode control is not considered in this paper. Therefore, an average PI current controller regulates the charge/discharge current for each cell, as shown in Fig. 4.

IV. Operation Modes and Their Performance

Three operation modes can be defined with this converter structure, depending on the power flow and the control requisite of the involved power sources:

a) DC grid to/from AC only – inverting control structures for M2C [8, 9]. The DC source is controlled by other means and the intervention of the energy storage unit is on request;
b) Energy storage units to/from AC only – the high voltage DC source is not present, this representing a pure energy storage converter mode;
c) Bidirectional power transfer between any of: DC grid, energy storage and AC grid.

To analyse the converter behaviour under the defined operation modes, the parameters from Table II are considered in the simulated converter model. Thus, 600V energy storage units are connected to medium voltage DC and AC grids.

TABLE II
Converter Model Parameters

Rated active power	P	5 MW
AC Grid line voltage	V_{LL}	4.16 kV
Rated RMS current	I	694 A
Rated AC frequency	f	50 Hz
DC Grid voltage	V_{DC}	6 kV
DC Grid resistance	R_{DC}	1 Ω
Arm inductance	l	100 μH
Grid filter inductance	L_f	1.3 mH
Cell capacitance	C	4 mF
Cell inductor	l_b	6 mH
Storage unit rated voltage	V_b	600 V
Storage unit rated current	i_b	240A
Cell capacitor rated voltage	V_C	1 kV
Number of arm cells	n	6

In the operation mode (a) the transistors (S_3 , S_4) of all cells are turned *off* normally, and the exchange power is between the DC and AC grids. In Fig. 5 this operation mode is illustrated, for unity power factor and nominal transferred power. This case considers the DC voltage as supplied to the converter terminals and controlled by other means. Therefore, the DC controller is disabled and the AC current control with the parameters given in Table III calculates the voltage references for the required power transfer. It can be noticed the converter behaviour as voltage source, when the buffer inductor is kept as small as necessary to reduce the circulating current and therefore optimized for the operating frequency at twice the output alternating frequency. To reduce its core size, if any, the coupling of the upper and lower inductor for each arm can be done. In these cases, the output currents must receive smoothening from an output L filter. It can be noticed the dominant fundamental frequency components of the arm currents on their conduction period equal with a low share of second and fourth harmonics.

In the second case, illustrated in Fig. 6, the power transfer is between energy storage units and AC grid. Here the DC voltage controller is enabled and regulates the voltage to keep the balance power. The storage unit's currents are controlled to a constant level and therefore the cells capacitors will take over the excess power, which translates in an increase of the voltage ripple. This makes the spectrum of the arm current to have a comparable level of first and second harmonics together with multiples of second.

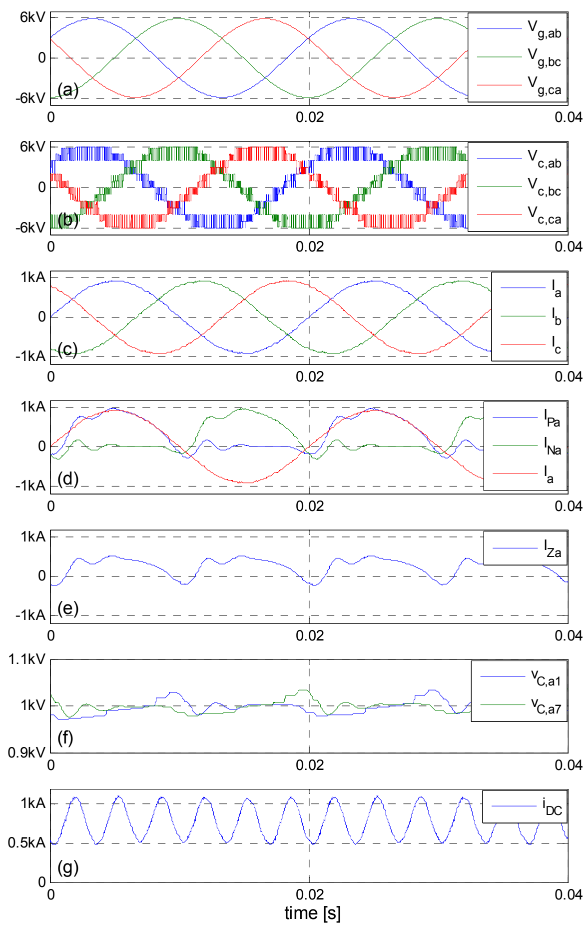

Fig. 5. Mode (a) – High voltage DC to AC: (a) AC grid line voltages; (b) Converter output line voltages; (c) Output AC grid currents; (d) Positive, negative arms currents and grid current for phase *a* (e) Phase *a* circulating current; (f) Phase *a* cell 1 and 7 capacitors voltages; (g) DC current.

TABLE III
CONTROL PARAMETERS

Voltage control proportional gain	$K_{p,dc}$	0.5 A/V
Voltage control integral time	$K_{i,dc}$	100 (A/V·s)
Current control proportional gain	$K_{p,i}$	1.5 V/A
Current control resonant gain	$K_{res,i}$	1000
DC-DC current control proportional gain	$K_{p,dc\text{-}dc}$	0.01 V/A
DC-DC current control integral time	$K_{i,dc\text{-}dc}$	1 (V/A·s)
Switching frequency for AC devices	$f_{sw,AC}$	1050 Hz
Switching frequency for DC-DC devices	$f_{sw,DC\text{-}DC}$	2100 Hz
Sampling Time	T_S	1/(2*1050) s

In Fig. 7, the last scenario is presented, where the DC voltage is controlled according to (6). Both the DC and AC grids receive 2.5MW each, half the converter power rated. The capacitors voltage ripple is similar to mode (b), and here the second harmonic in the arm current is dominant over the fundamental frequency. The latter is reduced, proportional to the AC grid current controlled to a half from the rated power. This makes the DC grid current to have not only the 6th harmonic over the DC offset as in mode (a), but also 12th.

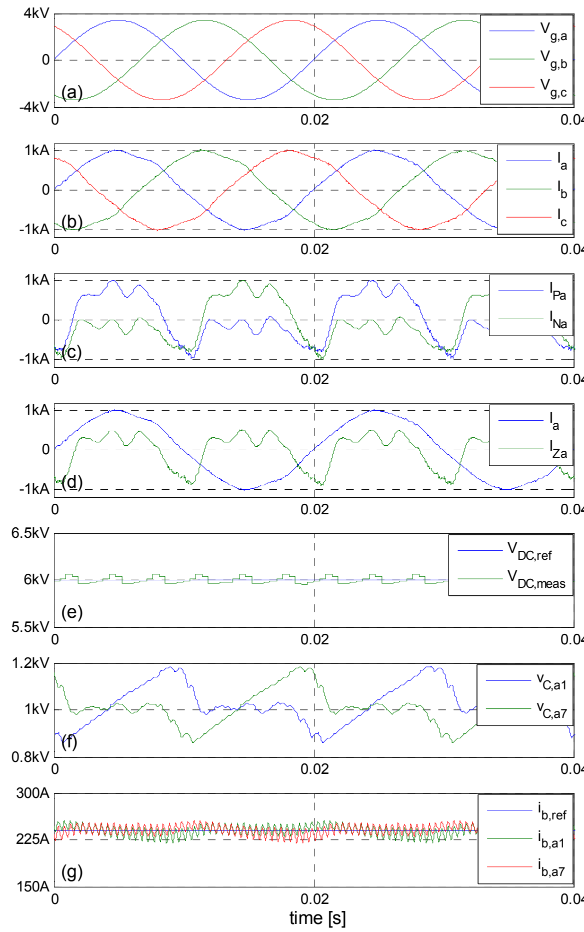

Fig. 6. Mode (b) – Energy storage to AC: (a) AC grid phase voltages; (b) Output AC grid currents; (c) Positive and negative arms currents for phase *a* (d) Circulating and phase *a* currents; (e) DC voltage control; (f) Phase *a* cell 1 and 7 capacitors voltages; (g) Energy Storage reference and controlled currents for cell *a1* and *a7*.

V. STORAGE SYSTEM DESIGN CONSIDERATIONS

Considering a battery energy storage system, the parasitic elements must be considered in the design phase. Fig. 8 shows the parasitic capacitances for batteries and semiconductors, elements which are critical for system reliability, efficiency and the EMI performance. At each switching state transition, the converter cell potential to ground changes. Therefore, leakage currents will flow to ground, currents proportional with the applied dV/dt. Measures to reduce the parasitic capacitances have to be used, in batteries for example an insulation material placed between batteries and shelf will significantly reduce the capacitance.

VI. CONCLUSIONS

A new modular converter structure with integrated energy storage was introduced to interface low and medium voltage energy storage units to medium and high voltage grids. This represents a complete modular solution

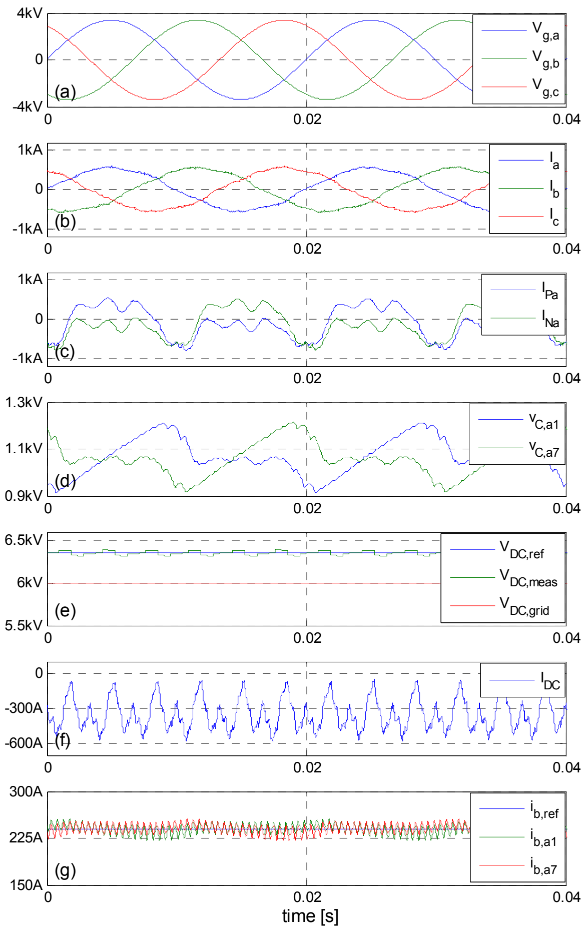

Fig. 7. Mode (c) – Energy storage unit to DC and AC grids: (a) AC grid phase voltages; (b) Output AC grid currents; (c) Positive and negative arms currents for phase *a* (d) Phase *a* cell 1 and 7 capacitors voltages; (e) DC voltage control and DC grid voltage (R_{DC} =1Ω); (f) DC grid current; (g) Energy Storage reference and controlled currents for cell *a1* and *a7*.

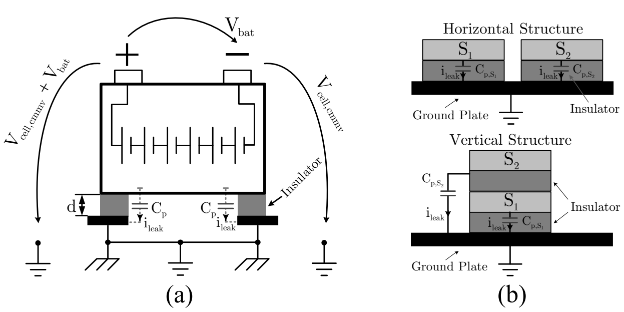

Fig. 8. Parasitic capacitances to ground: (a) battery; (b) semiconductors

with energy storage and power electronics building blocks. Furthermore, the topology is independent on the energy storage characteristic, since each cell can be independently controlled. Therefore, it's scaling in voltage, power and energy levels have many degrees of freedom. The converter functionality and control structures were demonstrated in this paper. The interconnection of a DC and AC grid with bidirectional power flow, where both of them can receive or generate excess power to the energy storage units integrated in each converter sub-module was demonstrated with particularities for each operating scenarios.

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