



SCAPE
POWERING E-MOBILITY

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D3.7 – Guidelines for the design of modular and scalable EV powertrain architectures

SWITCHING-CELL-ARRAY-BASED POWER ELECTRONICS CONVERSION FOR FUTURE ELECTRIC VEHICLES

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Executive Summary

This document presents the guidelines for the design of power conversion systems for electric vehicles following the modular and scalable approach devised in SCAPE. These guidelines involve hardware and software aspects, and they are classified into the three hierarchical module levels defined in the methodology: switching cell (SC), converter leg (CL) and full converter (FC). At the SC level, they include a list of compulsory and optional functions, together with the SC subcircuit structure and layout design guidelines to minimize the parasitic inductance. At the CL level, they treat the optimal configuration of the CL, the definition of the CL control, and the layout design to minimize the parasitic inductance. At the FC level, the set of suitable topologies to configure the main conversion systems in electric vehicles is provided, and guidelines for the definition of the FC control, involving the FC modulation and closed-loop control, are discussed. These guidelines aim to facilitate the design process and to ensure that critical aspects are considered. This document presents a first version of these guidelines arising from the current knowledge and experience of the SCAPE team.



List of Figures

Figure 1 – Illustration of SCAPE’s modular and scalable power conversion architecture through a 3-level 3-phase traction inverter example, with identification of the three hierarchical levels: switching cell, converter leg, and full converter.	8
Figure 2 – Generic tree structure of the control in a power converter.	9
Figure 3 – SC structure.	12
Figure 4 – Recommended SC power-loop layout.	12
Figure 5 – Converter leg configurations to reach different voltage and current ratings [5]. The first (top) row presents the leg functional model with a single-pole multiple-throw switch. The second row presents the configuration with just one switching cell in the outer diagonals. The third row presents the configuration with two parallel switching cells in the outer diagonals. The fourth (bottom) row presents the configuration with three parallel switching cells in the outer diagonals. (a) Two-levels. (b) Three levels. (c) Four levels. (d) Five levels.	14
Figure 6 – Insertion of voltage limiting devices to prevent eventual SC overvoltages under the CL OFF state. (a) Two-levels. (b) Three levels. (c) Four levels. (d) Five levels.	15
Figure 7 – Multilevel ANPC topology. (a) Three levels. (b) Four levels. (c) n levels.	17
Figure 8 – CL switching states in the baseline control of an example three-level ANPC CL configured with 8 SCs. (a) Connection to dc_1 . (b) Connection to dc_2 . (c) Connection to dc_3	18
Figure 9 – Possible layout to minimize CL power-loop parasitic inductances. (a) CL schematic. (b) CL Layout.	20
Figure 10 – Representation of multilevel NPC legs. (a) Two levels. (b) Three levels. (c) Four levels. (d) Five levels.	21
Figure 11 – Selected generic dc-ac converter topology for the traction inverter (n levels, p legs). The p CLs are connected in parallel to the same dc-link nodes dc_1 to dc_n , and each CL features its own independent ac terminal.	22
Figure 12 – Selected generic converter topology for the single-phase battery charger.	23
Figure 13 – Single-phase DAB dc-dc converter.	24
Figure 14 – Three-phase DAB dc-dc converter.	24
Figure 15 – Selected generic converter topology for the three-phase battery charger.	25
Figure 16 – Distribution of the stator windings in a symmetrical six-phase machine with open-end windings.	26
Figure 17 – Topology 1, based on a symmetrical six-phase machine with open-end windings.	26
Figure 18 – Operating modes of topology 1. (a) Propulsion with two machine neutral points. (b) Propulsion with a single machine neutral point. (c) Single-phase charging/V2G. (d) Three-phase charging/V2G.	26
Figure 19 – Topology 1a.	27
Figure 20 – Operating modes of topology 1a. (a) Propulsion. (b) Single-phase charging/V2G.	28
Figure 21 – Topology 1b.	28
Figure 22 – Operating modes of topology 1b. (a) Propulsion. (b) Single-phase charging/V2G. (c) Three-phase charging/V2G.	29
Figure 23 – Topology 1c.	30
Figure 24 – Operating modes of topology 1c. (a) Propulsion. (b) Single-phase charging/V2G. (c) Three-phase charging/V2G.	30



Figure 25 – Topology 1d.	31
Figure 26 – Operating modes of topology 1d. (a) Propulsion. (b) Single-phase charging/V2G.	31
Figure 27 – Distribution of the stator windings in an asymmetrical six-phase machine with open-end windings.	32
Figure 28 – Topology 2, based on an asymmetrical six-phase machine with open-end windings.	33
Figure 29 – Operating modes of topology 2. (a) Propulsion with two machine neutral points. (b) Propulsion with a single machine neutral point. (c) Single-phase charging/V2G. (d) Three-phase charging/V2G.	33
Figure 30 – Topology 2a.	34
Figure 31 – Operating modes of topology 2a. (a) Propulsion. (b) Single-phase charging/V2G.	34
Figure 32 – Topology 3.	35
Figure 33 – Operating modes of topology 3. (a) Propulsion. (b) Single-phase charging/V2G. (c) Three-phase charging/V2G.	36
Figure 34 – Selected generic BIC topology.	38
Figure 35 – Basic structure of the FC control (tertiary control).	39

List of Tables

Table 1 – CL switching states for the baseline control.	17
Table 2 – List of connection paths in the CL example of Figure 8.	18
Table 3 – Summary of IIC topology features.	37



List of Acronyms and Abbreviations

ANPC: Active neutral-point clamped
ASIC: Application specific integrated circuit
BIC: battery interfacing converter
CL: Converter leg
CPLD : Complex programmable logic device
DAB: Dual Active Bridge
EV: Electric vehicle
FC: Full Converter
FPGA: Field-programmable gate array
GaN: Gallium Nitride
HEMT: High-electron-mobility transistor
HV: High voltage
HVSC: High voltage switching cell
IIC: Integrated inverter charger.
LV: Low voltage
LVSC: Low voltage switching cell
MOSFET: Metal-oxide-semiconductor field-effect transistor
NPC: Neutral-Point Clamped
OBC: Onboard battery charger
SC: Switching cell
SiC: Silicon Carbide
SoC: State of charge
SoH: State of health
SPMT: Single-pole multiple-throw
V2G: Vehicle-to-grid
VLD: Voltage limiting device



Contents

Document History	1
Executive Summary	2
List of Figures	3
List of Tables	4
List of Acronyms and Abbreviations	5
1. Introduction	8
2. Switching Cell	10
2.1. Functions	10
2.1.1. Compulsory	10
2.1.2. Optional	10
2.2. Structure	11
2.3. Layout	11
3. Converter Leg	13
3.1. Configuration	13
3.2. Control	15
3.2.1. Functions	15
3.2.1.1. <i>Receiving the CL command</i>	15
3.2.1.2. <i>Receiving the state of the SCs and capacitors within the CL</i>	15
3.2.1.3. <i>Generating the SC commands</i>	16
3.2.1.4. <i>Generating the state of the CL</i>	16
3.2.2. Degrees of freedom	16
3.2.2.1. <i>Selection of connection paths in each CL position</i>	16
3.2.2.2. <i>Selection of the SC withstanding the switching losses</i>	18
3.2.3. Strategy for conduction and switching loss distribution	19
3.3. Layout	19
4. Full Converter	21
4.1. Topologies	21
4.1.1. Traction inverter	22
4.1.2. Onboard battery charger	23



4.1.2.1. <i>Single phase OBC</i>	23
4.1.2.2. <i>Three phase OBC</i>	24
4.1.3. <i>Integrated inverter-charger (IIC)</i>	25
4.1.3.1. <i>Topology 1, based on a symmetrical six-phase machine</i>	25
4.1.3.1.1. <i>Topology 1a</i>	27
4.1.3.1.2. <i>Topology 1b</i>	27
4.1.3.1.3. <i>Topology 1c</i>	29
4.1.3.1.4. <i>Topology 1d</i>	31
4.1.3.2. <i>Topology 2, based on an asymmetrical six-phase machine</i>	32
4.1.3.2.1. <i>Topology 2a</i>	34
4.1.3.3. <i>Topology 3, based on a nine-phase machine</i>	35
4.1.3.4. <i>Summary of the main features of the IIC topologies</i>	37
4.1.4. <i>Battery interfacing converter (BIC)</i>	37
4.2. <i>Control</i>	38
5. <i>Conclusion</i>	39
6. <i>References</i>	39



1. Introduction

One of the main goals in SCAPE is to devise a power converter design approach where all possible power conversion systems can be built from a single elementary module, in a lego-like fashion, so that scale economies can be fully exploited. SCAPE's modular and scalable power conversion architecture is conceived upon the definition of three hierarchical levels. Figure 1 illustrates these hierarchical levels in the example of a three-level three-phase traction inverter for an electric vehicle (EV). The first or bottom level consists of the switching cell (SC), which represents the most elementary module to configure power conversion systems. It consists of an electronic switch with self-powered intelligent driving, monitoring and protection circuitry. By properly combining several instances of the SC, a multilevel neutral-point-clamped (NPC) converter leg (CL) is obtained. They behave as single-pole multiple-throw (SPMT) switches. These converter legs represent, at a second hierarchical level, non-elementary modules to build power conversion systems. Finally, at the top or third level, one or more converter legs are combined to form the full power converter (FC).

The control of the system is also distributed through these three hierarchical levels: the primary control at the SC level, the secondary control at the CL level, and the tertiary control at the FC level.

Thus, in a converter, one will typically find an interconnected tree structure of these three different types of controllers, as shown in Figure 2, where information is exchanged bidirectionally in between nearest levels: information is exchanged in both directions between the tertiary and secondary controls, and between the secondary and primary controls. The FC modulation and closed-loop control are included in the tertiary control.

The purpose of this deliverable is to present the design guidelines arising from the project research activity and results. These design guidelines are aimed at facilitating the development of new power converters based on SCAPE's design approach.

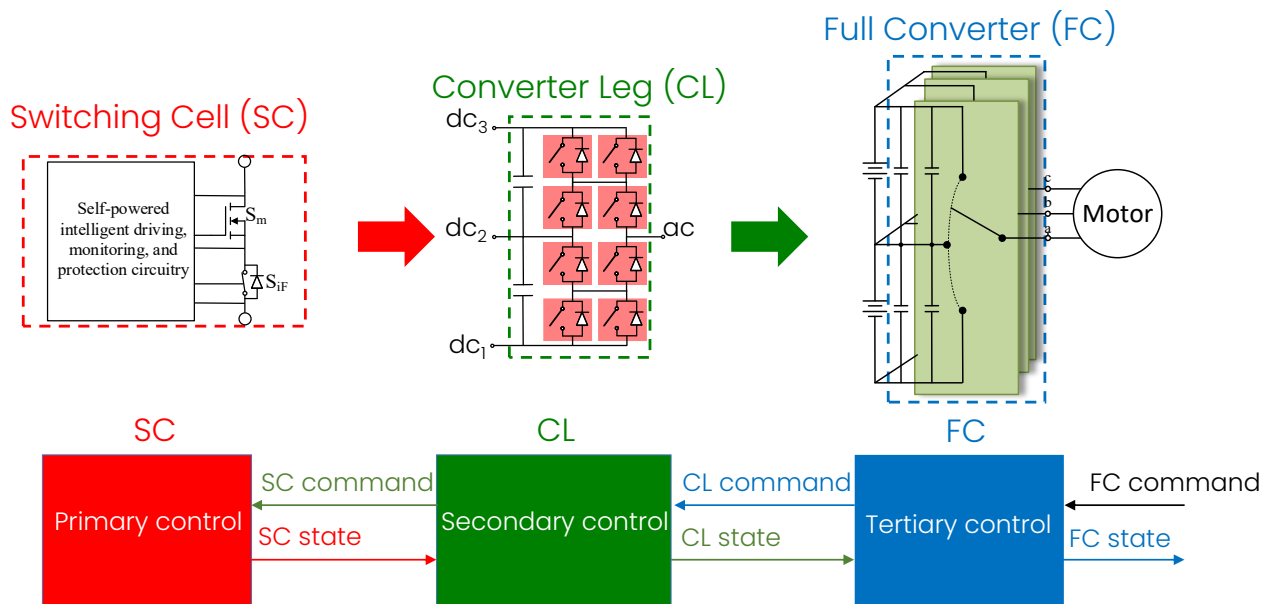


Figure 1 – Illustration of SCAPE's modular and scalable power conversion architecture through a 3-level 3-phase traction inverter example, with identification of the three hierarchical levels: switching cell, converter leg, and full converter.

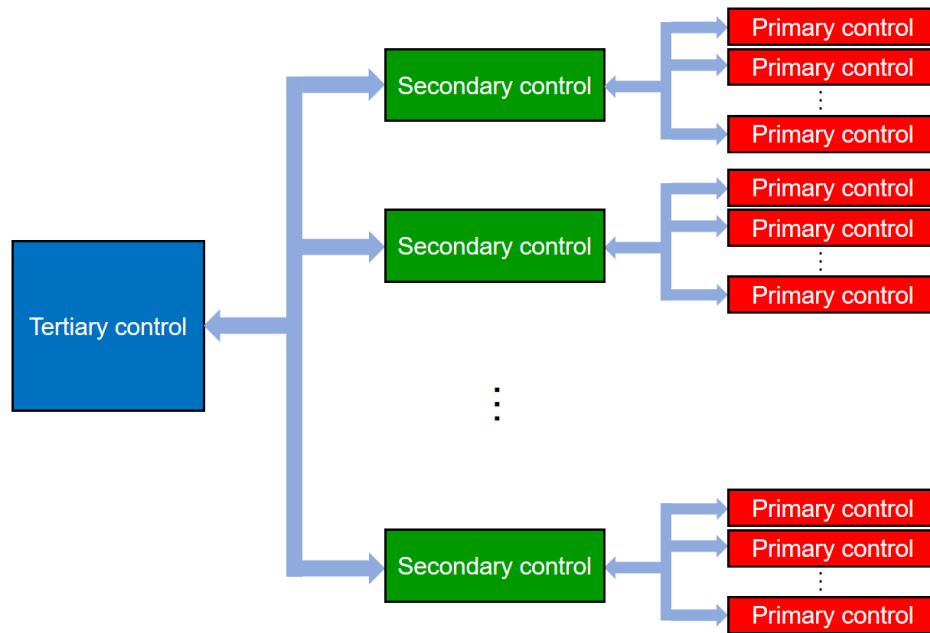


Figure 2 – Generic tree structure of the control in a power converter.

The document has been structured according to the above-mentioned three hierarchical levels. The outline is as follows. Section 2 presents the guidelines related to the design of SCs. Section 3 discusses the design guidelines for the CLs. Section 4 introduces the guidelines for the design the FC. Finally, Section 5 presents the conclusions.

2. Switching Cell

The SC is the most elementary module, which behaves as a quasi-ideal controlled electrical switch with antiparallel diode, with two possible states: ON and OFF. In order to be able to configure all the conversion systems in an EV with a moderate complexity, it is convenient to design two SCs: a high-voltage SC (HVSC) [1] and a low-voltage SC (LVSC) [2], characterized by a breakdown voltage around 600 V and 30 V, respectively. Both SCs enable covering a wide range of power converter voltage ratings with a moderate number of CL levels.

2.1. Functions

The list of functions to be performed by the SC is given below, classified as compulsory and optional.

2.1.1. Compulsory

- Perform as an electrical switch with antiparallel diode between the two SC power terminals, at the request of a binary control signal, with two possible states: ON, where the SC behaves as a small resistance, and OFF, where the SC is characterized by a large impedance and it is able to block voltages below the breakdown voltage.
- Self-powering of the SC circuitry by means of the voltage across the SC or the current through the SC. Alternatively, if suitable technology is available, these circuits could be powered through an external source of energy that is completely decoupled from the electrical circuit in which the SC is operating (e.g., through a light source external to the SC and the corresponding receiver integrated in the SC).
- Turn off the SC when the power supply voltage is below a given threshold.

2.1.2. Optional

- Measure the SC current.
- Measure the SC voltage.
- Measure the SC temperature.
- Report to the secondary controller when the SC current exceeds a given threshold value.
- Report the SC temperature to the secondary controller.
- Turn-off the SC under overcurrent.
- Assess the state of health of the SC through the measured values of voltage, current and temperature and report this information back to the secondary controller.
- Force an open circuit (high impedance) between the two SC power terminals, with an eventual antiparallel diode, capable of blocking voltages up to the SC breakdown voltage, to isolate the SC under the occurrence of severe SC faults; i.e., when the SC remains in high impedance under an ON command (open-circuit fault), or when the SC remains in low impedance under an OFF command (short-circuit fault).
- Force an open circuit (high impedance) between the two SC power terminals, with an eventual antiparallel diode, capable of blocking voltages up to the SC breakdown voltage, to isolate the SC at the request of an external binary signal.
- Report the isolation of the SC to the secondary controller due to occurrence of the previous events.



2.2. Structure

Figure 3 shows the recommended general structure of a SC. The two SC power terminals are labelled as top (T) and bottom (B). The S_m metal oxide semiconductor field-effect transistor (MOSFET) is the main electronic switch performing the switching function at the request of an external binary control signal. It can be implemented with a 600 V SiC MOSFET in the HVSC and with a 30 V Si MOSFET or a 30 V GaN High Electron Mobility Transistor (HEMT) in the LVSC. The S_{iFuse} MOSFET is optional. It is permanently ON under normal conditions and it is in charge of isolating the SC under a severe SC fault or at the request of an external signal. Ideally, S_{iFuse} should be a device with very low conduction loss, while the switching performance can be poor. A Si transistor could be the optimal choice to implement it. The optional shunt resistor R_{shunt} can be used to provide a measurement of the SC current. Alternatively, if a S_{iFuse} device is incorporated, which is modelled in conduction as a small resistance, the S_{iFuse} device can be used as a shunt resistor to obtain a rough measurement of the current.

The SC structure is completed by a set of subcircuits or blocks:

- *Power_bot*: in charge of powering all subcircuits referenced to the source node of S_{iFuse} (SB).
- *Driver_bot*: in charge of driving S_{iFuse} .
- *Power_top*: in charge of powering all subcircuits referenced to the source node of S_m (ST).
- *Driver_top*: in charge of driving S_m .
- *Sensing_and_conditioning*: in charge of measuring the SC current, voltage and temperature.
- *Digital_processing*: in charge of processing the relevant information coming from the SC input signals and SC measurements to determine the signals to drive transistors S_m and S_{iFuse} and to generate the necessary output signals.
- *Connectors*: defining the interfacing for the SC power terminals and input/output signals.

2.3. Layout

In the layout of the SC, it is especially important to minimize the parasitic inductance of the power loop between terminals T and B. To do so, according to Figure 4, it is recommended to place the T and B terminals close to each other, and then minimize the area of the loop by placing the forward and backward current paths (tracks) one on top of the other, by reducing the length of both paths and by reducing the distance between them (e.g., placing them into neighbor printed circuit board layers). In addition, the width of the paths should be maximized.

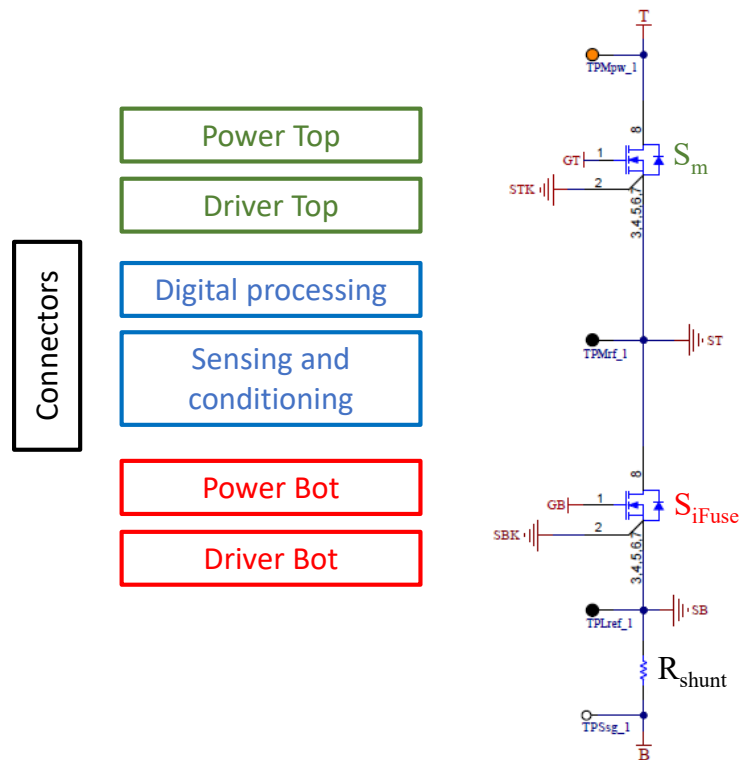


Figure 3 – SC structure.

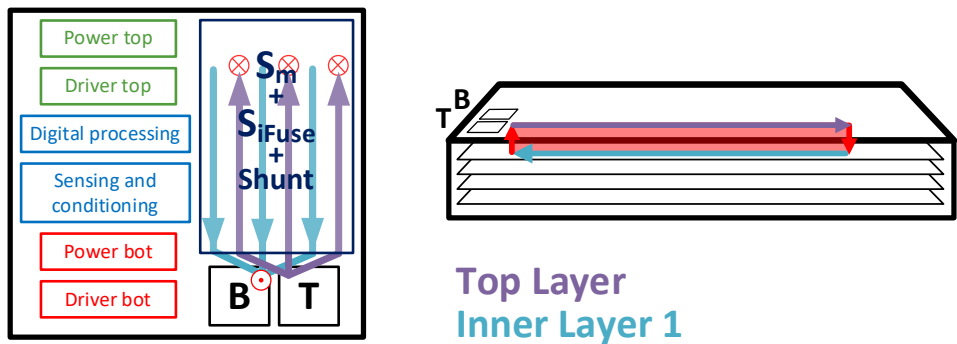


Figure 4 – Recommended SC power-loop layout.



3. Converter Leg

The CL is a module formed by a combination of SCs and small capacitors (typically ceramic), which behaves as a SPMT switch. Its control, the so-called secondary control, receives as inputs the requested position of the SPMT switch together with the state of all SCs, and provides as outputs the command for each SC and the state of the CL (see Figure 1). The aforementioned capacitors are in charge of providing the currents involved in the leg commutations. In the design of these CLs, it is important to define the number and interconnection of the SCs according to the necessary CL voltage and current ratings, as well as the control functions and strategy used to distribute conduction and switching loss among these SCs. Finally, the CL layout has to be conceived to minimize the parasitic inductance, since it degrades the switching transitions. Design guidelines addressing these issues are provided in the following subsections.

3.1. Configuration

CLs are configured following the multilevel active neutral-point-clamped (ANPC) topology presented in [3]. The number and interconnection of SCs will depend on the required voltage and current rating. As illustrated in Figure 5, the voltage rating can be adjusted through the number of voltage levels and the current rating can be a priori adjusted through the number of SCs in parallel in the outer diagonals of the CL, especially if the FC nominal operating conditions feature large CL duty-ratios of connection to the outer dc-link points (e.g., in the case of inverters with large nominal modulation indices or in dual-active-bridge converters). However, once the number of levels is determined based on the voltage rating, the true optimal CL configuration should be determined by means of optimization studies considering aspects such as efficiency, reliability and complexity [4]–[7].

Another aspect to consider regarding the configuration of the CLs is the following. In the CL OFF state, where all SCs are OFF, the dc-link voltage is distributed across the SCs according to their equivalent impedance. Due to the self-powering subcircuits of the SCs or for other reasons, SCs may feature a non-linear varying impedance with the blocking voltage, that together with small differences among SCs, may lead to a significant unbalance of the blocking voltage of the SCs. To prevent excessive blocking voltages in some SCs arising from this situation, a voltage limiting device (VLD) such as a transient voltage suppressor diode or Zener diode, can be inserted across the half-bridges that are not directly connected to the dc-link, as shown in Figure 6. The VLD should feature a voltage limit above the operating voltage of an elementary dc-link capacitor and below the breakdown voltage of a SC.



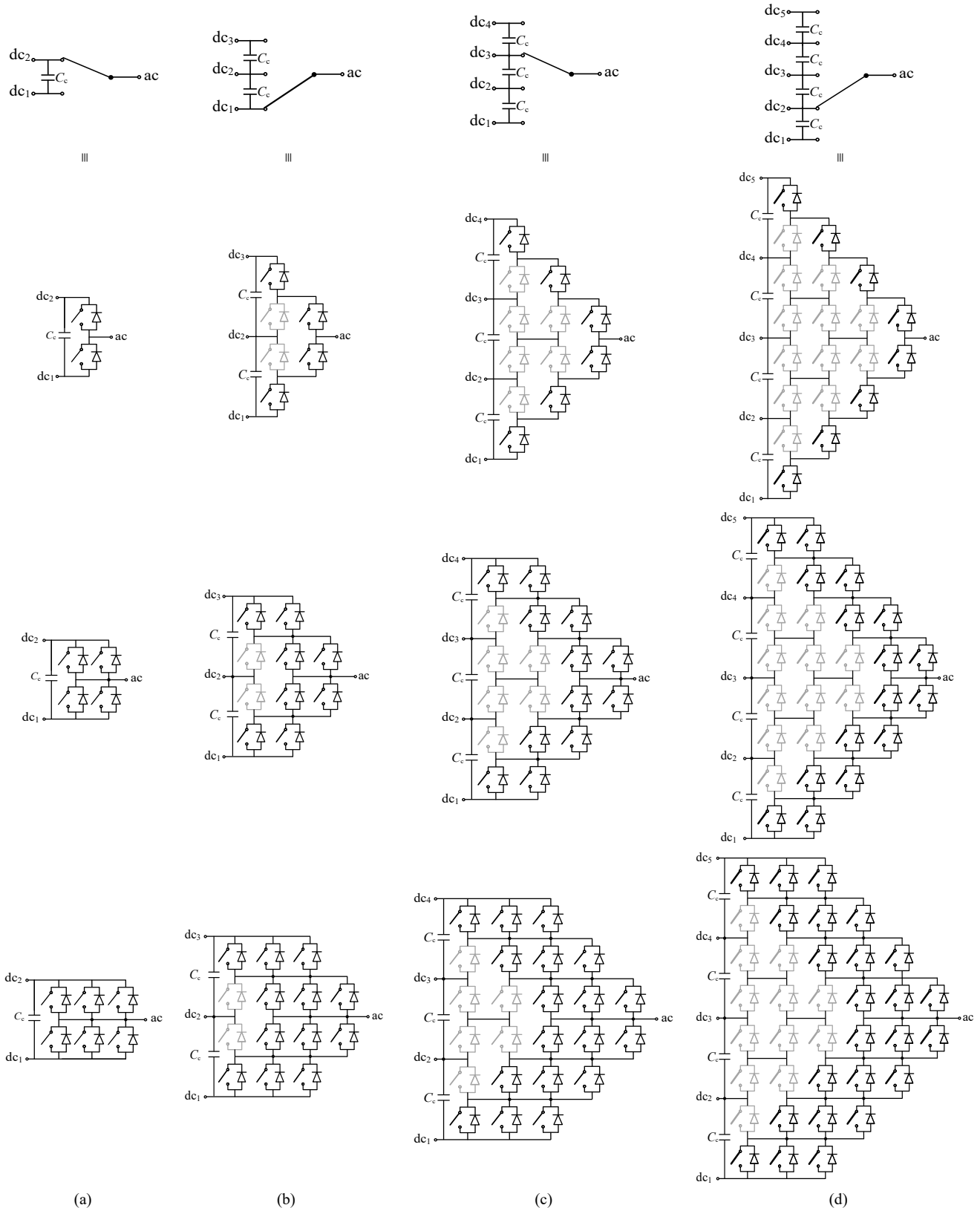


Figure 5 – Converter leg configurations to reach different voltage and current ratings [5]. The first (top) row presents the leg functional model with a single-pole multiple-throw switch. The second row presents the configuration with just one switching cell in the outer diagonals. The third row presents the configuration with two parallel switching cells in the outer diagonals. The fourth (bottom) row presents the configuration with three parallel switching cells in the outer diagonals. (a) Two levels. (b) Three levels. (c) Four levels. (d) Five levels.

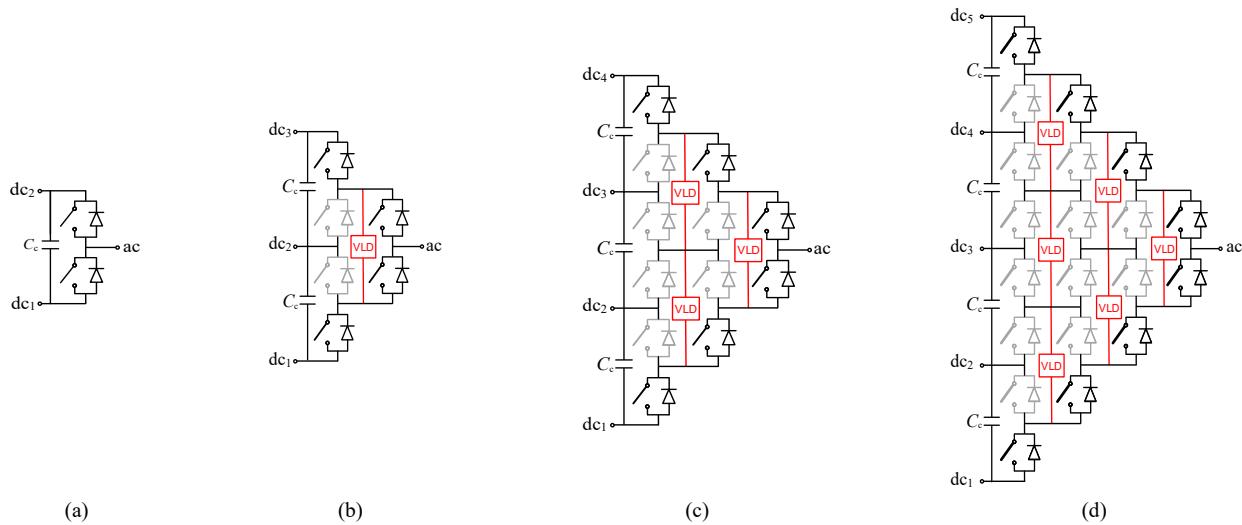


Figure 6 – Insertion of voltage limiting devices to prevent eventual SC overvoltages under the CL OFF state. (a) Two levels. (b) Three levels. (c) Four levels. (d) Five levels.

3.2. Control

The CL control can be implemented in any fast digital-information-processing device able to control with enough timing resolution the total amount of required binary SC command signals (ASIC, CPLD, FPGA, etc.).

3.2.1. Functions

According to Figure 1, at an abstract level, the secondary controller must receive as inputs the command for the CL (CL command) and the state of all leg's SCs (SC state). Then, from this information, it should generate as outputs the commands to all SCs within the leg (SC command) and the CL state (CL state). In the following, these basic functions of the secondary controller are elaborated in more detail.

3.2.1.1. Receiving the CL command

The CL behaves as a SPMT switch. At any point in time, the ac terminal of a CL should be electrically connected to one and only one of the dc-link terminals or, alternatively, it should be disconnected from all of them. Thus, the secondary controller should receive from the tertiary controller the command for the desired position of the SPMT switch at every point in time. For an n -level leg, with n dc-link points, the CL switching state can correspond to the connection of the ac terminal to any of the n dc-link points or to the disconnection from all of them. Therefore, a total of $n+1$ switching states must be coded. Since the SPMT switch position must evolve sequentially to the nearest upper or lower dc-link point, a Gray code is ideal for coding these switching states, since only one bit changes in every switching state change. A total of $\log_2(n+1)$ bits, rounded to the nearest higher integer, will be necessary.

3.2.1.2. Receiving the state of the SCs and capacitors within the CL

The secondary controller should also receive the information regarding the state of all SCs within the CL. By state, here we refer, on one hand, to the thermo-electrical stress that this SC is

withstanding, and, on the other hand, to the state of health (SoH) of the SC. The SC temperature, current and voltage define its thermo-electrical stress. With regard to the SoH, the bare minimum information that the secondary controller should receive from the primary controller is whether the SC is operational or in failure. If the SC is operational, a finer determination of the SC SoH can then be performed from the information of the SC thermo-electrical stress over time. Therefore, a possible subsequent function of the secondary controller within this section is the determination of a fine-grained value of the SoH of each SC from the received information. Alternatively, this fine-grained value of the SC SoH could be provided directly by the primary controller in the SC.

In addition to the state of the leg's SCs, the secondary controller can also receive information regarding the state of the leg dc-link capacitors. Again, their thermo-electrical stress is defined by their temperature, voltage and current.

3.2.1.3. Generating the SC commands

From the received CL command and from the received information regarding the state of each SC within the CL, the secondary controller must generate the commands for each SC. These SC commands, are essentially the ON/OFF switching state command, and eventually a command to disable the SC and leave it in permanent open circuit. The SC ON/OFF commands should be such that the desired CL switching state is guaranteed. The command to disable the SC should be activated if its SoH falls below a minimum threshold.

3.2.1.4. Generating the state of the CL

From the received SC state information and the information regarding the state of the leg dc-link capacitors, the secondary controller should also generate and submit to the tertiary controller the information regarding the state of the CL. Again, by state here we refer, on one hand, to the thermo-electrical stress that this CL is withstanding, and, on the other hand, to the SoH of the CL. The state of the CL will be computed in the secondary controller from the information of the state of all leg's SCs and capacitors. For instance, the thermal stress can be determined from the average and peak values of the SC temperatures. Similarly, the SoH of the CL will be determined from the value of the SoH of the SCs and the capacitors. The secondary controller does not need to submit information already available in the tertiary controller, such as the leg output current and dc-link capacitor voltages, which are necessary to perform the basic tertiary control functions.

One important CL SoH piece of information to submit to the tertiary controller is the availability to connect the CL ac terminal to all dc-link terminals (i.e., inform if any of the levels has been lost). This information should be derived from the SoH of the leg's SCs and submitted promptly to the tertiary controller.

3.2.2. Degrees of freedom

3.2.2.1. Selection of connection paths in each CL position

As discussed before, through properly interconnecting SCs, one can produce CLs featuring the multilevel ANPC topology of Figure 7, where each switch position can have one or more SCs in parallel [3], [4].



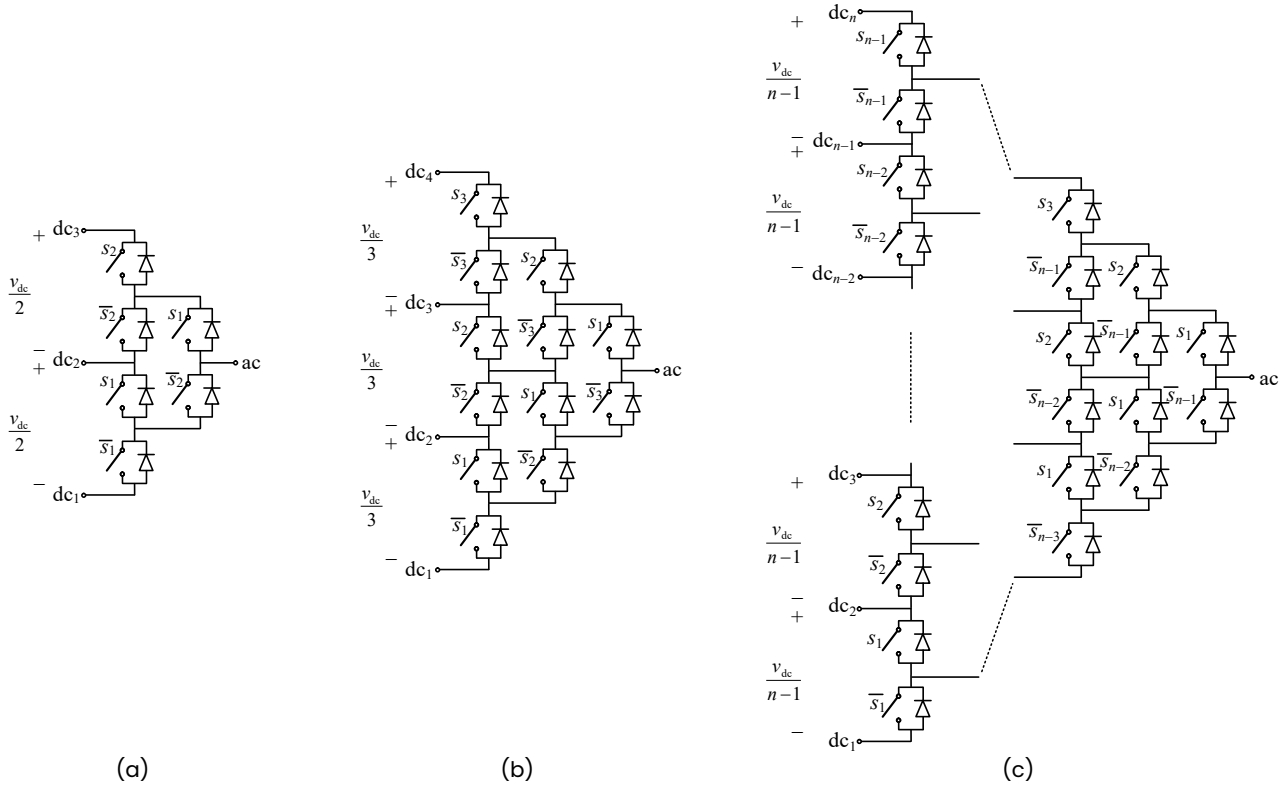


Figure 7 - Multilevel ANPC topology. (a) Three levels. (b) Four levels. (c) n levels

The fundamental function of the secondary controller is to establish, at each point in time, the switching state of each SC from the desired CL SPMT switch position command. In a baseline control approach, this can be done efficiently as follows. First we assign the binary switch control variables s_k , $k \in \{1, 2, \dots, n-1\}$, as indicated in Figure 7, where a value of 0 means that the corresponding switch is OFF and a value of 1 means that the corresponding switch is ON. Then, through the thermometric code established in Table 1, we set the CL switching states assigned to each CL position. Obviously, in addition, the CL position corresponding to a “no connection” of the ac terminal, requires all CL switches to be OFF.

CL position	ac terminal connection to	s_1	s_2	s_3	...	s_k	...	s_{n-2}	s_{n-1}
1	dc ₁	0	0	0	...	0	...	0	0
2	dc ₂	1	0	0	...	0	...	0	0
3	dc ₃	1	1	0	...	0	...	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
k	dc _{k}	1	1	1	...	0	...	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
$n-1$	dc _{$n-1$}	1	1	1	...	1	...	1	0
n	dc _{n}	1	1	1	...	1	...	1	1

Table 1 – CL switching states for the baseline control.



Figure 8 illustrates these CL switching states in the simple case of a three-level CL with two SCs in parallel in the top and bottom switch positions. It can be observed that in all three connections of the ac terminal to the dc-link points, two parallel paths for the connection are enabled. These parallel paths are listed in Table 2. In a general case, multiple parallel paths for the connection of the ac terminal will be available. Enabling all possible parallel paths for a connection of the ac terminal facilitates the reduction of conduction losses and, thus, maximizes efficiency. However, activating only a subset of the possible paths could be interesting to better distribute the conduction loss and subsequent thermal stress. This is a degree of freedom that can be used in the control to improve performance and SoH. For example, in the connection of the ac terminal to dc_2 in Figure 8, three options are possible: activating only path SC_{31} – SC_{32} , activating only path SC_{21} – SC_{22} , and activating both paths.

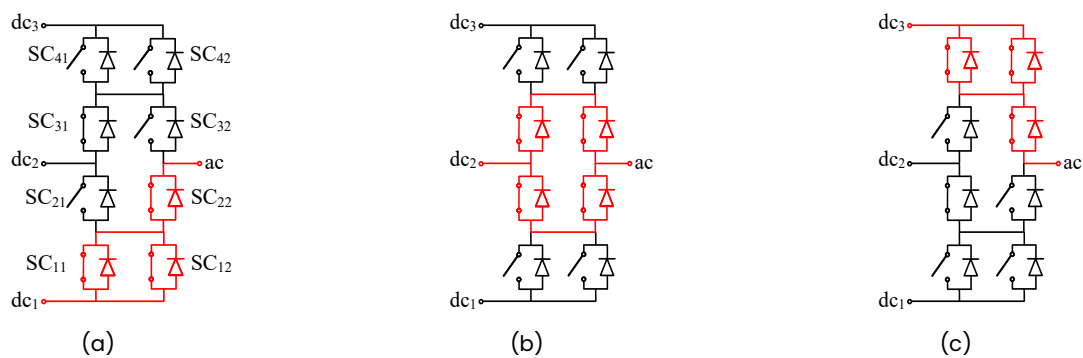


Figure 8 – CL switching states in the baseline control of an example three-level ANPC CL configured with 8 SCs.
(a) Connection to dc_1 . (b) Connection to dc_2 . (c) Connection to dc_3 .

CL position	ac terminal connection to	Path 1	Path 2
1	dc_1	SC_{11} – SC_{22}	SC_{12} – SC_{22}
2	dc_2	SC_{21} – SC_{22}	SC_{31} – SC_{32}
3	dc_3	SC_{41} – SC_{32}	SC_{42} – SC_{32}

Table 2 – List of connection paths in the CL example of Figure 8.

3.2.2.2. Selection of the SC withstanding the switching losses

In the transition from one leg position to another, a number of SCs need to change their switching state. These transitions will produce some switching loss. If the ac terminal current flows in the outwards direction, switching losses occur in one of the transitioning switches from Figure 7 with a non-complementary control variable. If the ac terminal current flows in the inwards direction, switching losses occur in one of the transitioning switches from Figure 7 with a complementary control variable. Among all possible switches, switching losses concentrate in the last device being turned off and the first device being turned on [3], [8]. This offers a second degree of the freedom in the control to distribute the switching loss and subsequent thermal stress, in order to improve performance and SoH of SCs and CLs.

3.2.3. Strategy for conduction and switching loss distribution

As seen in the previous subsection, the CL features degrees of freedom to distribute conduction loss and switching loss among the SCs. This is due to the fact that the connection of the ac terminal to a dc-link point usually features several possible parallel paths and that the transition from the connection to one dc-link point to another dc-link point usually involves the turn-on and turn-off of multiple SCs.

A simple default control strategy is to activate all parallel conduction paths in order to minimize conduction loss. Then, the SCs selected to withstand switching losses can be those from the pole closest to the dc-link, with reference to Figure 7, as the power-loop parasitic inductance involved in the switching transition will be the smallest possible, and this will facilitate minimizing switching loss. If the switch is implemented with several SCs in parallel, the withstanding of switching losses can be alternated among all parallel SCs to be shared equally.

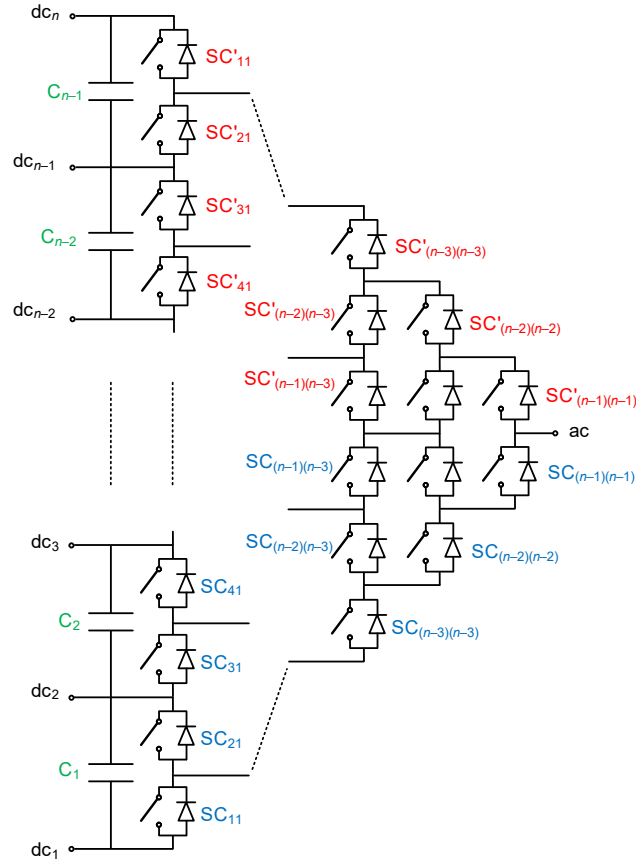
A more elaborated control strategy consists on, again, activating all parallel conduction paths, and then, distributing switching loss to achieve the balancing of the SC temperatures as much as possible. In practice, this requires adjusting the proportion of times over a given period that each SC takes switching loss. If necessary, to avoid significant temperature unbalances, certain conduction paths might eventually be deactivated.

Other advanced control strategies can be conceived. For instance, distributing conduction and switching loss according to a health management strategy to improve the reliability of the CL; i.e., distributing losses to reach the proper balance of SCs SoH according to the relevance of each SC.

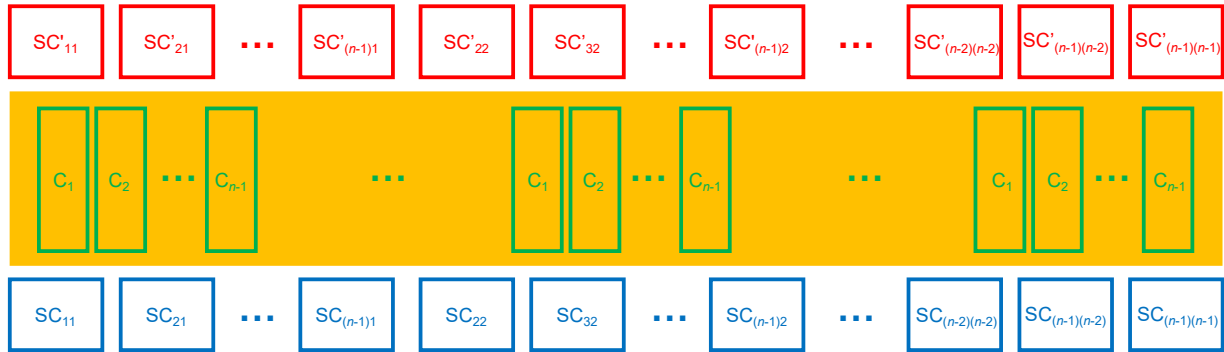
3.3. Layout

In order to improve the CL switching performance, it is important to minimize the parasitic inductances of all commutation power loops. These parasitic inductances are highly dependent on the CL layout. A possible layout to minimize them is illustrated in Figure 9. The SCs are located around a central hallway (in orange), with the top half of the CL SCs (red) located on one side of the hallway, and the bottom half of the CL SCs (blue) located on the other side. The dc-link capacitors (green) are distributed along this central hallway. In addition, the interconnection of SCs takes place through wide overlapping tracks along this central hallway, located in several layers, being these layers as close as possible one to each other.





(a)



(b)

Figure 9 – Possible layout to minimize CL power-loop parasitic inductances. (a) CL schematic. (b) CL Layout.

4. Full Converter

The FC is the highest-level module in Figure 1, formed by a combination of CLs together with eventual capacitors, inductors and transformers. This section provides guidelines for the selection of the topology and the design of the tertiary control, including both the modulation strategy and the closed-loop regulation of the command variables, suitable for the modular and scalable power conversion design approach proposed in SCAPE.

4.1. Topologies

This subsection presents the topologies for the main power conversion systems in an EV: the traction inverter, the on-board battery charger, a fully integrated inverter-charger (IIC), and the power converter interfacing the high voltage traction battery with the low-voltage service battery (BIC). The presented topologies, properly combined, enable dc-dc, dc-ac, and ac-ac power conversion, with bidirectional power flow, and with or without galvanic isolation, at a wide voltage, current and power ratings. Hence, they can be potentially applied to any EV power conversion system, and their use can be extended beyond the EV application.

According to SCAPE's design approach, these topologies should ideally only combine multilevel NPC converter legs with eventually capacitors, inductors and transformers. Figure 10 shows the symbol used to represent these NPC converter legs and their functional model as SPMT switches. The extension to an arbitrary number of levels is straightforward. From now on, these legs will be represented with the symbol on top of Figure 10: a simple box with dc-link terminals dc_1 to dc_n and an ac terminal.

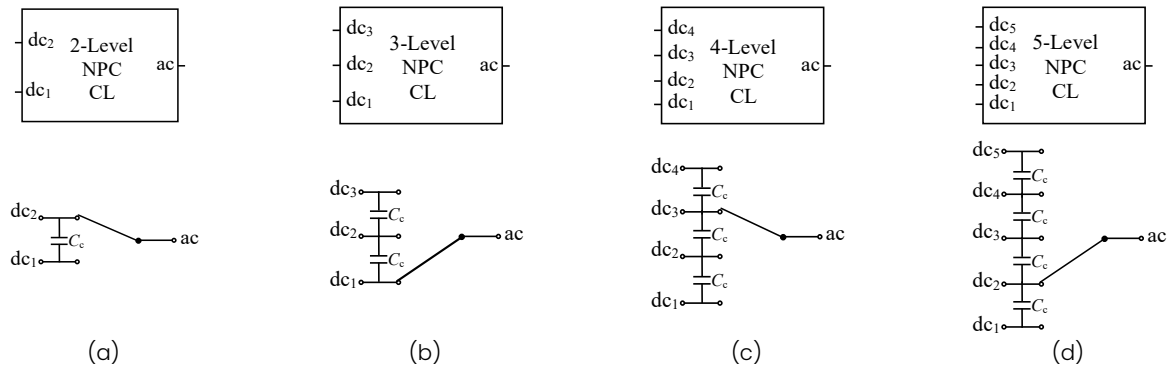


Figure 10 – Representation of multilevel NPC legs. (a) Two levels. (b) Three levels. (c) Four levels. (d) Five levels.

The outline of this subsection is as follows. Section 4.1.1 is devoted to the traction inverter. Section 4.1.2 analyzes the case of the onboard battery charger, supplied by either a single-phase or a three-phase grid. Section 4.1.3 then presents the most suitable topologies that integrate the traction inverter and the battery charger functions in a single converter (IIC). Finally, Section 4.1.4 discusses the topologies to implement the dc-dc converter interfacing the high-voltage traction battery with the low-voltage service battery (BIC).

4.1.1. Traction inverter

The traction inverter is the power converter within an EV in charge of controlling the torque and speed of the electric motor. It manages the power flow between the traction battery and the electric motor. Figure 11 presents the selected generic topology for the traction inverter, featuring n levels and p legs. The converter interfaces the traction battery, formed by a series connection of $n-1$ battery modules, and the electric motor, with p phases. The capacitors shown (C_f , typically film capacitors) are in charge of providing the dc-link current components at frequencies in the order of the switching frequency.

The converter is capable of bidirectional power flow, enabling regenerative braking. The maximum peak fundamental line-to-line voltage across motor terminals is equal to v_{batT} in the linear modulation range, and it is equal to $1.1 \cdot v_{batT}$ in the overmodulation region. Accordingly, enough battery modules should be connected in series to be able to reach and operate with the rated motor voltage. The converter can take care of balancing the state of charge (SoC) among the battery modules. Thus, stacking a considerable number of battery modules in series is a feasible solution for the battery implementation. This topology then avoids the need to place a step-up dc-dc converter in between the battery bank and the inverter, to adapt a relatively low battery voltage to a higher required inverter dc-link voltage.

The typical number of phases is 3, 5, 6 and 9. Increasing the number of phases enables an increase of the traction system power rating for the same CL current rating or, alternatively, a reduction of the CL current rating for the same traction system power. In addition, it improves the fault tolerance of the converter and motor and it typically leads to a higher system power density.

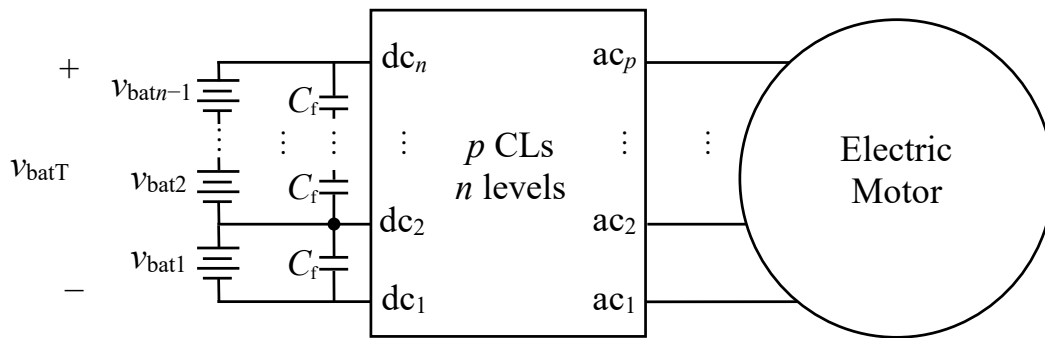


Figure 11 – Selected generic dc-ac converter topology for the traction inverter (n levels, p legs). The p CLs are connected in parallel to the same dc-link nodes dc_1 to dc_n , and each CL features its own independent ac terminal.

4.1.2. Onboard battery charger

The onboard battery charger (OBC) is the power converter within an EV responsible for ensuring the power transfer from the ac grid to the battery in order to recharge it. Ideally, it should also allow the power flow from the battery to the grid so that the vehicle can contribute to provide grid services, in what it is usually designated as the vehicle-to-grid (V2G) mode. In the following, the selected topologies for both single-phase grid and three-phase grid are presented.

4.1.2.1. Single phase OBC

The selected onboard charger topology for a single-phase grid is presented in Figure 12. The power converter allows a bidirectional power flow and it is composed of two cascaded converter stages: a dc-ac converter stage connected at the grid side and a dual active bridge (DAB) dc-dc converter [9]–[11] at the battery side. Both stages are interfaced through an m -level dc-link, whose total voltage (v_{dc}) must exceed the peak value of the grid voltage.

The dc-ac converter is composed of 2 CLs and a filter inductor. It is in charge of regulating the grid current so that it is sinusoidal at the grid frequency, and with the proper displacement factor (unity displacement in charging mode and with the requested displacement factor in the V2G mode). It is also in charge of regulating the total voltage v_{dc} of the intermediate dc bus, and it can contribute to the balancing of the dc-link capacitor voltages.

The DAB dc-dc converter can be single-phase, as depicted in Figure 13, or three-phase, as depicted in Figure 14. It is composed of $2/3+2/3$ CLs and a single-phase/three-phase transformer. The number of levels on each side (n and m) can be equal or different. The transformer provides galvanic isolation and an extra impedance to limit the leakage common-mode currents. The system can be configured with any ratio of the battery-to-dc-link voltages (v_{bat}/v_{dc}) through the adjustment of the transformer turns ratio. The mission of the DAB is to control the power flow between the battery and the dc-link while ensuring the SoC balancing of the battery modules and the balancing of the dc-link capacitor voltages.

Additional inductors and capacitors can be connected in series or parallel at the DAB transformer to block dc voltage components or to enable operation in resonant mode (e.g., the so-called LLC and CLLC topologies).

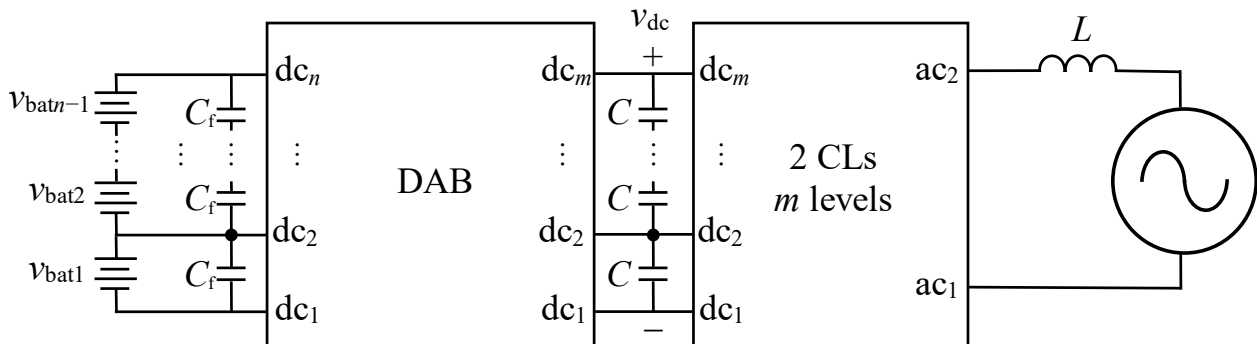


Figure 12 – Selected generic converter topology for the single-phase battery charger.

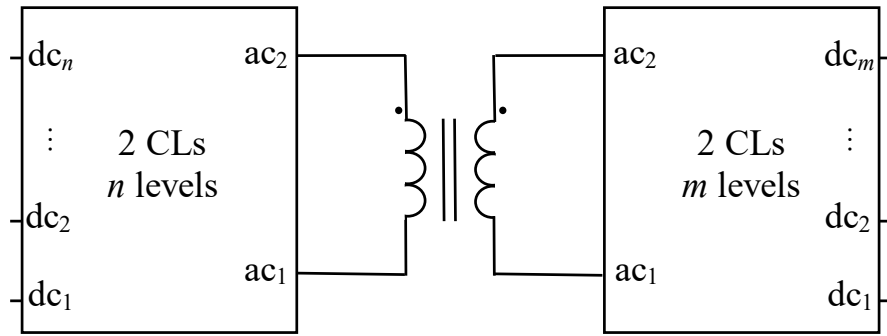


Figure 13 – Single-phase DAB dc-dc converter.

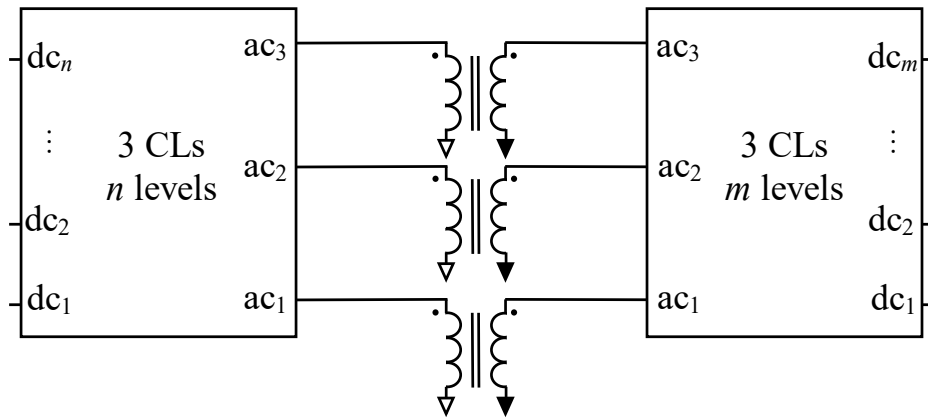


Figure 14 – Three-phase DAB dc-dc converter.

4.1.2.2. Three phase OBC

The selected onboard charger topology for the three-phase grid is presented in Figure 15. Similar comments apply as in the single-phase grid case. The main differences are that the dc-ac converter now features 3 CLs instead of 2, 3 inductors instead of 1, and that the total dc-link voltage v_{dc} must now exceed the peak value of the line-to-line grid voltage. In addition, while in the single-phase case the converter has to handle a component at twice the grid frequency in the instantaneous transferred power, in the three-phase case the instantaneous transferred power is constant and, thus, it does not contain the previously mentioned component. This leads to a simpler control and/or lower required dc-link capacitance.

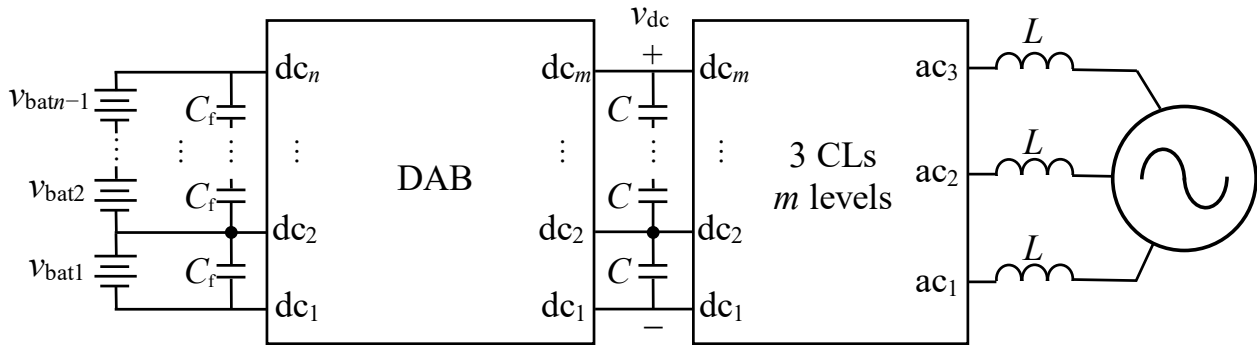


Figure 15 – Selected generic converter topology for the three-phase battery charger.

4.1.3. Integrated inverter-charger (IIC)

After an extensive literature review [12]–[22], this section discusses a selection of the identified conversion topologies that combine the traction and the onboard charging functions in one single conversion stage. These topologies basically reuse the traction inverter and the motor stator windings to recharge the battery from the ac grid.

It is established that the selected topologies must fulfill the following minimum requirements:

- The topology should not require the introduction of active power semiconductor devices in addition to those used for traction.
- The topology should not require the introduction of bulky capacitors or inductors/transformers in addition to those used in traction.
- The charging configuration should not require more than one motor. In vehicles where more than one motor is needed, the proposed IIC for one motor will be replicated for all motors and a proper coordinated and balanced control will be established (interleaving while charging, etc.).
- Charging should be possible through a single-phase or a three-phase connection to the ac grid.
- The charging process should be performed with unity displacement factor.
- The charging mode should produce a zero average torque over the rotor. Obviously, zero instantaneous torque is preferred, but at least zero average torque should be guaranteed.
- The topology should be able to operate in V2G mode, transferring power from the vehicle to the grid.

4.1.3.1. Topology 1, based on a symmetrical six-phase machine

The first topology is based on the use of a symmetrical six-phase machine with open-end windings, depicted in Figure 16. The topology is presented in Figure 17. It includes 6 CLs to form a dc-ac converter and the six-phase machine with open-end windings. Although the number of CLs is higher than usual (3), this leads to a lower CL and motor phase current rating and a higher system power density.

This topology requires a proper configuration of the connections of the machine open-end terminals to operate in the different modes. In traction or propulsion mode there are two possible configurations. Figure 18(a) shows the configuration for propulsion with two machine neutral points. Figure 18(b) shows the configuration for propulsion with one machine neutral point. Each

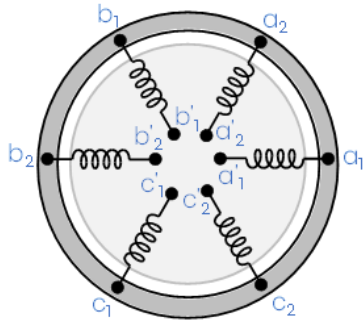


Figure 16 –Distribution of the stator windings in a symmetrical six-phase machine with open-end windings.

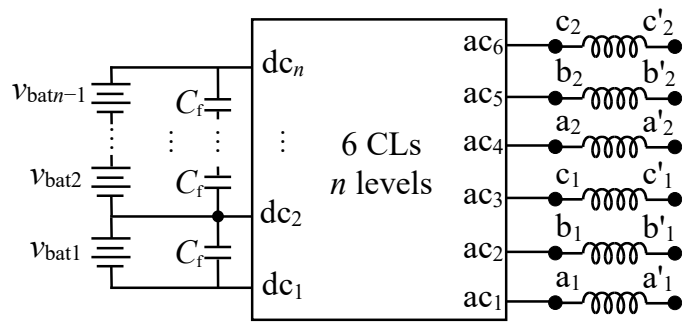


Figure 17 – Topology 1, based on a symmetrical six-phase machine with open-end windings.

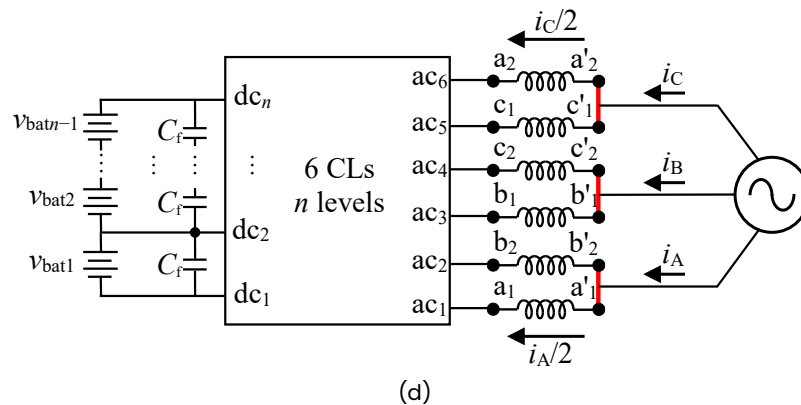
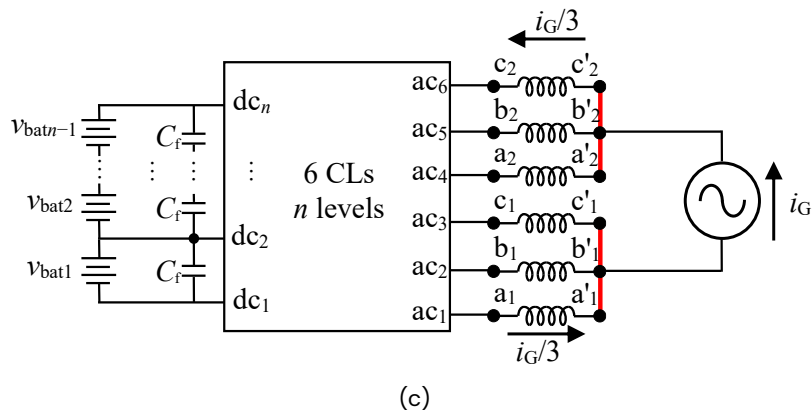
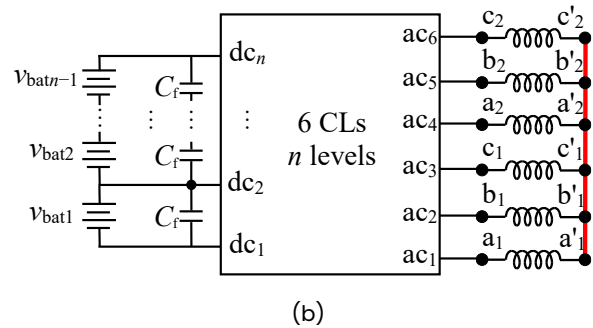
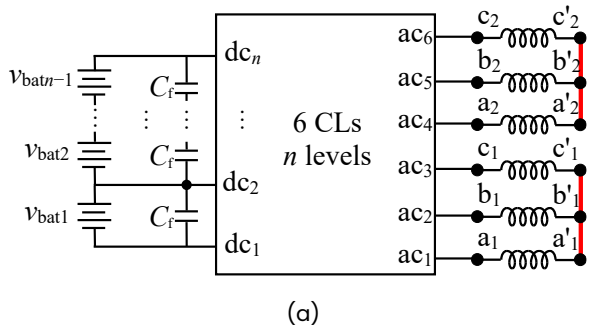


Figure 18 – Operating modes of topology 1. (a) Propulsion with two machine neutral points. (b) Propulsion with a single machine neutral point. (c) Single-phase charging/V2G. (d) Three-phase charging/V2G.

propulsion configuration has its benefits. While the system in Figure 18(a) enables generating a 15% higher machine ac voltage than the system in Figure 18(b), Figure 18(b) tolerates 3 CL faults versus only 2 in Figure 18(a).

Figure 18(c) and Figure 18(d) show the configurations to operate in single-phase and three-phase charging/V2G, respectively. In both cases, a zero instantaneous torque can be guaranteed.

Note that the red lines in Figure 18 indicate connections that are not fixed and that must be modified when switching between operating modes.

Variations of topology 1 can be conceived to reduce the hardware reconfiguration needs (the number of electrical connections to be changed in the inverter-motor to switch between operating modes) or to reduce the number of CLs. They are discussed in the following subsections.

4.1.3.1.1. Topology 1a

Figure 19 presents the first variant of topology 1. The connections of the motor terminals are fixed as indicated, so that no reconfiguration is required to operate in the different modes. Figure 20(a) shows the system in propulsion mode and Figure 20(b) shows the system operating in single-phase charging/V2G mode. Three-phase charging/V2G is not possible.

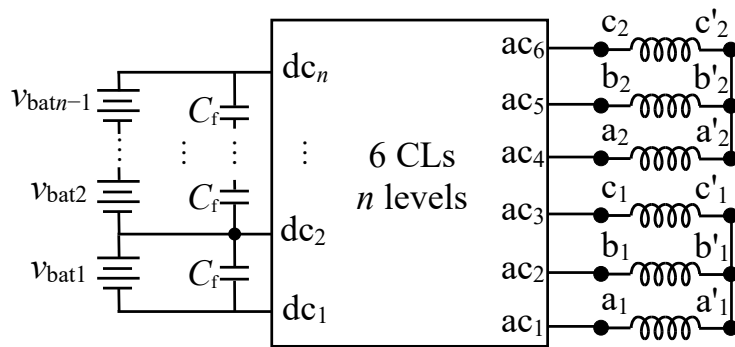


Figure 19 – Topology 1a.

4.1.3.1.2. Topology 1b

Figure 21 presents the second variant of topology 1 [18], [19]. The connections of the motor terminals are fixed as indicated, so that no reconfiguration is required to operate in the different modes. Figure 22(a) shows the system in propulsion mode. Figure 22(b) and Figure 22(c) show the system operating in single-phase and three-phase charging/V2G mode, respectively.

Although no reconfiguration is required and both single-phase and three-phase charging are possible, this topology features a 15% reduction in the maximum motor ac voltage, compared to the previous topologies, due to the need to avoid zero-sequence currents. In addition, it features a reduced leg fault tolerance, since only one CL can fail. Finally, in single-phase charging/V2G, the rated power is 2/3 of the power available for propulsion, since 1/3 of the CLs and phases are not used. This is not typically an issue, since the maximum allowed single-phase charging power is usually much lower than the nominal inverter power.

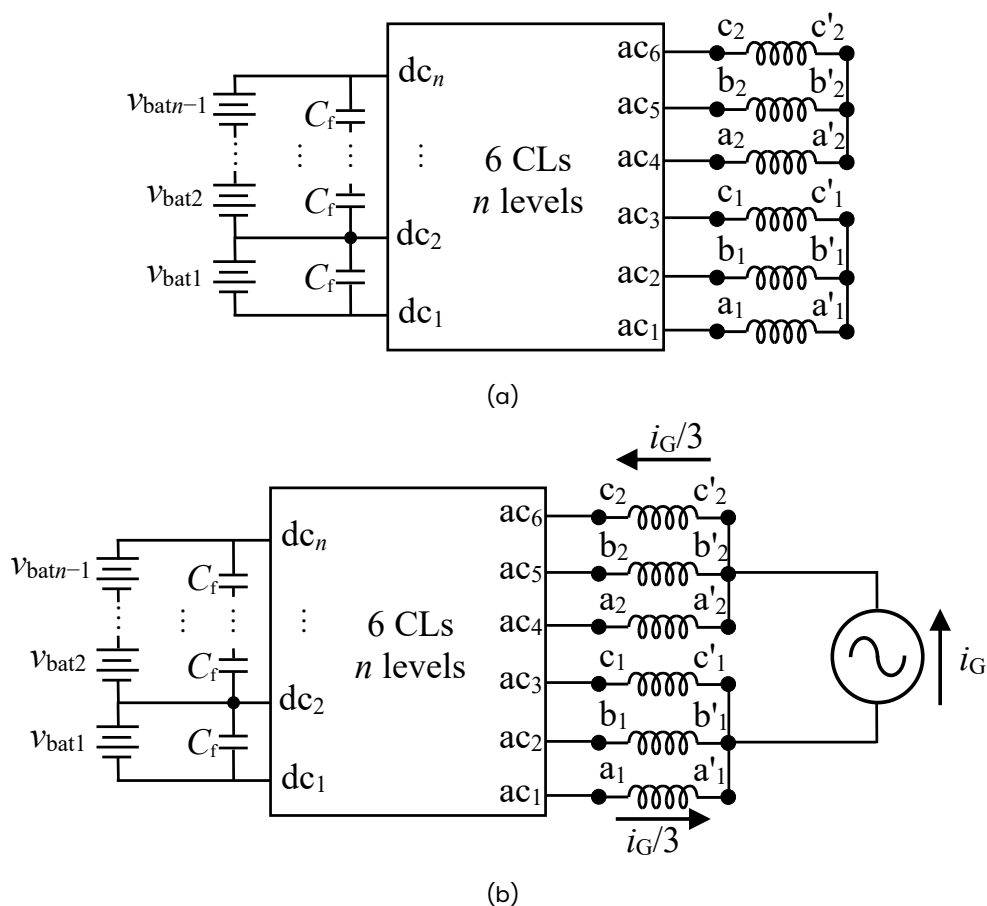


Figure 20 – Operating modes of topology 1a. (a) Propulsion. (b) Single-phase charging/V2G.

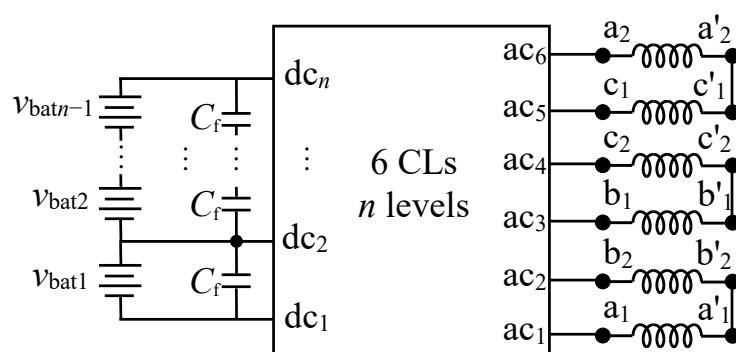


Figure 21 – Topology 1b.

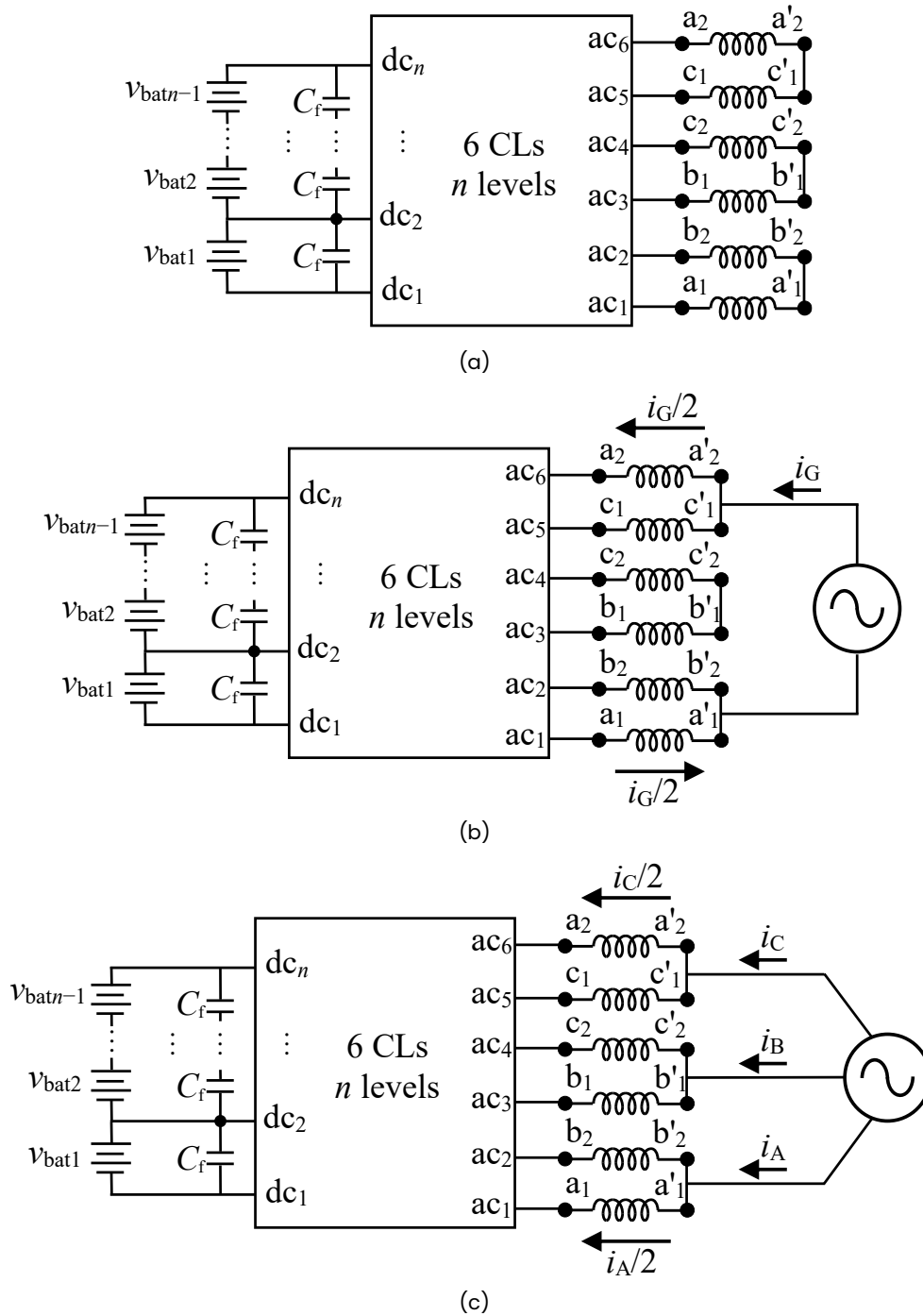


Figure 22 – Operating modes of topology 1b. (a) Propulsion. (b) Single-phase charging/V2G. (c) Three-phase charging/V2G.

4.1.3.1.3. Topology 1c

Figure 23 presents the third variant of topology 1. This topology requires only 3 CLs. However, it requires reconfiguration of the connection of the open-end machine terminals, the legs need a higher current rating (for the same propulsion power) and the topology has no fault tolerance.

Figure 24(a) shows the configuration to operate in propulsion mode. Figure 24(b) and Figure 24(c) show the configuration to operate in single-phase and three-phase charging/V2G mode,

respectively. Single-phase charging/V2G features zero instantaneous torque, but three-phase charging/V2G features non-zero instantaneous torque (zero average torque is guaranteed in all cases).

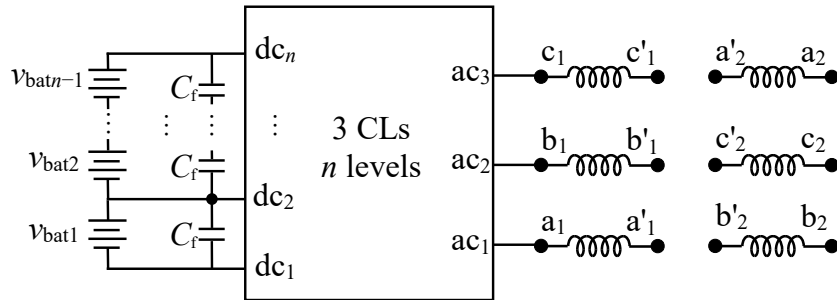


Figure 23 – Topology 1c.

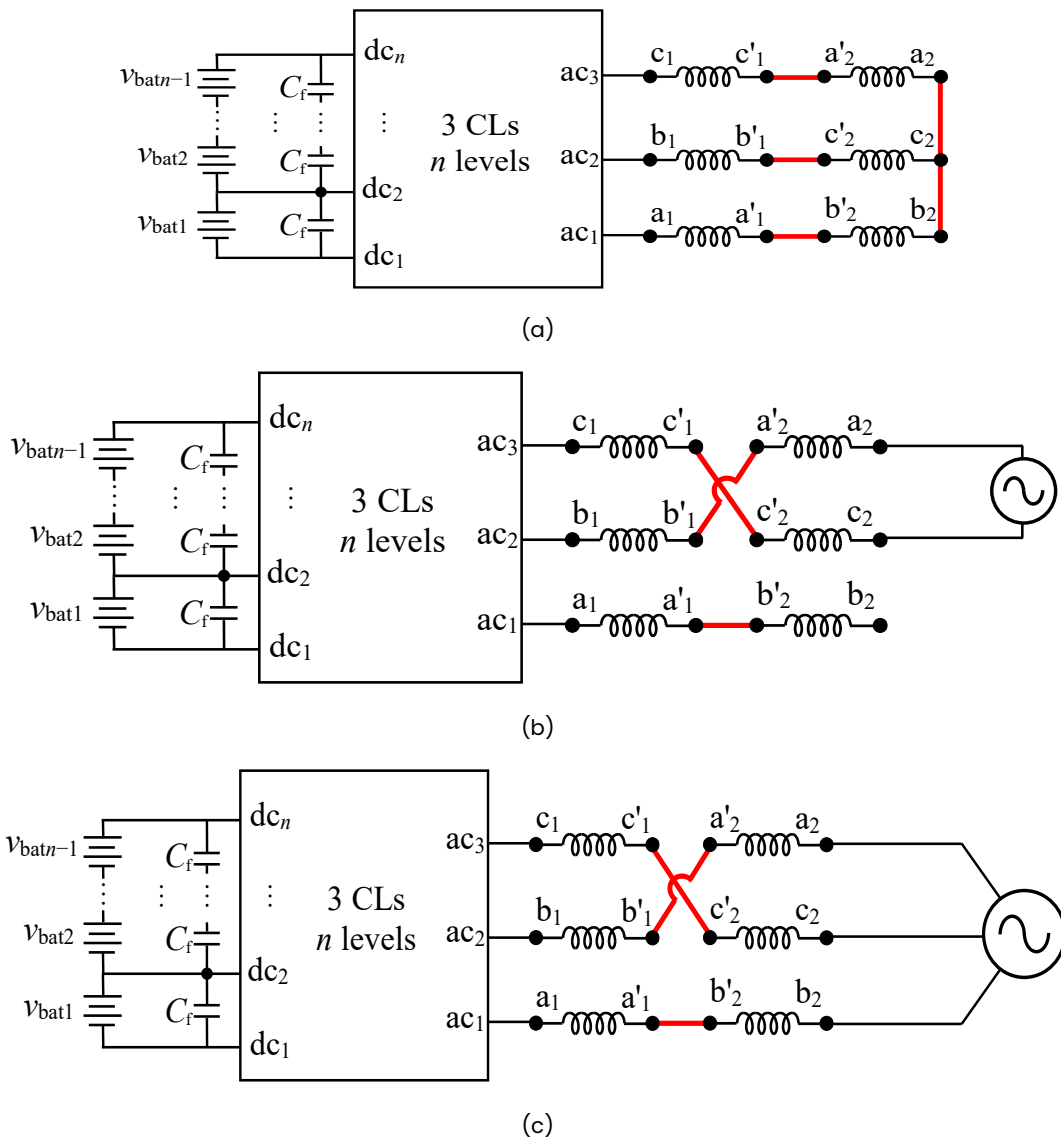


Figure 24 – Operating modes of topology 1c. (a) Propulsion. (b) Single-phase charging/V2G. (c) Three-phase charging/V2G.

4.1.3.1.4. Topology 1d

Figure 25 presents the fourth variant of topology 1. This topology offers galvanic isolation in charging mode, which is of interest to reduce the common-mode current, but it requires reconfiguration of the connection of the open-end machine terminals. Since the machine is not designed to have a good coupling between windings, as this is the optimal design condition for traction, the charging mode may not be highly efficient.

Figure 26(a) shows the configuration to operate in propulsion mode and Figure 26(b) shows the configuration to operate in single-phase charging/V2G mode. The topology can be operated in single-phase charging mode producing a zero instantaneous torque. Three-phase charging/V2G is not possible because it would lead to non-zero average torque.

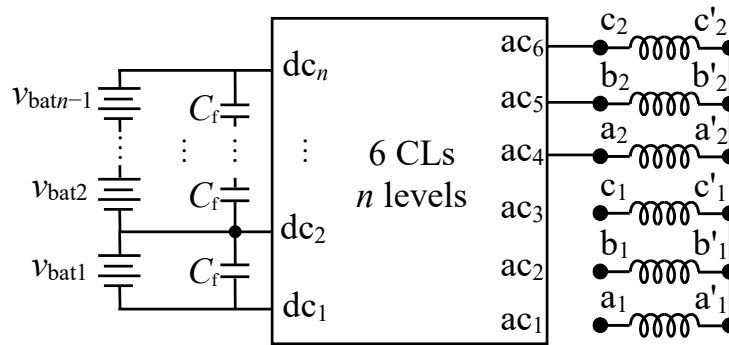
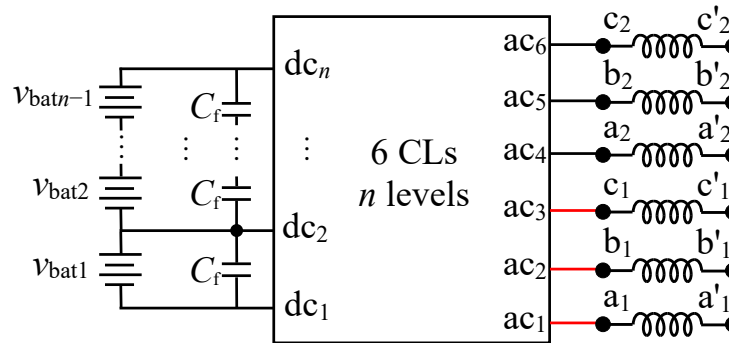
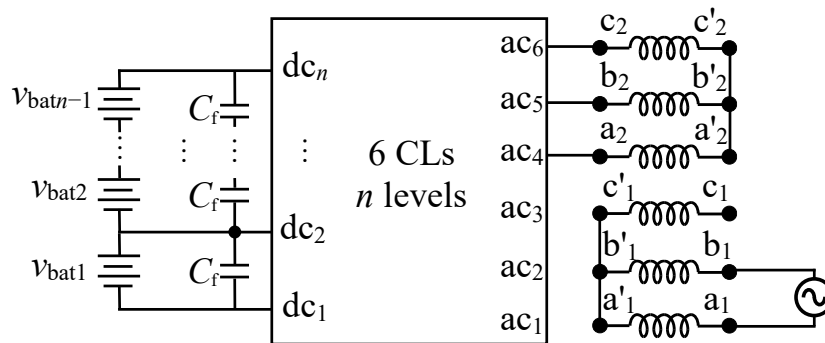


Figure 25 – Topology 1d.



(a)



(b)

Figure 26 – Operating modes of topology 1d. (a) Propulsion. (b) Single-phase charging/V2G.

4.1.3.2. Topology 2, based on an asymmetrical six-phase machine

The second topology is based on the use of an asymmetrical six-phase machine with open-end windings, depicted in Figure 27. Each pair of homologous windings are separated 30° . The topology is presented in Figure 28. It includes 6 CLs to form a dc-ac converter and the six-phase machine with open-end windings. Although the number of CLs is higher than usual (3), this leads to a lower CL and motor phase current rating and a higher system power density. Compared to topology 1, the use of an asymmetrical machine enables a reduction of the torque ripple in propulsion mode at the expense of losing zero instantaneous torque in three-phase charging and reducing the number of possible topology variants.

This topology requires a proper configuration of the connections of the machine open-end terminals to operate in the different modes. In traction or propulsion mode there are two possible configurations. Figure 29(a) shows the configuration for propulsion with two machine neutral points. Figure 29(b) shows the configuration for propulsion with one machine neutral point. Each propulsion configuration has its benefits. While the system in Figure 29(a) enables generating a 15% higher machine ac voltage than the system in Figure 29(b), Figure 29(b) tolerates 3 CL faults versus only 2 in Figure 29(a).

Figure 29(c) and Figure 29(d) show the configurations to operate in single-phase and three-phase charging/V2G, respectively. A zero instantaneous torque can only be guaranteed in single-phase charging/V2G.

Again, note that the red lines in Figure 29 indicate connections that are not fixed and that must be modified when switching between operating modes.

Variations of topology 2 can also be conceived to reduce the reconfiguration needs or to reduce the number of CLs. One of them is discussed in the following subsection.

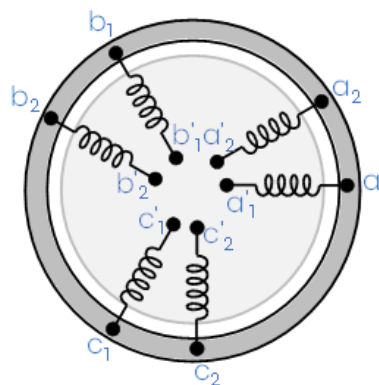


Figure 27 – Distribution of the stator windings in an asymmetrical six-phase machine with open-end windings.

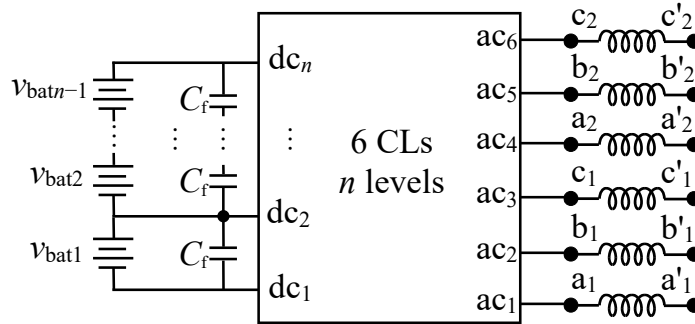


Figure 28 – Topology 2, based on an asymmetrical six-phase machine with open-end windings.

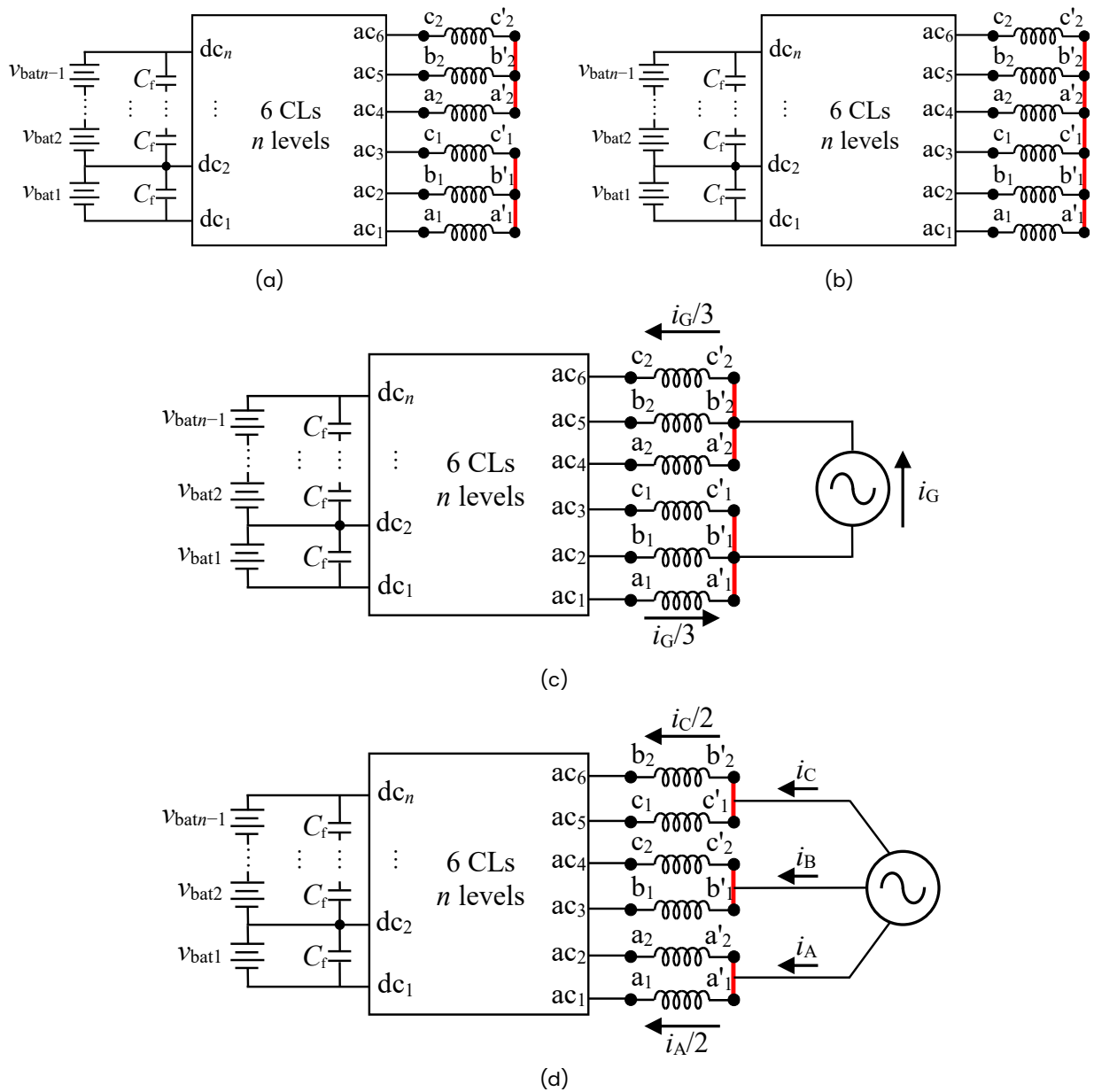


Figure 29 – Operating modes of topology 2. (a) Propulsion with two machine neutral points. (b) Propulsion with a single machine neutral point. (c) Single-phase charging/V2G. (d) Three-phase charging/V2G.

4.1.3.2.1. Topology 2a

Figure 30 presents a variant of topology 2. The connections of the motor terminals are fixed as indicated, so that no reconfiguration is required to operate in the different modes. Figure 31(a) shows the system in propulsion mode and Figure 31(b) shows the system operating in single-phase charging/V2G mode. Three-phase charging/V2G is not possible.

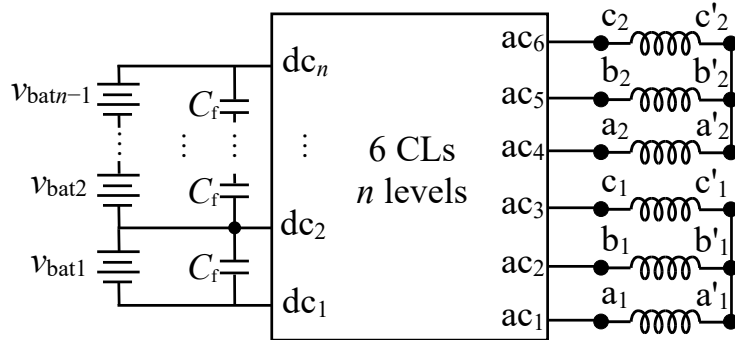
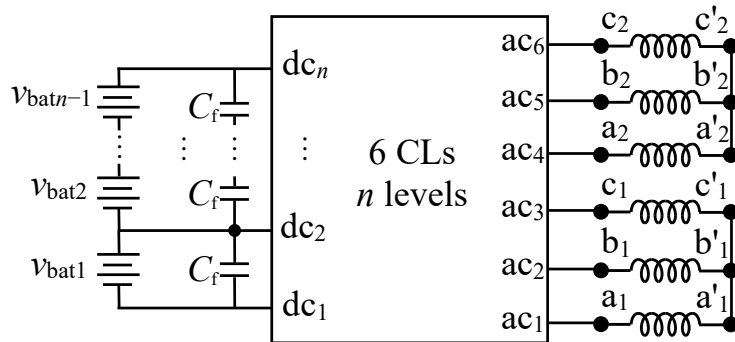
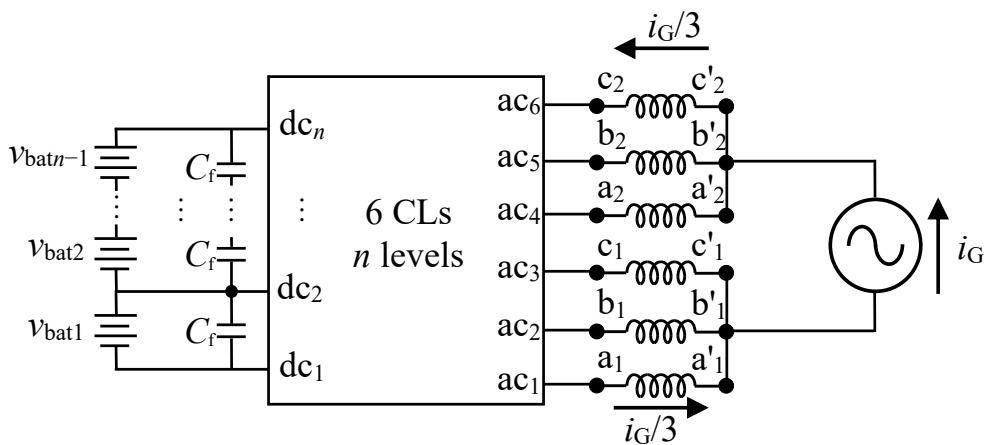


Figure 30 – Topology 2a.



(a)



(b)

Figure 31 – Operating modes of topology 2a. (a) Propulsion. (b) Single-phase charging/V2G.

4.1.3.3. Topology 3, based on a nine-phase machine

The third topology is based on the use of a nine-phase machine with three neutral points, one for each of the 3 sets of three-phase windings. The topology is presented in Figure 32. It includes 9 CLs to form a dc-ac converter and the nine-phase machine. Although the number of CLs is higher than usual (3), this leads to a lower CL and motor phase current rating and a higher system power density. The topology is capable of propulsion and single/three-phase charging without hardware reconfiguration and features zero instantaneous torque production during charging.

Figure 33(a) shows the system in propulsion mode. Figure 33(b) and Figure 33(c) show the system operating in single-phase and three-phase charging/V2G mode, respectively.

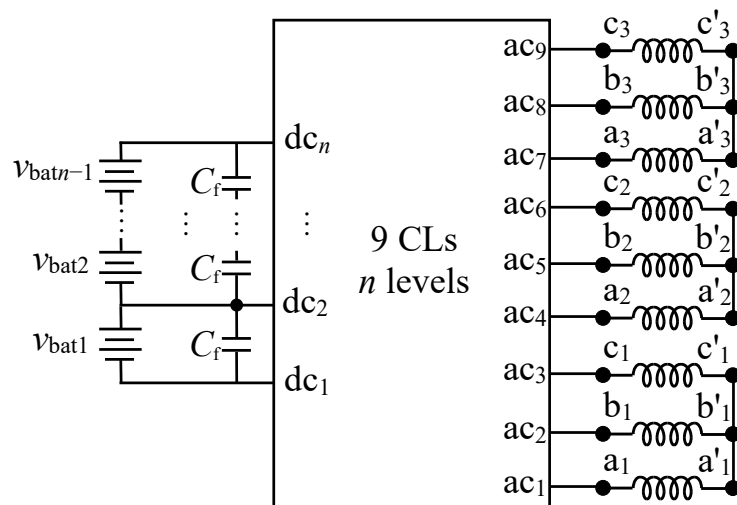


Figure 32 – Topology 3.

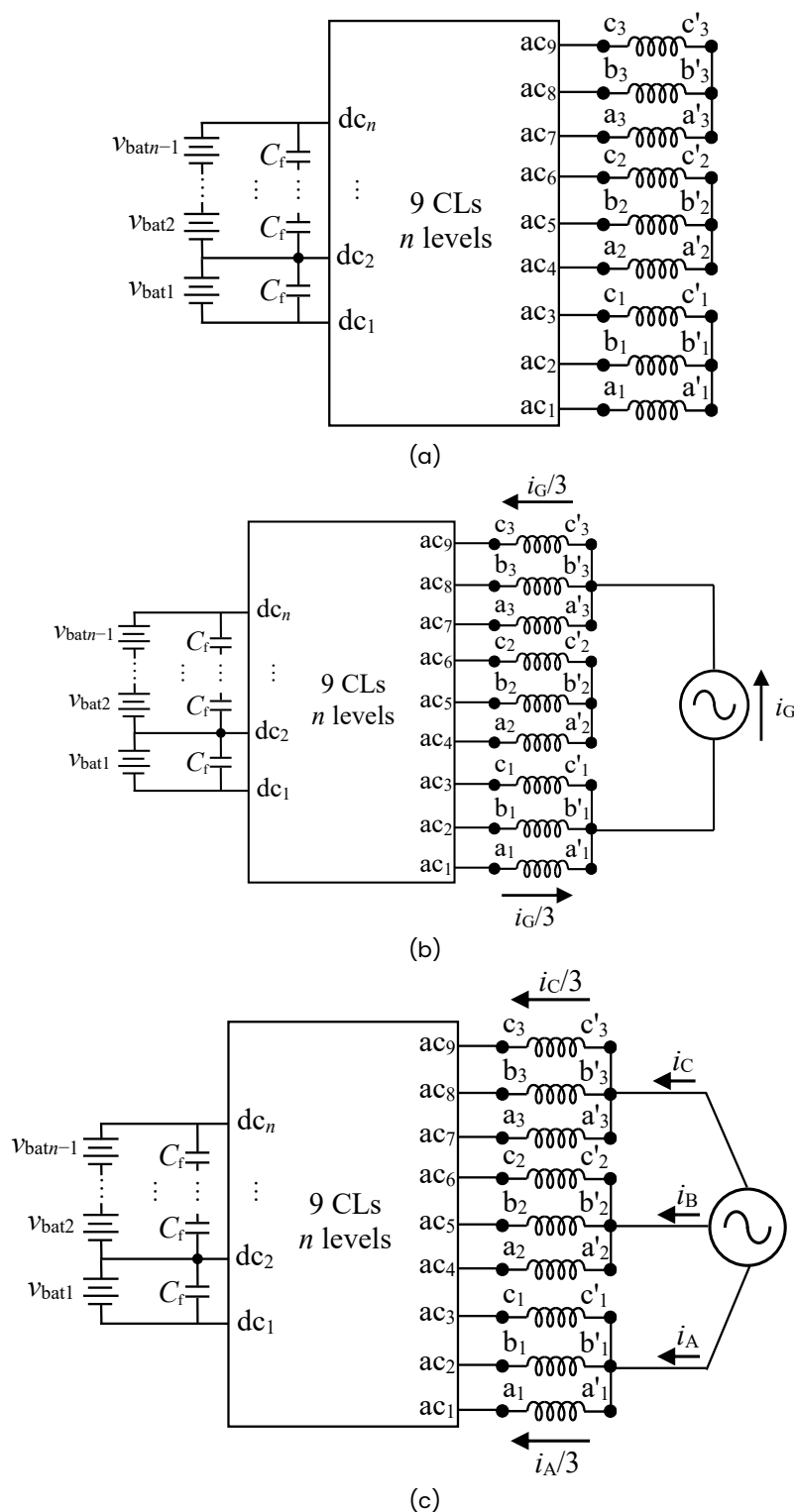


Figure 33 – Operating modes of topology 3. (a) Propulsion. (b) Single-phase charging/V2G. (c) Three-phase charging/V2G.

4.1.3.4. Summary of the main features of the IIC topologies

Table 3 presents a summary of the most relevant features of the different topologies presented and discussed in the previous sections: 1, 1a, 1b, 1c, 1d, 2, 2a, and 3. In topology 1 and its variants, the number of machine phases is 6, although this machine could be seen as a dual three-phase machine.

Table 3 – Summary of IIC topology features.

Topology	1	1a	1b	1c	1d	2	2a	3
Number of machine phases	6	6	6	6	6	6	6	9
Number of converter legs	6	6	6	3	6	6	6	9
Single-phase charging	Y	Y	Y	Y	Y	Y	Y	Y
Three-phase charging	Y	N	Y	Y	N	Y	N	Y
Zero average torque in charging (single phase / three-phase)	Y / Y	Y / –	Y / Y	Y / Y	Y / –	Y / Y	Y / –	Y / Y
Zero instantaneous torque in charging (single-phase / three-phase)	Y / Y	Y / –	Y / Y	Y / N	Y / –	Y / N	Y / –	Y / Y
Charging power to propulsion power (single-phase / three-phase)	100%/100%	100% / –	66% / 100%	66% / 100%	33% / –	100%/100%	100% / –	66% / 100%
Hardware reconfiguration needed	Y	N	N	Y	Y	Y	N	N
Vehicle to grid	Y	Y	Y	Y	Y	Y	Y	Y
Leg Fault-Tolerance (propulsion)	3	2	1	N	2	3	2	4
Galvanic isolation in charging	N	N	N	N	Y	N	N	N

4.1.4. Battery interfacing converter (BIC)

The battery interfacing converter is the power converter within an EV in charge of feeding the low-voltage (LV) service battery bank from the high-voltage (HV) traction battery bank. It is of interest that the BIC also allows the power flow from the service battery to the traction battery, just in case it is needed.

The selected BIC topology is presented in Figure 34. It consists of a DAB dc-dc converter controlling the power flow between both battery banks, while ensuring the SoC balancing of the battery modules. Not all modules in the HV traction battery need to be connected. The DAB can be single-phase, as depicted in Figure 13, or three-phase, as depicted in Figure 14. It is composed of 2/3+2/3 CLs and a single-phase/three-phase transformer. The number of levels on each side (n and m) can be different. The transformer provides galvanic isolation and an extra impedance to limit the leakage common-mode currents.

Additional inductors and capacitors can be connected in series or parallel at the DAB transformer to block dc voltage components or to enable operation in resonant mode (e.g., the so-called LLC and CLLC topologies).

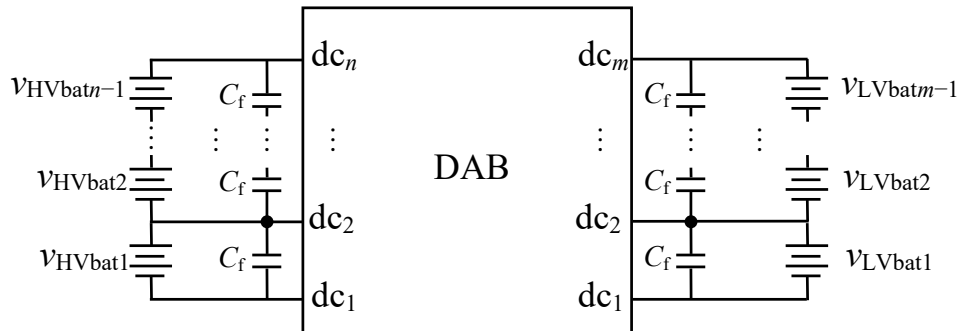


Figure 34 – Selected generic BIC topology.

4.2. Control

The FC receives as inputs the FC command and the state of the CLs, and generates as outputs a suitable set of CL commands and the FC state to be reported to a higher-level controller. This tertiary control essentially involves a closed-loop regulation of the commanded variables followed by a modulator, [23]–[39], as shown in Figure 35. The closed-loop control can be divided into two sections:

- The closed-loop control in charge of regulating the global power flow between the external systems interfaced through the power converter. This control generates the commands for the differential-mode component of the CL ac-terminal voltages which are sent to the modulator.
- The closed-loop control in charge of regulating the imbalance among dc-link capacitor voltages or among battery module SoC. This control generates the commands of the neutral-point currents, which are sent to the modulator. These commands typically affect the common-mode component of the CL ac-terminal voltages.

The first closed-loop control can be the usual in typical two-level conversion systems, while the second is more specific to the multilevel NPC topology [27]–[29].

It is recommended to select a modulator that can guarantee zero dc-link neutral-point currents, on average in every switching cycle, such as those modulators based on virtual vectors [23]–[25], to be able to have a tight control of the dc-link with small dc-link capacitors. Virtual-vector pulse width modulations have been defined for dc-ac conversion with any number of levels and phases. Modulations with zero dc-link neutral-point currents, on average in every switching cycle, have also been defined for dc-dc conversion with any number of levels [29]. All the aforementioned modulation strategies can be implemented with simple equations and with a low computational effort.

If the self-powering solution selected for the switching cells does not allow a permanent SC on state, the selected modulation strategy should guarantee that no SC stays on for longer than the maximum specified time [26].

Advanced modulation and closed-loop controls can be devised to assess and eventually manage the state-of health (SoH) of the converter and the external systems connected to it, such as batteries and motors (e.g., [39]).

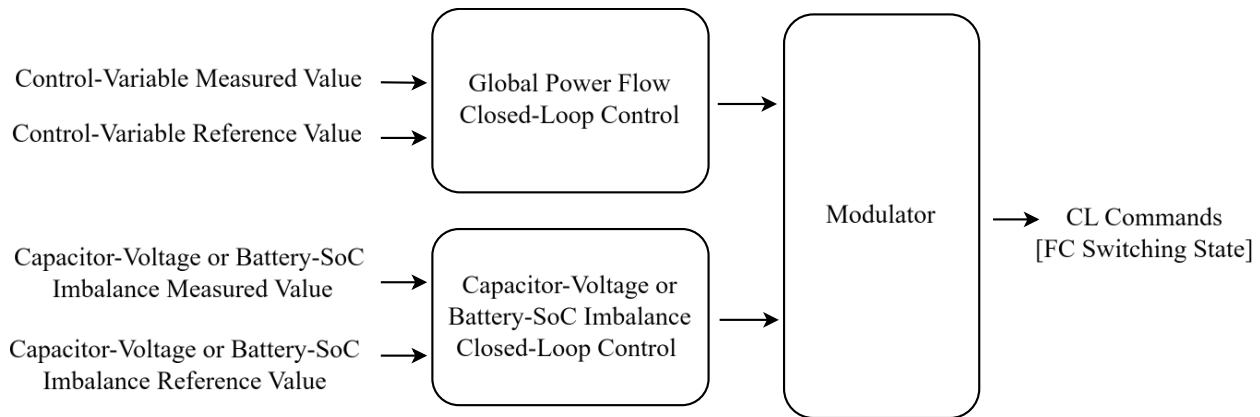


Figure 35 – Basic structure of the FC control (tertiary control).

5. Conclusion

This document has presented guidelines for the design of power conversion systems for electric vehicles following the modular and scalable approach devised in SCAPE. These guidelines, provided at all three module levels (SC, CL and FC), aim to facilitate the design process and to ensure that critical aspects are considered. This document presents a first version of these guidelines arising from the current knowledge and experience of the SCAPE team. They are open to be reviewed and extended in the future, with the continuous goal of simplifying and standardizing the EV power converter design process as much as possible, while improving the electrothermal performance, increasing the power density, improving the reliability, and reducing the costs of the designs.

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