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POWER ELECTRONIC ARCHITECTURE OF SUPPLY SYSTEMS FOR ELECTRIC VEHICLE CHARGING

ABSTRACT *The paper discusses the basic requirements and power electronics converters used in charging systems for electric vehicle battery charging stations. Architecture of power systems with AC bus and DC bus are characterized as well as centralized and distributed. Possible power combinations with local energy stores are described. It also presents a modern architecture based on cascade converters allowing the elimination of a medium voltage transformer. The considerations are illustrated by an exemplary four-level converter with 1.2 MW power developed and constructed at the Electrotechnical Institute (IEL) in Warsaw.*

Keywords: *Power electronics, Electromobility, architecture of supply systems for EV charging*
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1. INTRODUCTION

Recently, Electromobility is the subject of extensive research and development both in the world and in the country. The most important factors for the development of electric vehicles (Battery Electric Vehicle – BEV) are:

- no exhaust and noise,
- low cost of expolaitation compared to cars with internal combustion engines (1:3),
- high efficiency (electric motors > 90%, internal combustion of 35 – 40%),
- simple construction of electric drive without gearbox and clutch,
- the ability to recover energy during braking and recharging the batteries (depending on the driving style from 5 to 20%),
- possibility of charging batteries during periods of reduced demand for electricity (at night and at noon) – which reduces costs.

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However, despite of significant advances in BEV technology, there are still restrictions on their mass use. These include, above all:

- high price of electric cars (about 30 – 50% higher than its equivalent with an internal combustion engine),
- small range based on one battery charging,
- long battery charging time,
- lack of developed battery charging infrastructure,
- charging infrastructure requires generation of an additional energy (power).

Many of these problems help to solve advanced and modern power electronics. Therefore, the Power Electronics system has broadly entered Electromobility in the area that can be divided into three specific groups: architecture of the power supply of charging station (in particular ultra-fast charging), battery charger systems themselves, and regulated electric drives with AC motors. However, in this paper, due to the space limitation, we discuss only the architecture of power systems.

The infrastructure for charging electric vehicles, its costs, availability and performance are very important factors that directly affect the smoothness of the transition to Electromobility and have a wider application. There are varieties of charging technology for electric vehicles, standards, requirements, different technological approaches and different charging levels (both in terms of power and time). Table 1 presents the classification and parameters as well as the assigned types of sockets currently used in charger terminals.

TABLE 1

Types of charging terminals[1]

Grid connection		**Normal charging 1-phase grid**	**Normal charging 3-phase grid**	**Fast and ultra fast charging**	
		U = 230 V AC I = 16 A P = 3,7 kW	U = 400 V AC I = 32 A P = 22/43 kW	U = 500 V AC I = 250 A **P = 220 kW**	U = 600 V DC I = 400 A **P = 240 kW**
	Type of supply socket	Typ 2 Mennekes	Typ 2 Mennekes	CCS	CCS CHAdeMO
Chargig time	**Battery capacity**	(A)	(B)	(C)	(C)
	100 kWh	ca. 27 h	4.5/2.5 h	ca. 30 min	ca. 25 min
	40 kWh	ca. 11 h	60/120 min	ca. 10 min	ca. 10 min
	20 kWh	ca. 5,5 h	30/60 min	ca. 5 min	ca. 5 min
	10 kWh	ca. 3 h	15/30 min	< 5 min	< 5 min

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[1] According to IEC 61851-1, VDE 0122-1

2. REQUIRED CHARGING POWER

To ensure fast and ultrafast charging of BEV batteries, a sufficiently large power chargers are necessary, which results from the basic laws of physics: $P = E/t$, where: P – charger power in W, E – battery energy in Wh, t – charging time in h. Therefore, for example, to charge 80% of the 100 kWh battery (Tesla S 100D car) in 15 min. a charger with power of 320 kW is required (Fig. 1).

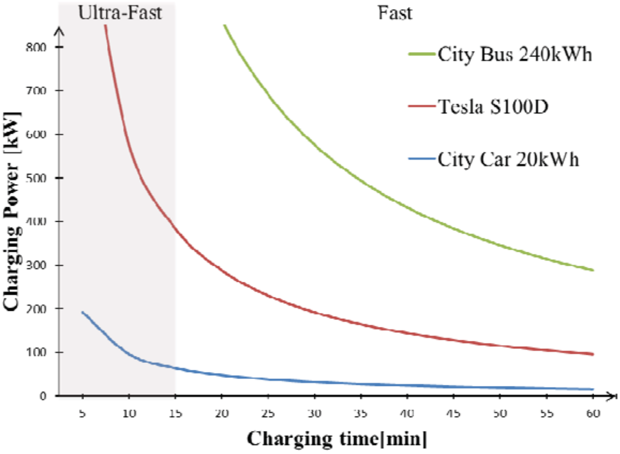

Fig. 1. Required charging power as a function of charging time up to 80% of battery capacity

If there are 10 ultra-fast charging points on the public station, the simultaneous charging requires 10 x 320 kW = 3.2 MW of power. Of course, even more power is required when charging electric bus batteries or ultra-short charging times (< 5 min) [1, 2]. The required power level may not be available in every location, especially in areas with poorly developed electricity networks or in cities with high density of charging stations. It may also not be optimal in the sense of using the available power. Therefore, modern concepts of charging station energy architecture are currently being developed, taking into account Renewable Energy Sources – RES and local energy storage – LES.

3. BASIC TOPOLOGIES OF POWER ELECTRONIC CONVERTERS

Prior to the presentation of power supply architecture, the basic topologies of the converters constituting their main components will be discussed. Generally, they cover two groups: AC-DC active rectifiers and DC-DC converters.

Figure 2 shows the topologies of AC-DC active rectifiers, which, thanks to the use of power transistors (IGBT-Isolated Gate Bipolar Transistor or recently MOSTEF SiC) and passive filters, as well as appropriate digital signal processing (DSP) systems provide a number of important advantages from the point of view of the power supply grid as [3]:

- sinusoidal shape of current drawn from the grid,
- they constitute a linear receiver for the network that meets the requirements of standards with a low harmonic content factor (THDi ≤ 5%),
- the ability to independently control of active and reactive power flow while ensuring high dynamics of control,
- in particular, the ability to work with a unit power factor, i.e. no reactive power consumption from the grid,
- provide bi-directional energy flow between the AC and DC sides.

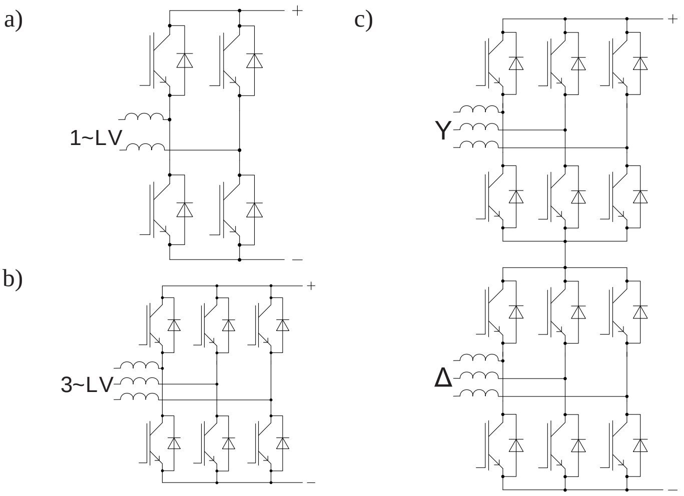

Fig. 2. Topologies of bi-directional active AC-DC rectifiers:
a) single-phase bridge, b) three-phase bridge, c) 12-pulse combined system

In grid supplied systems, except for low power systems (Fig. 2a), three-phase active rectifiers are usually used (Fig. 2b) and in the higher power range combined 12-pulse systems powered from MV/LV transformer with double secondary winding △ and Y (Fig. 2c). Transistor switches can be replaced by GTO thyristors, which are characterized by lower conduction losses, however, due to the low switching frequency, they require large induction filters. In the group of DC-DC voltage converters, non-isolated circuits (Fig. 3) and systems isolated with HV transformer are distinguished (Fig. 4).

As a final stage of DC voltage converter supplied from the DC bus, all known topologies can be used, e.g., Buck, Buck-Boost, Cuk, SEPIC and ZETA for bi-directional energy flow. Figure 3 presents the three most frequently used topologies, with the variant in Figure 3b generating the polarization change from "+" to "-" at the output, which is not always desirable.

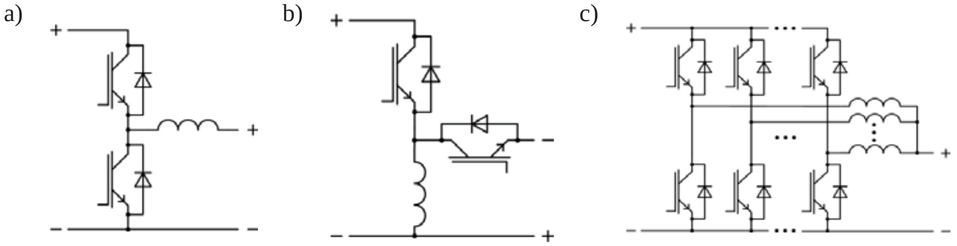

Fig. 3. Topologies of non-isolated DC-DC voltage converters:
a) Buck-Boost DC-lowering and decreasing converter, b) Buck-Boost DC-lowering converter with polarity change of the output voltage, c) interleave converter

An efficient solution, in particular in the power range above 100 kW, is the division of energy flow into *n* identical sections (Fig. 3c). This significantly reduces the current pulsation due to the technique of shifting the voltage pulses, and also ensures high efficiency of 98.5% and easy optimization of parameters and dimensions thanks to the modular design.

There are many topologies with an HF isolation transformer. Figure 4 shows two of them. If two bridges are independently modulated, then such topology is called DAB (Dual Active Bridge) and provides bi-directional energy flow and the ability to work at variable primary and secondary voltage ranges, being an universal solution. In addition, you can use a resonant technique to reduce switching losses in transistors and electromagnetic interference (EMI). The three-phase DAB versions are also used.

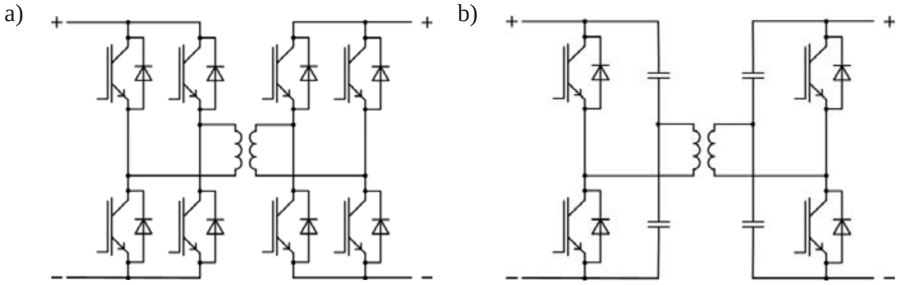

Fig. 4. Topologies of bi-directional DC-DC converters with HV isolating transformer:
a) bridge circuit, b) half-bridge circuit

4. EXAMPLES OF POWER ARCHITECTURES

There are many solutions of power systems architecture characterized by the features listed in Figure 5.

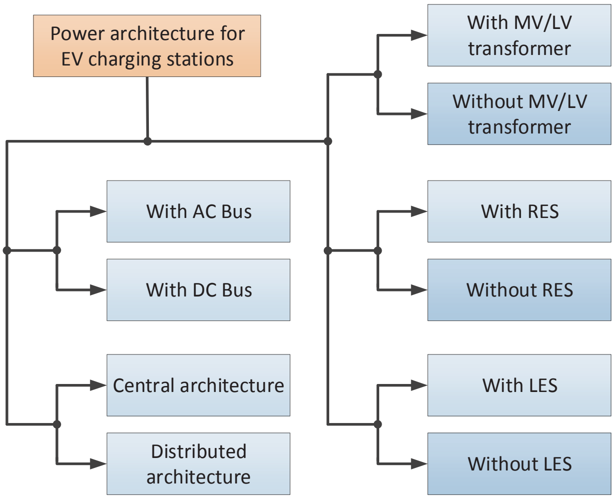

Fig. 5. Characteristic features of the classification of charging station architecture.
RES – Renewable Energy Sources, LES – Local Energy Storages

Many of the solutions used in practice, include several of the features listed, so strict classification is not used. Selected examples of charging station power systems will be presented below.

4.1. Systems supplied from low voltage grid LV (Fig. 6)

When using a low-voltage public grid (LV) of low-power charging systems (Level (A) in Tab. 1), single-phase systems are used (Fig. 6). However, in the version with a 50 Hz grid instead of isolation transformer (Fig. 6a) a cheaper, non-isolated DC-DC voltage converter can be used (see eg. Fig. 4). However, in the version from Fig. 6b), the isolation transformer is placed in the DC-DC converter (Fig. 4) which, with a switching frequency of 20 kHz and higher, allows a significant reduction of its weight and overall dimensions. For level chargers (B) from Table 1, identical power supply architectures can be used, but with a three-phase active rectifier in a bridge system (Fig. 2b).

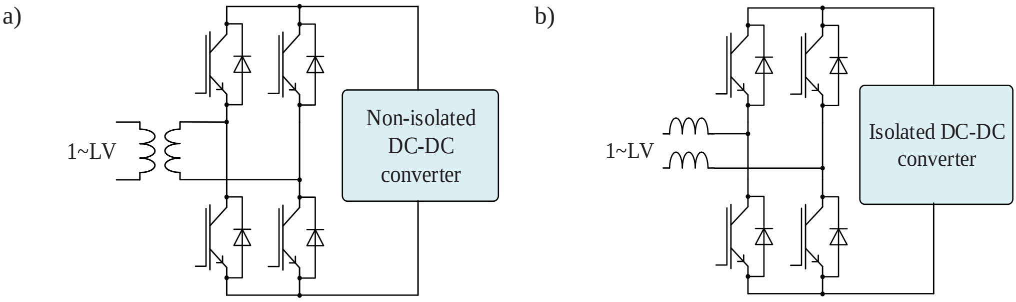

Fig. 6. Single-phase power supply architecture with bi-directional DC-DC converter:
a) with a 50 Hz isolating transformer on the mains side, b) with an HF isolation transformer in DC-DC side

4.2. Architecture of systems supplied from medium voltage grid MV (Fig. 7)

In fast and ultrafast charging systems (level (C) in Tab. 1), medium voltage MV/LV transformer is used, which supplies the common AC bus (Fig. 7a) or DC bus (Fig. 7b) [4, 5]. Currently, production and transmission of electricity is based on AC current and energy is distributed to consumers (lighting, electric motors, household appliances, computers, etc.) supplied from AC installations. Therefore, the architecture of BEV vehicle charging systems is based on a common AC bus to enable the management and distribution of energy between charger systems, renewable energy

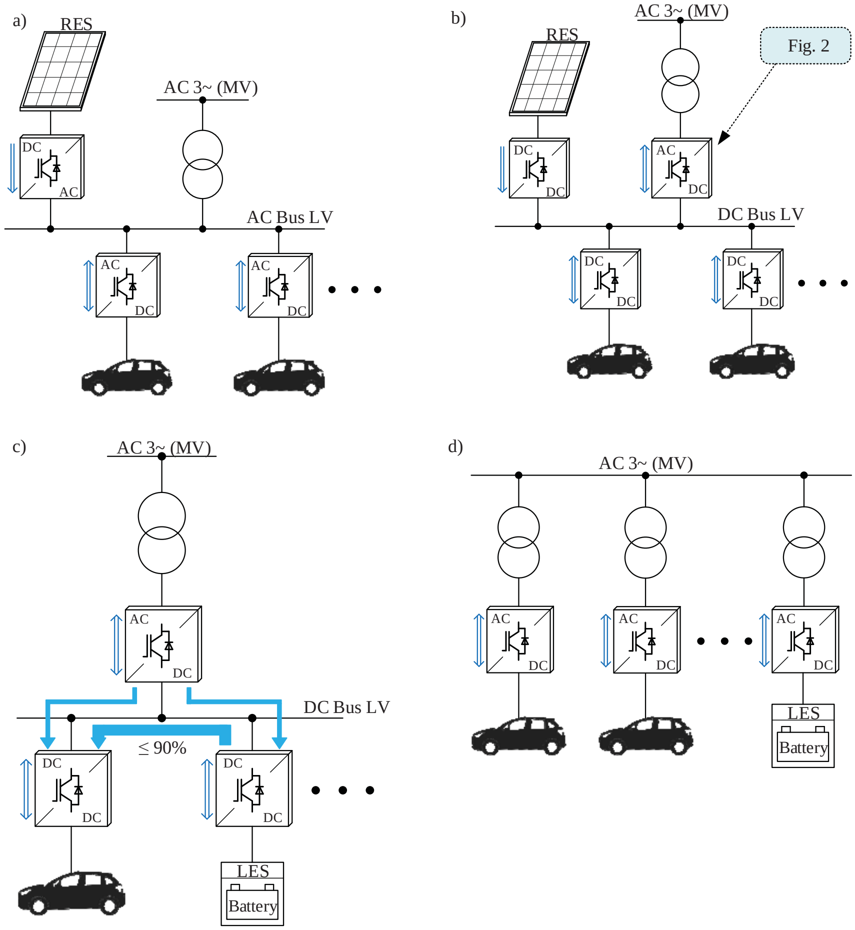

Fig. 7. Examples of three-phase power supply systems:
a) central architecture with a shared AC bus, b) central architecture with a common DC bus, c) DC central architecture with a local LES energy store, and d) an example of distributed architecture.
The arrows indicate the direction of energy flow in the power electronic converter

sources and the power grid, as exemplified in Fig. 7a). Electricity is distributed and controlled through appropriate bi-directional AC-DC active rectifiers that can also perform the function of intelligent networks enabling the return of energy from batteries to the network (*V2G – Vehicle to Grid* functionality). Recently, due to the development of distributed energy and renewable energy, interest in energy distribution and management based on DC current has increased [4]. In this architecture, shown in Figure 7c, one large AC-DC active high efficiency rectifier connected on the LV AC side realizes a common DC voltage supply bus. Therefore BEV loaders are connected by bi-directional DC-DC voltage converters, not as in architecture with AC bus through AC-DC active rectifiers (Fig. 7a). This has a beneficial effect on both overall efficiency and costs.

As mentioned in Section 2, the main problem of implementing ultra-fast charging stations is the amount of required power that must be supplied from the grid to the charging point. Therefore, Figure 7c shows the version of the architecture equipped with a local energy storage (supercapacitors, electrochemical batteries, etc.) which, connected to the DC bus, relieves the main AC grid [9, 10]. In this system, the energy required for ultra-fast charging of BEV batteries is supplied both from the grid by the AC-DC active rectifier, as well as from the LES storage by the DC-DC converter. The energy flowing from the grid is constant and much smaller than required for ultra-fast charging. Thanks to this, the AC-DC active AC charger can be dimensioned for much lower power rating.

The distributed architecture shown in Figure 7d is opposed to central architecture. As you can see, it is based on individual MV/LV network transformers, but requires only one stage of energy conversion in AC-DC active rectifiers. Other advantages of distributed architecture include: distribution of power grid load, shorter cables, lower losses, unification and redundancy, higher reliability, lower costs due to the scale effect.

4.3. Modern power supply architecture without MV/LV transformer with cascade converter and local energy storage (Fig. 8)

Recently, intensively developed cascaded AC-DC and DC-AC multi-level converters have the following advantages [6]:

- ability to work at medium and high voltages (> 1000 V),
- reduction of harmonic content by multiplying the frequency of the output voltage relative to the frequency of switching of the power transistors (the possibility of eliminating the outgoing passive filters),
- high efficiency,
- modular design, higher reliability,
- reduction of costs and dimensions.

Thanks to these advantages, cascade converters are used in distribution systems enabling the connection to the medium voltage network without the use of large, heavy and expensive MV/LV transformers [7, 8, 11]. Then the problem of providing galvanic isolation is shifted to the low voltage level in DC-DC voltage converters (Fig. 4). An example of such a modern power supply architecture is shown in Figure 8, whereas in version a) the output of each module can be connected directly to the vehicle, while in version b) the module outputs, in order to increase the current, are connected in parallel, reducing the number of vehicles connected to three (one per phase). Each module (Fig. 8c)) has a bi-directional AC-DC active rectifier connected to the energy store (eg. batteries, supercapacitors) on the network side and an isolated DC-DC voltage converter on the output.

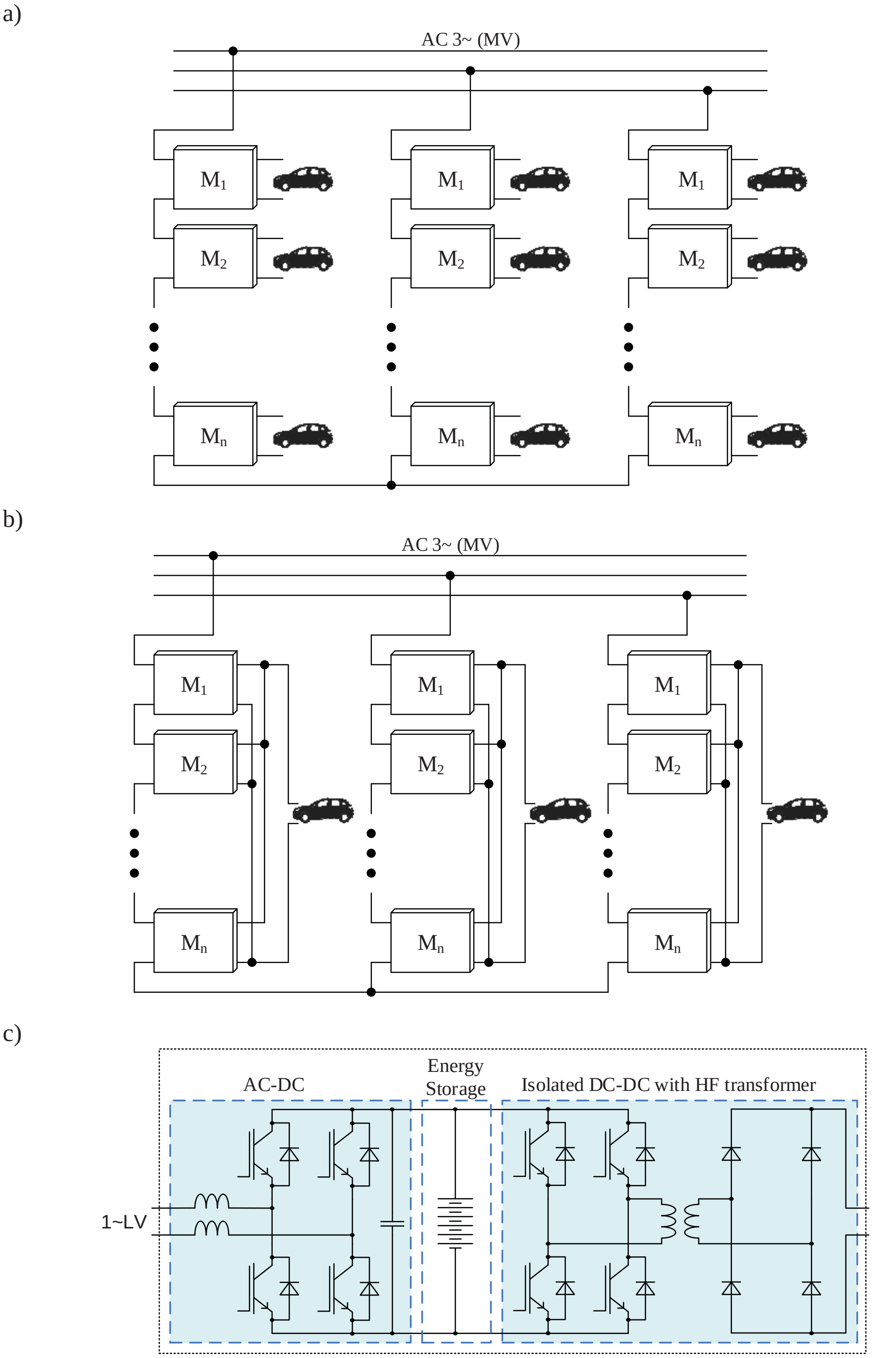

Fig. 8. Power supply architecture without MV/LV transformer based on a modular cascade converter: a) with vehicles loaded from each module, b) with vehicles loaded from each branch (phase), c) topology of the converters of each module

To ensure proper operation of the charging station's power supply architecture, a hierarchical control system (Fig. 9) is used, consisting of three levels:

- control of active and reactive power flow,
- control of the charge level adjustment (SoC – State of Charge) of the battery of local store,
- controlling the BEV battery charging process.

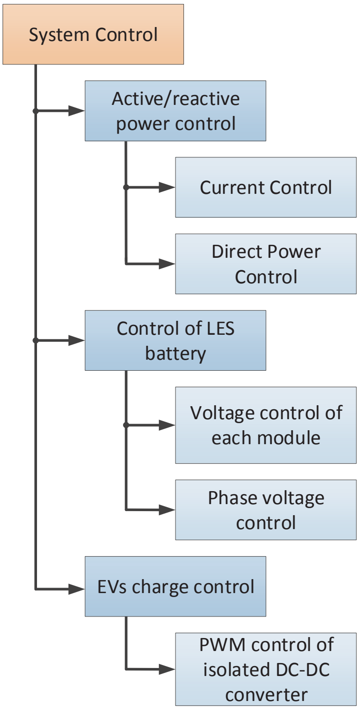

Fig. 9. Hierarchical management of the power system control from Figure 8

The first level of active and reactive power control takes place in the active rectifier and can be implemented in a structure with subordinate regulation of currents (so-called voltage-oriented control) or in the direct power control structure (without current regulation) [3]. The second level is divided into two sublevels: DC voltage regulation for charging and discharging the energy storage battery of each module, and DC voltage compensation equalization for each phase of the converter. The third level, by controlling the voltage and current output of the DC-DC converter, implements the battery charging strategy of the BEV vehicle.

4.4. High voltage active rectifier developed in IEL

In the Department of Power Converters of the Electrotechnical Institute, research works have been conducted for many years in the field of multilevel high voltage converters.

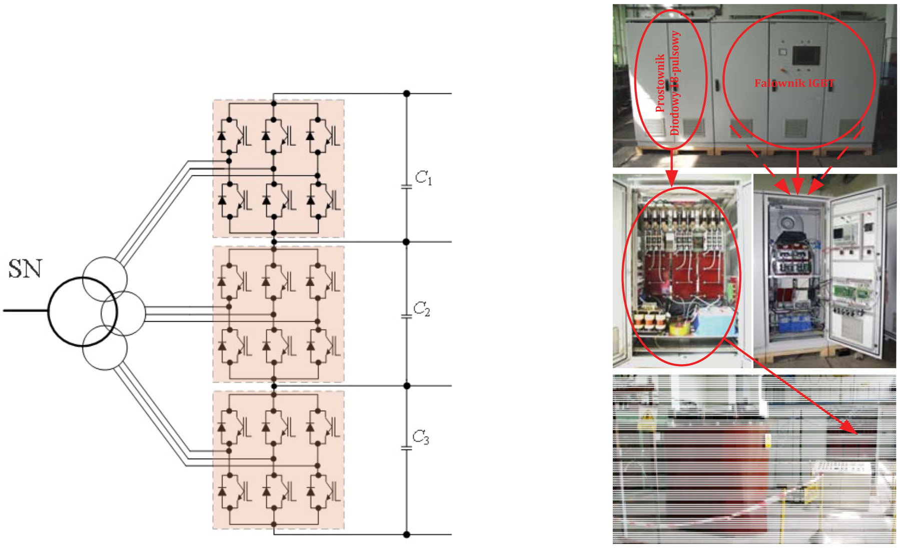

Fig. 10. Four-level active rectifier 1.2 MW, DC side voltage 3.3 kV;
Left: circuit topology; Right: view of the converter cabinet's

An example of an active four-level rectifier with a capacity of 1.2 MW and a DC output voltage of 3.3 kV is shown in Figure 10 [12]. The switching frequency of the IGBT power transistors is constant and equal 1.2 kHz. This technology can be easy adopted for applications in supply systems of ultra fast charging stations.

5. SUMMARY AND CONCLUSIONS

At present, power electronics systems in the issues of Electromobility are developed in three main groups: architecture of charging station energy systems, battery chargers and adjustable drives with AC motors.

With regard to the architecture of power systems, in particular for ultra fast high-power charging terminals, multi-level cascade converters create the possibility of eliminating low-efficiency, heavy and large MV/LV 50 Hz transformers. In addition, the development of architecture based on DC power buses is in line with the trends in the development of distributed energy systems and renewable energy sources, and in the future will allow easier integration and control of the energy system.

Generally, with regard to power electronics systems in Electromobility, it is to be expected that the use of next-generation power semiconductor devices based on SiC and GaN materials and multi-level topologies will allow further reduction of losses as well as their dimensions and weight. However, designing such systems due to the large number of non-linear related parameters and variables is a complicated issue and requires the use of multi-criteria optimization methods. Therefore, according to the authors opinion, this topic is very interesting for future research and development.

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ARCHITEKTURA ENERGOELEKTRONICZNYCH SYSTEMÓW ZASILANIA ŁADOWAREK POJAZDÓW ELEKTRYCZNYCH

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STRESZCZENIE *W pracy omówiono podstawowe wymagania oraz układy energoelektroniczne stosowane w systemach zasilania stacji ładowania akumulatorów pojazdów elektrycznych. Scharakteryzowano systemy zasilania z szyną AC oraz szyną DC, a także architektury scentralizowane i rozproszone. Opisano możliwe kombinacje zasilania z lokalnymi magazynami energii. Przedstawiono także nowoczesną architekturę na bazie przekształtników kaskadowych pozwalających na eliminację transformatora średniego napięcia. Rozważania zilustrowano przykładowym przekształtnikiem czteropoziomowym o mocy 1,2 MW opracowanym i wykonanym w Instytucie Elektrotechniki w Warszawie.*

Słowa kluczowe: *energoelektronika, elektromobilność, systemy ładowania samochodów elektrycznych*