Power Electronics and Power Systems

Liwei Zhou
Matthias Preindl

Software-Defined Power Electronics

Converter Configuration, Control, and Optimization

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Chapter 1
Introduction

1.1 Background

The power electronics (PE) are widely applied in the electrified energy conversion systems ranged from low power chip level supplies, consumer electronics, middle power domestic compliance, server power supplies, to high power electric vehicle charger, solar energy, E-motor traction, wind power generation, and so on. The power electronics techniques mainly focus on leveraging electronics knowledge to design and control the electric power conversion systems. With the increasing global carbon dioxide emissions, the electrification of energy conversion system is attracting significant research interests. Especially in the transportation systems, the carbon dioxide generated by burning fossil fuels accounts for the majority of greenhouse gas (GHG) emissions. In the automobile industry, the traditional internal combustion engines are the main source of GHG emissions. The fuel burning efficiency is positively related to the degree of electrification in the automotive propulsion system as is shown in Fig. 1.1 [1]. From hybrid electric vehicle (HEV) to plug-in hybrid electric vehicle (PHEV) then to all-electric vehicle (BEV), the ratio of electrification is scaled up. Accordingly, the GHG emissions are reduced due to the improvement of fuel efficiency. Besides the attenuation of GHG emissions, the electric vehicles also have comfortable driving experience, intelligent autopilot techniques, and safe propulsion system. Thus, the global electric vehicle stock is surging in the recent 10 years as is shown in Fig. 1.2.[1] Power electronics techniques are crucial to the electrification of transportation since the EV battery charging/discharging, electric motor traction, and automotive electronics system are all relying on the design and control techniques of PE. Besides the automobile industry, the usage of renewable energy resources for electricity power demanding is another

[1] IEA, Global electric passenger car stock, 2010–2020, IEA, Paris https://www.iea.org/data-and-statistics/charts/global-electric-passenger-car-stock-2010-2020.

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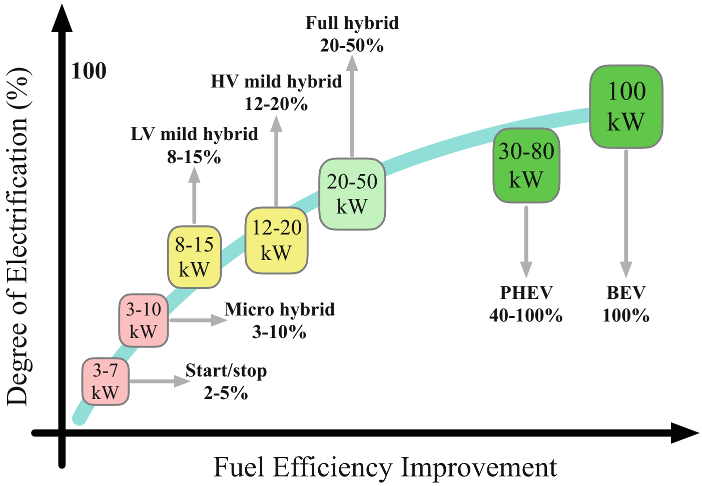

Fig. 1.1 Degree of electrification: typical fuel efficiency improvement and electric traction motor power

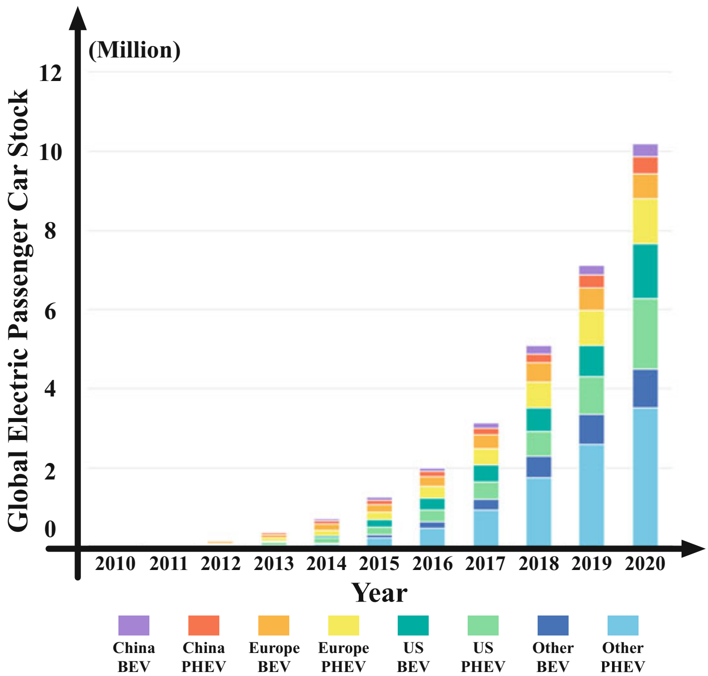

Fig. 1.2 Global electric passenger car stock from 2010 to 2020

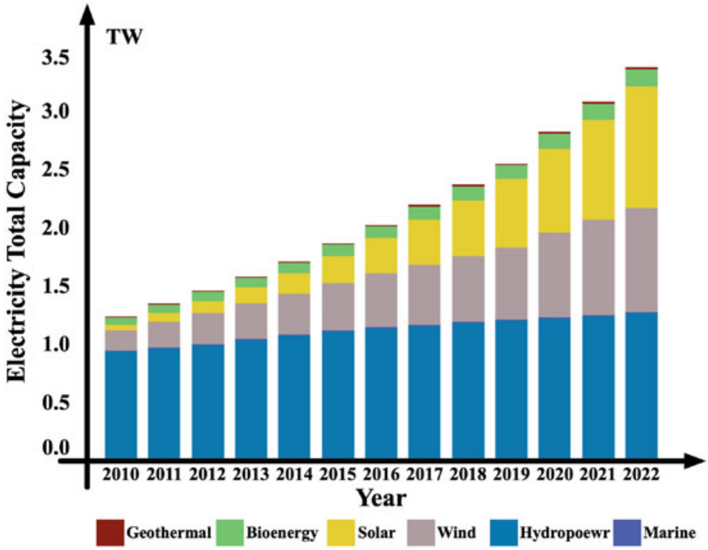

Fig. 1.3 Global renewable energy capacity from 2010 to 2022

crucial application of power electronics which has drawn significantly increasing attentions as shown in Fig. 1.3. Among various renewable energy applications in the electrified energy conversion systems, solar energy, wind power, grid-connected power supplies rely on the power electronic techniques to convert the energy for our satisfied purposes as shown in Fig. 1.4. The main components of PE system are power converters to transform the electric power between alternate current (AC) and direct current (DC) formats. Four typical power converters include DC/DC converter, DC/AC inverter, AC/DC rectifier, and AC/AC converter as is shown in Fig. 1.5. Thus, generally speaking, the PE techniques focus on the design and development of hardware/software based on the four types of power converters.

Power electronics design and development are typically specialized field for different types of electrified energy conversion systems. The design of the power electronics devices is always application-oriented since the requirements of different electrified load/source may vary. Thus, the corresponding hardware and software design will be diverse. Conventionally, to design a power converter, the specific parameter configuration requirement should firstly be comprehensively analyzed. On the one hand, for the hardware part, the rated voltage/current/power requirements determine the device selection and PCB board design. The power converter topologies can also vary and are largely dependent on the interfaced load/source. Different types of interfaced load/source would also require disparate sensing circuits. On the other hand, for the software part, various types of applications need different number of sampling information, I/O channels, control function algorithms, and so on. The different detailed configuration requirements of various industrial products make the power electronics design an application-oriented

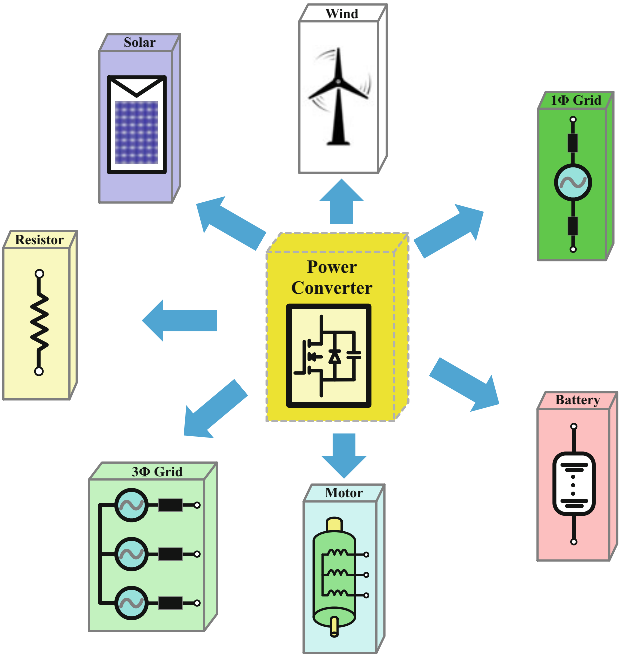

Fig. 1.4 Different applications of power electronics

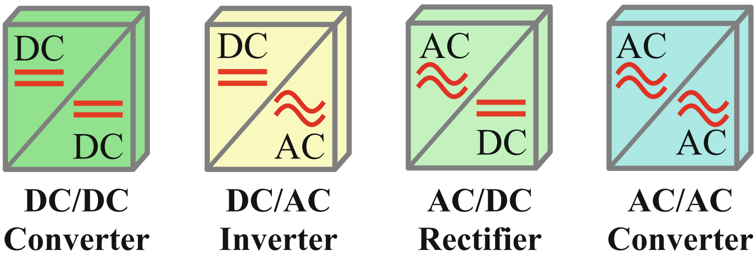

Fig. 1.5 Typical power converter structures

profession. The existing studies rarely focus on the generalization of the electrified energy conversion system.

1.1.1 Power Electronics for Renewable Energy

The renewable energy resources are the key solutions to achieve the Net Zero Emission target. Thus, substantial studies have been focusing on the discovery, usage, and optimization of the renewable energy related technologies. Generally, the renewable energy is defined as the energy that can be obtained from the natural resources which are replenished at a higher rate than they are consumed.

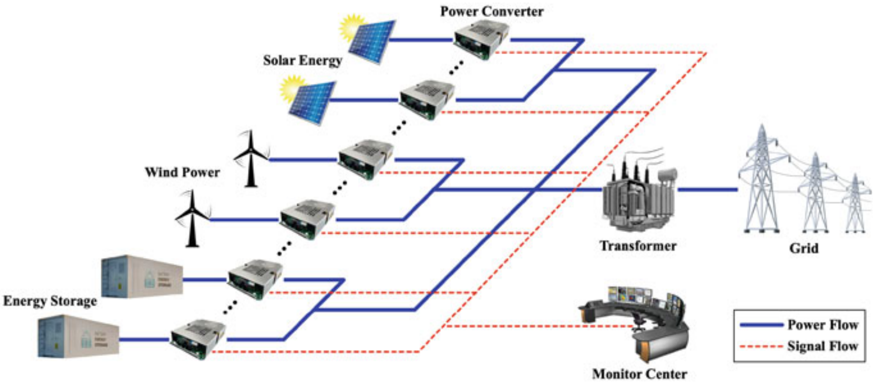

Fig. 1.6 Power electronics in renewable energy system interfaced grid utility

Typical types of the renewable energy resources include solar energy, wind power, geothermal energy, hydropower, ocean energy, bioenergy, and so on. The typical renewable energy interfaced microgrid system can be sketched in Fig. 1.6 where different resources have been connected to the grid utility through power electronic components and transformers.

The pursuit of achieving net zero targets has intensified the focus on renewable energy conversion systems. These techniques are diverse and innovative, aiming to harness energy from sustainable sources while minimizing environmental impact. The key renewable energy conversion system techniques include solar power, wind energy, hydropower, bioenergy, geothermal energy, ocean energy, energy storage, and so on. Specifically, solar power systems are designed to convert sunlight directly into electricity using solar cells. Wind Turbines capture kinetic energy from wind and convert it into electrical energy. Both onshore and offshore wind farms are pivotal in this sector. Hydropower is composed of Run-of-the-river by generating electricity from the natural flow of rivers, without large dams and pumped storage by pumping water uphill to a reservoir and releasing it through turbines during peak demand for energy storage. Bioenergy includes the biomass by involving the burning organic materials (wood, agricultural waste) to produce heat and electricity and the biogas by anaerobic digestion of organic matter for heating, electricity generation, or as a vehicle fuel. Geothermal energy utilizes heat from the Earth's interior for heating and electricity generation, with techniques varying from deep-earth drilling to shallow ground heat extraction. Ocean energy covers the tidal energy by exploiting the energy from the rise/fall of tides and the wave energy by converting the energy from surface waves into electricity.

1.1.1.1 Solar Energy Interfaced Power Electronics

Firstly, for the solar energy interfaced grid connection system, Fig. 1.7 shows the diagram that the solar panels can be connected to the grid utility by the distributed power converters and transformers. Different number of solar cells can be integrated

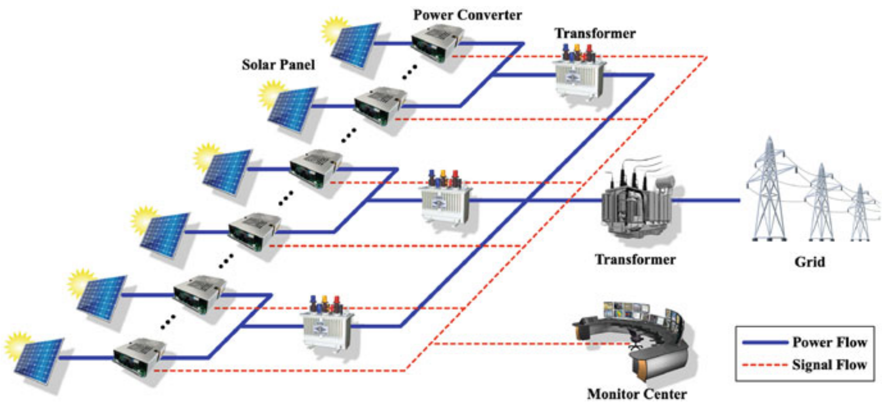

Fig. 1.7 Solar energy grid connection system

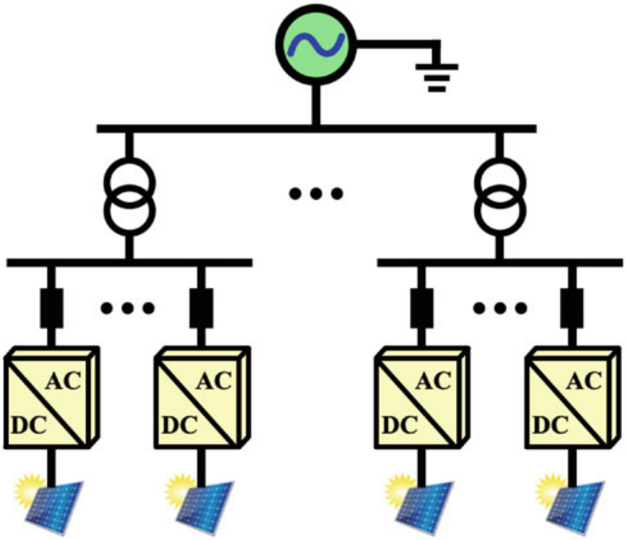

Fig. 1.8 Integrated solar energy power converters system connected to the grid

to collect the solar energy and convert it into electricity through photovoltaic effect. And the specially designed solar inverters can further convert the solar energy from the DC panel side to AC grid. Since the voltage levels of point of common coupling (PCC) are usually higher than the individual solar inverter output voltage, transformers are typically leveraged to step-up the AC voltage from the solar inverters. The integrated solar inverter grid-connected system and the individual solar power converter diagrams have been shown in Figs. 1.8 and 1.9, respectively.

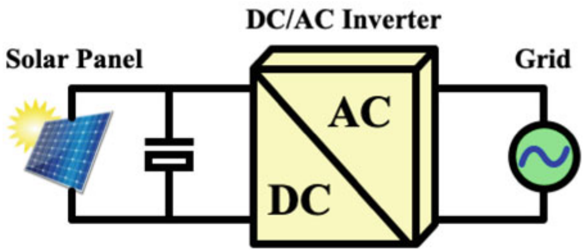

Fig. 1.9 Individual solar energy power converter connected to the grid

1.1.1.2 Wind Power Interfaced Power Electronics

Another crucial type of renewable energy resource is wind power. Wind power energy conversion systems utilize the kinetic energy of wind to generate electricity which also plays a significant role in the global shift toward renewable energy sources and net zero emissions. The typical wind power grid-connected system has been sketched in Fig. 1.10 where different distributed wind turbines are connected to the grid utility through the power electronic blocks and the transformers. The wind turbine is the most crucial component to collect the wind power and transfer the corresponding mechanical energy to AC format of the energy into the grid utility. Two typical types of the wind turbine power conversion systems have been shown in Figs. 1.11 and 1.12. Specifically, Fig. 1.11 demonstrates the Doubly Fed Induction Generator (DFIG) wind turbine system. It is a type of wind turbine where both the rotor and the stator windings are connected to the electric grid, allowing for more efficient energy conversion and control. In a DFIG system, the wind turbine's rotor is connected to the grid through a set of power converters. This allows for variable speed operation, meaning the turbine can operate efficiently over a wide range of wind speeds. Figure 1.12 shows the Permanent Magnet Synchronous Generator (PMSG) wind turbine system. It is gaining popularity due to its efficiency and reliability in converting wind power into electrical energy. PMSG wind turbines leverage a generator that has permanent magnets in its rotor. This design eliminates the need for electrical power to generate a magnetic field which leads to the improvement on energy conversion efficiency.

1.1.1.3 Fuel Cell Energy Interfaced Power Electronics

Fuel cell energy conversion systems represent a clean, efficient, and versatile technology for generating electricity. They convert the chemical energy from a fuel, typically hydrogen, directly into electricity and heat through an electrochemical reaction, rather than combustion. A typical fuel cell energy system integrated into the electric motor has been shown in Fig. 1.13. Basically, the fuel cells generate electricity through an electrochemical reaction process where hydrogen and oxygen combine to form water and in the same time the energy will be released within the process.

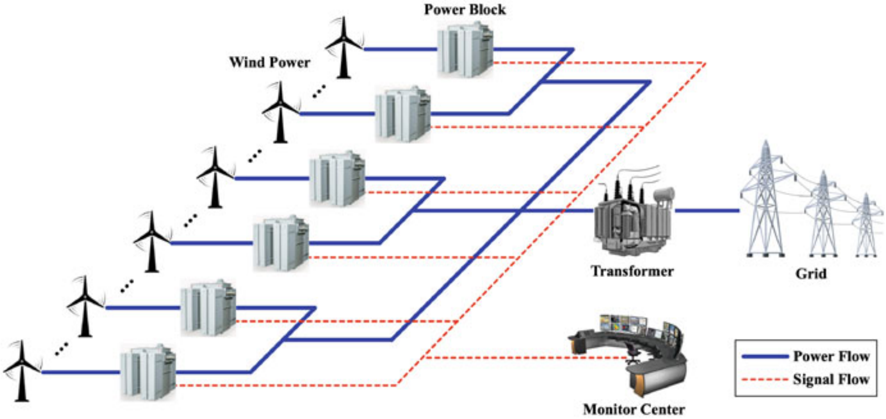

Fig. 1.10 Wind power grid connection system

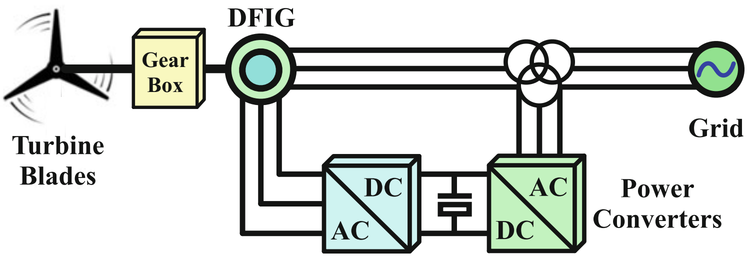

Fig. 1.11 DFIG wind turbine power converter connected to the grid

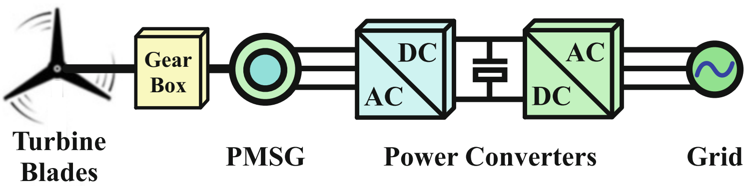

Fig. 1.12 PMSG wind turbine power converter connected to the grid

1.1.2 Power Electronics for Electric Vehicle

Electric vehicles (EVs) are a crucial component for net zero emissions, as they offer a significant reduction in greenhouse gas emissions compared to traditional internal combustion engine vehicles. The typical components for the EV energy conversion system include the following parts: (1) electric motor to convert the electrical energy into mechanical energy to drive the wheels; (2) battery pack to store electrical energy. Lithium-ion batteries are most common due to their high

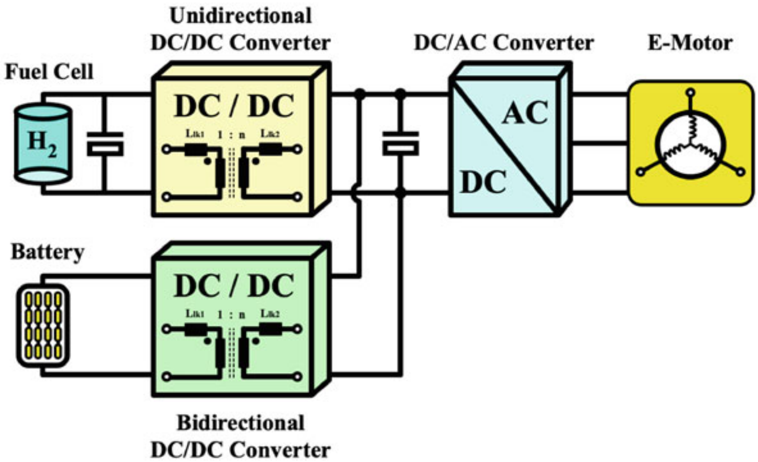

Fig. 1.13 Fuel cell energy integrated into the electric motor drive energy conversion system

energy density and efficiency; (3) power electronics which includes inverters and converters to manage the flow of electrical energy within the vehicle between DC and AC; (4) charging system that allows the vehicle to recharge its battery from the electrical grid or other charging sources; (5) regenerative braking system to capture the kinetic energy during braking and convert it back into electrical energy for the improvement of efficiency. Among the aforementioned key components, the power electronic system is playing a role as an interconnected manager among different EV energy sources and loads to manipulate the energy flows within their rated levels. The typical EV energy conversion system with the power electronic diagram has been shown in Fig. 1.14 where the EV internal electronic loads, electric motor, battery, and grid utility are interconnected through the power electronic components.

1.1.2.1 EV Charger Interfaced Power Electronics

The EV charging systems are a critical component of the EV ecosystem which is responsible for providing the necessary infrastructure to recharge EV batteries. The EV chargers are mainly composed of power converters to convert the energy from the grid utility to the EV batteries. Figure 1.15 shows the typical grid-connected EV charging system with different EVs and the corresponding chargers to be interfaced with the grid utility. Based on the charging power levels and voltage levels, the EV charging systems can be classified as level 1, 2, and 3. Specifically, level 1 charging (slow charging) uses a standard 110–120 V household outlet. It is the slowest charging method, typically adding about 2–5 miles of range per hour of charging. Level 2 charging (fast charging) operates on 208–240 V and is much faster than level 1, typically found in public charging stations and homes. It can add about 10–60 miles of range per hour. Level 3 is also called DC fast charging (or ultra-fast

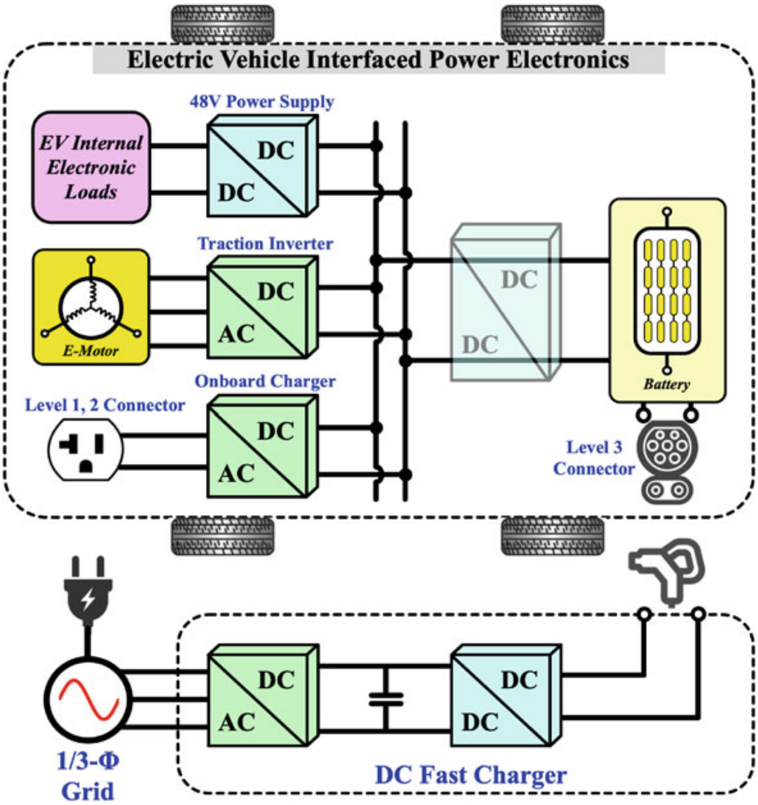

Fig. 1.14 EV energy conversion system with power electronic interfaces

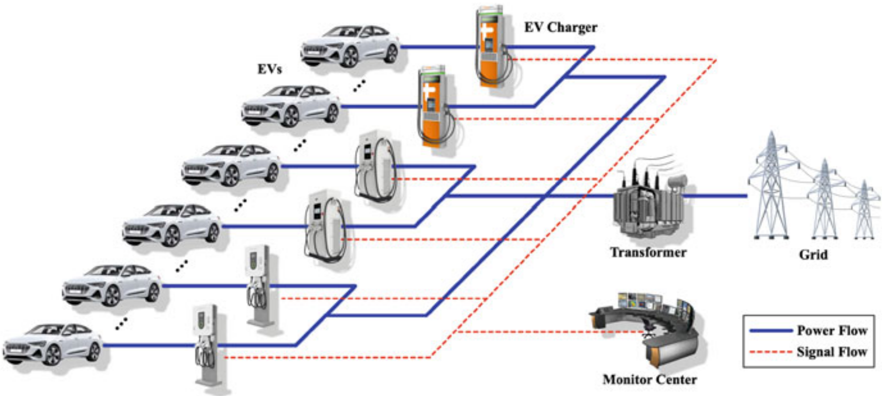

Fig. 1.15 EV charging grid connection system

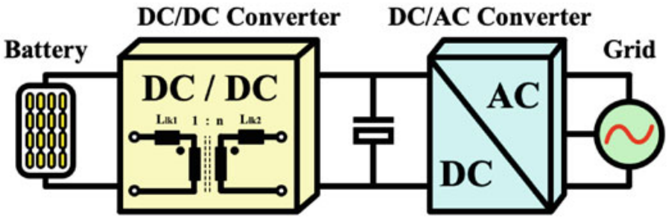

Fig. 1.16 EV charger power converter connected to the grid

charging) which uses direct current (DC) instead of alternating current (AC) and can charge an EV battery to 80% in around 20–30 minutes. It is an ideal option for highway rest stops and urban charging stations. Figure 1.16 demonstrates a typical DC charging system which includes battery, DC/DC energy stage, DC/AC energy stage, and grid utility.

1.1.2.2 Motor Drive Interfaced Power Electronics

EV motor drive interfaced power electronics are at the heart of the modern EV technology which plays a pivotal role in converting electrical energy from the battery into mechanical energy to drive the vehicle's motor. The energy efficiency and effective operation of EV are largely dependent on the EV motor drive system. The key components of EV motor driving system include (1) inverter to convert the DC power from the battery to AC power for the motor. It is a critical component for controlling the motor's speed and torque; (2) converter for the systems that need DC at different voltages, DC-DC converters adjust the voltage level to suit various components; (3) micro-controller to manage the operation of the motor by controlling the inverter and converter to achieve the desired speed, torque, and overall performance of the motor.

1.2 State of the Art for Modular Power Electronics

To manage various types of loads and sources for the electrified energy conversion to be connected to the grid utility or feed the electric facilities, the power electronic components need to be specially designed to meet different voltage/current and power requirements. The design cost could be high for the power converters from application to application. The concept of modular power electronics has been developed with standardized modules to satisfy various loads/sources requirements.

A concept of power electronics building block (PEBB) has been proposed to standardize the hardware components for stackable energy conversion systems [2–5]. The PEBB concept is more focusing on the physical components design to generalize the hardware power modules with extensible voltage/current capacity. Deshpande et al. [3] developed a T-type PEBB for the aircraft electric-propulsion drives with high current capability (>100 A) by leveraging the hybrid insulated gate bipolar junction transistor (IGBT) and silicon carbide switches. Guacci et al. [6] also targeted for the more electrical aircraft applications with all SiC, two-level PEBB. Iyer et al. [4] designed a direct AC/AC PEBB for medium-voltage grid-connected applications which can be applied to the grid utility of 13 kV, 1 MVA. Similarly, [7] developed three-level neutral-point-clamped PEBB for the AC transmission system application. The PEBB concept can also be leveraged to form typical circuitry topologies such as matrix converters in [8], modular multi-level converters (MMC) in [8, 9].

Besides the PEBB for the hardware reconfigurability, some studies have also developed power electronics control architectures in a high level perspective to cover various applications [10, 11]. Except for generalized hardware and software control architecture designs for power electronics, some research developed modular concept for power converters to further generalize the power electronics design procedures [12, 13]. Other technical concepts studied the building of universal platform or infrastructure for the real-time power electronics testing and design [14, 15].

1.3 Motivations

The typical power electronics design procedures are demonstrated in Fig. 1.17a. Various types of applications are featured with different power converter, hardware and software control configurations. Thus, it is hard to generalize a universal design protocol that can cover all types of electrified energy load/source. The specificity of power electronics design is mainly reflected in the following three aspects.

Firstly, the characteristics of the interfaced loads/sources to the power converters are disparate. For example, the energy loads/sources can be divided into DC and AC. DC types of electric power include battery, solar energy, automotive 48-volt system, and other low voltage power supplies. Among the DC electric power loads/sources, the required voltage/current or power control algorithms are different. Battery charging/discharging processes are typically featured with constant current (CC) and constant voltage (CV) control modes. The photo-electric effect in the solar energy system requires a maximum power point tracking (MPPT) technique to perform an optimal energy transformation efficiency. Grid-tied inversion systems demand a phase-locked loop (PLL) to synchronize the power converter with the grid frequency. Motor traction inverter of the electric vehicle needs to sample the rotor position for the speed and torque control.

Secondly, the difference of rated voltage and current configurations can lead to huge divergence on the power converter and the corresponding sensor circuit design. The rated voltage/current values limit the selection of power switches for the tolerable maximum current/voltage across the switch. The sensor circuit design

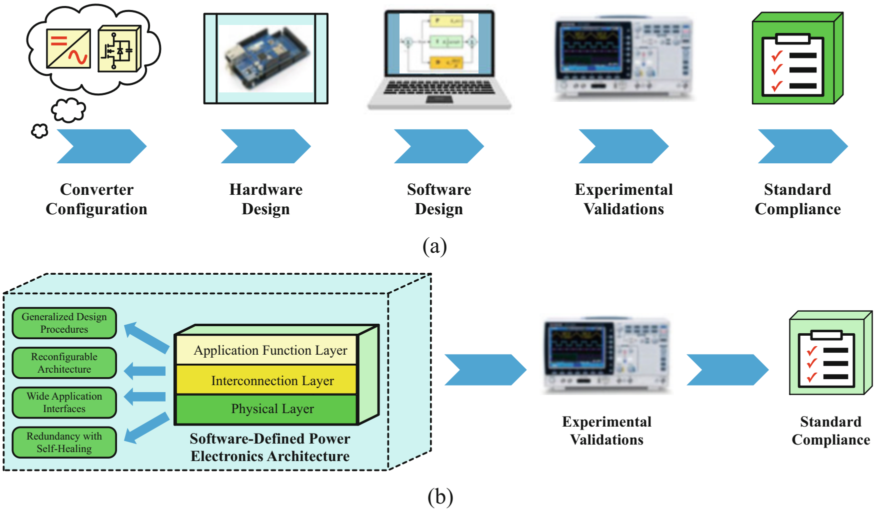

Fig. 1.17 The design procedures for (**a**) conventional power electronics system and (**c**) software-defined power electronics architecture

is also sensitive to the current/voltage ranges which could influence the sampling resolution and accuracy.

Thirdly, the time scales of the power electronics signals are different for various types of communicated information. The updating frequencies of the communication signals can be ranged from ns to min according to the control needs and micro-controller computation capability. For instance, the protection signals by detecting voltage/current samples may be iterated within ns to μs. The voltage/current signals for power control purposes can be updated with the time periods from μs to ms. Other grid service commands, user interfaced data monitoring may not require fast updating period which could be ranged from ms to s.

Since the existence of the three aspects of specificity for the power electronics design, the power converters need to be specifically designed based on the demands. The targets for the power converters design mainly include high energy conversion efficiency, high power density, low cost to improve the energy conversion performance. In detail, the high efficiency means low power losses during the energy conversion processes. The high power density requests a high power level and low volume in the mean time. Low cost pursues less cost on the hardware components per volume of the energy conversion system.

Comprehensively considering the specificity feature of power electronics design and the target of improving the energy conversion performance, this book develops a software-defined power electronics architecture to abstractly generalize the electrified energy conversion system and improve the energy conversion performance by leveraging advanced control, estimation algorithms, and novel design techniques.

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Part I
Physical Level