

Review

# A Review of Various Fast Charging Power and Thermal Protocols for Electric Vehicles Represented by Lithium-Ion Battery Systems

Peter Makeen <sup>1,2,\*</sup> , Hani A. Ghali <sup>1</sup> and Saim Memon <sup>2,3,\*</sup> 

<sup>1</sup> Electrical Engineering Department, Faculty of Engineering, The British University of Egypt (BUE), El-Sherouk 11837, Egypt; hani.amin@bue.edu.eg

<sup>2</sup> London Centre for Energy Engineering, Division of Electrical and Electronic Engineering, School of Engineering, London South Bank University, London SE1 0AA, UK

<sup>3</sup> Department of Engineering and Technology, School of Computing and Engineering, University of Huddersfield, West Yorkshire HD1 3DR, UK

\* Correspondence: besadap@lsbu.ac.uk (P.M.); s.memon@lsbu.ac.uk (S.M.)

**Abstract:** Despite fast technological advances, the worldwide adoption of electric vehicles (EVs) is still hampered mainly by charging time, efficiency, and lifespan. Lithium-ion batteries have become the primary source for EVs because of their high energy density and long lifetime. Currently, several methods intend to determine the health of lithium-ion batteries fast-charging protocols. Filling a gap in the literature, a clear classification of charging protocols is presented and investigated here. This paper categorizes fast-charging protocols into the power management protocol, which depends on a controllable current, voltage, and cell temperature, and the material aspects charging protocol, which is based on material physical modification and chemical structures of the lithium-ion battery. In addition, each of the charging protocols is further subdivided into more detailed methodologies and aspects. A full evaluation and comparison of the latest studies is proposed according to the underlying parameterization effort, the battery cell used, efficiency, cycle life, charging time, and increase in surface temperature of the battery. The pros and cons of each protocol are scrutinized to reveal possible research tracks concerning EV fast-charging protocols.

**Keywords:** electric vehicles; fast charging; constant current constant voltage; multi-stage charging current; pulsating charging current; thermal management



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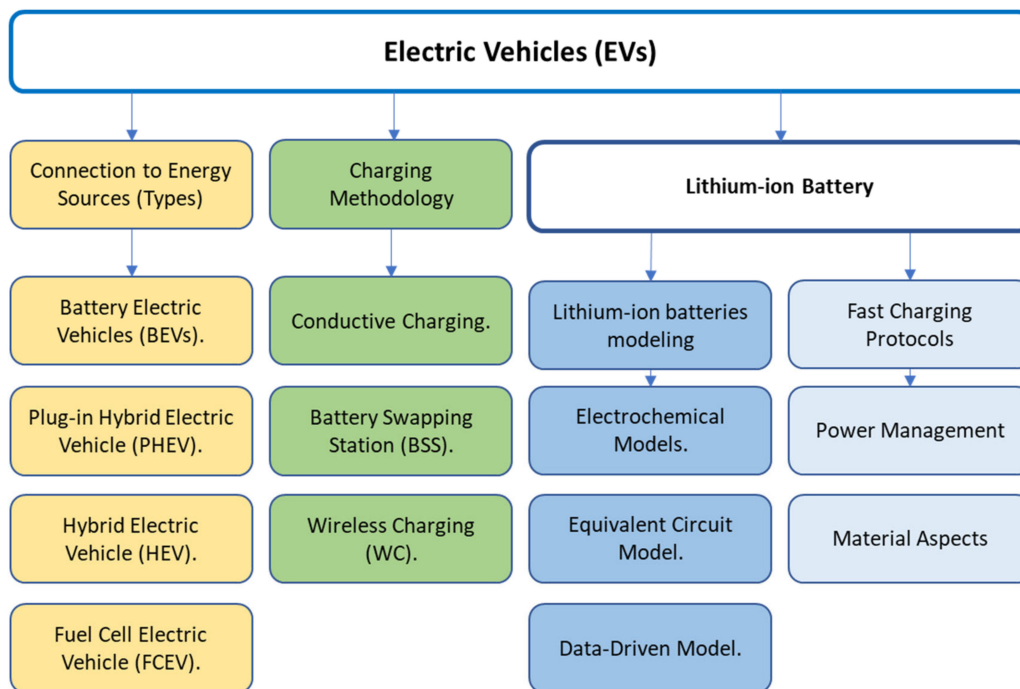


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## 1. Introduction

Presently, Electric Vehicles (EVs) are gaining strong momentum in the vehicle market due to their low price compared with conventional vehicles, low greenhouse gas (GHG) low emissions, low dependency on fossil fuels, low noise, and increasing climate and environmental awareness [1,2]. According to the report in [3], there were 10 million electric vehicles in the world at the end of 2020. In the first quarter of 2021, EV sales rose by 140% compared to the same period in 2020, despite the global pandemic (COVID-19).

In this article, an overview of different research tracks concerning EVs is presented; see Figure 1. We will briefly review the state of the art of the EV connection to energy source categories, charging standards, charging methodologies, the modeling of the lithium-ion battery, and scrutinize the various protocols of fast charging, presenting their pros and cons.



**Figure 1.** Overview of the electric vehicle (EV) research tracks.

1.1. Electric Vehicle (EV) Overview

EVs are divided into four main categories based on their connection to energy sources, namely plug-in hybrid electric vehicle (PHEV), hybrid electric vehicle (HEV), battery electric vehicle (BEV), and fuel cell electric vehicle (FCEV) [4,5]. PHEVs and HEVs depend on both electrical and internal combustion engines; BEV requires EVs that only run with electrical energy; and FCEVs use the on-board generation of hydrogen to reduce hydrogen storage and handling issues [6–8].

The authors in [9] predicted that around 130 million private chargers and 13 million public chargers will be needed by 2030 to fulfil the energy demand of different types of EVs. To facilitate this advancement, there is a direct need to invest in charging infrastructure. Chargers must be structured to charge EVs according to the standard set by international institutions such as the International Electrotechnical Commission (IEC), Society of Automotive Engineers (SAE), and CHAdeMO [1,10]. EV standards, according to IEC-62196, SAE-J1772 and CHAdeMO, are provided in [1,11–14]. Those standards are proposed in Table 1, and categorized based on the available maximum power rating, voltage, maximum rating current, and charging time.

Charging methodologies are classified into three main categories, namely conductive charging, wireless charging (WC), and a battery-swapping station (BSS) [8]. The battery can be charged anywhere, from an electric vehicle charging station (EVCS) to separate street chargers, workplace chargers, and private in-home chargers. The conductive charging technique depends on the advancement of the EV, which can have on-board and off-board properties. On-board chargers are widely known as AC chargers, which can be single-phase Level 1 and Level 2, as defined in SAE-J1772, and three-phase AC charging, as defined in SAE-J3068. Off-board chargers are referred to as DC chargers, which ensure higher charging current rates, as defined in SAE-J1772-Combo/CHAdeMO standards [15–17]. Wireless charging (WC) allows EVs to charge without any physical contact or cable connection between the supply and the battery [18,19]. Battery-swapping stations (BSS) are stations where an empty battery can be replaced with a fully charged battery within a few minutes [20,21].

**Table 1.** Charging rates of IEC standards, SAE standards, and CHAdeMO.

Charging Levels	Maximum Power Rating (kW)	Voltage (V)	Maximum Current Rating (A)	Charging Time
IEC-62196 Standard [1]				
AC Level 1	3.8	230–240 V AC	16	NA
	7.6	480 V AC		
AC Level 2	7.6	230–240 V AC	32	
	15.3	480 V AC		
AC Level 3	60	230–240 V AC	32–250	
	120	480 V AC		
DC	400	600–1000 V DC	250–400	
SAE-J1772 Standards [22]				
AC Level 1	1.9	120 V AC	16	PHEV: 7 h
				BEV: 17 h
AC Level 2	3.3	240 V AC	80	PHEV: 3 h
				BEV: 7 h
	7			PHEV: 1.5 h
DC Level 1	20	200 to 500 V DC	80	BEV: 3.5 h
	40			PHEV: 22 min
DC Level 2		200 to 500 V DC	200	BEV: 1.2 h
	Up to 100			PHEV: 22 min
				BEV: 1.2 h
				PHEV: 10 min
				BEV: 20 min
CHAdeMO [1,23]				
DC Fast Charging	400	400 DC	200	20 min

Increasing the charging current accelerates battery aging disproportionately, leading to capacity and power fade and posing an unacceptable safety hazard during operation [24]. Several protocols have been developed to solve the trade-off between charging speed, battery surface temperature, and battery aging. In addition, car manufacturers have aimed for faster charging times by calculating charging time in km/min to achieve a more user-oriented and comparative figure for different vehicle sizes. For example, the Tesla Model S has a charging speed of 16.3 km/min, which is considered the fastest BEV [24]. However, in an ideal case, the battery pack in an EV can accept high charging currents independent of the conditions present in the battery, while providing a long lifetime, low-cost maintenance and high sustainability. Unfortunately, these ideas usually pose several trade-offs, in reality, specifically a slow charging rate, which is considered to be one of the major limitations [24–26]. Consequently, researchers are currently aiming at understanding and improving the charging process of the battery pack, especially lithium-ion batteries.

### 1.2. Lithium-Ion Battery

Rechargeable Lithium-ion batteries are the intrinsic technology of EVs and they are commercialized for energy storage devices due to their high energy density, low self-discharge rate, high efficiency, fast charging capability, and longer lifespan [27–29]. However, Li-ion batteries are sensitive to fast charging which accelerates the aging effect and capacity loss [15,30]. Hence, the charging processes can be influenced substantially by the manufacturers throughout realizing and implementing a specific charging protocol, that combines the charging time, capacity, and cycle life [31,32]. Section 2 will provide an overview of the various categories of charging protocols and their characteristics, pros, and cons. However, the experimental procedures for each protocol vary among the publications, which impedes a direct comparison. Due to the different cell types that have been used in the experiments, no independencies are revealed between the charging protocol

and cell type. Consequently, it is very difficult to compare the performance of various charging protocols.

Before discussing the different categories of the charging protocols, the dynamic behaviour of the Lithium-ion battery has to be established using various models based on mathematical equations and/or collected data [33,34]. The most common models used are the electrochemical-mechanism model, which describes the internal chemical process of the battery, the equivalent circuit model which represents the chemical nature as electrical components, and the data-driven model which includes artificial neural network, support vector machine, black box, etc. [33,35–37]. Electrochemical models can describe the battery chemistry through the reactions that take place in the electrodes and the electrolyte deployed and can be classified as a Single Particle Model (SPM) [38,39], P2D model [40,41], a comprehensive capacity degradation model [42], as well as an Equivalent Circuit model such as the Rint model, PNGV model, Thevenin model, modified Thevenin model, RC first-order transient, RC second-order transient model, and RC cascaded transient model [25,43–45]. Finally, the Data-driven model consists of the black-box model that is considered as a linear and nonlinear mapping function of the terminal voltage, instead of providing a description of the electrochemical physics process of the battery, machine learning techniques with pattern recognition, clustering, and classification, and an artificial neural network, which are otherwise employed to predict the charging and discharging behaviour of the battery, etc., as stated in [33].

After an extensive literature review of different charging protocols, it was observed that a fair comparison of the various types of charging protocols has not yet been provided, because of the various lithium-ion batteries capacity used in each study. This paper reveals the comparison between the methodologies for each protocol, thereby providing a fair comparison. The main contributions of this review are as follows.

1. Clearly and systematically presents and classifies various charging protocols and the main controllable input and output parameters for each.
2. Reveals a full comparison between the sub charging methodologies of each charging protocol and the impact on the charging time, efficiency, lifetime, and energy loss.
3. Defines new up-to-date strategies depending on the power management, thermal management, and material aspects that are not mentioned in other literature reviews. In addition, a full identification of the pros and cons of each protocol may provide scope for the researchers to improve the existing protocols.

## 2. Introduction of Fast Charging Protocols

Fast charging protocols aim for a minimal charging time requirement, optimum efficiency, effective cycle life, and minimum charging loss. Researchers seek to eliminate the high C-rate charging and high depth of discharge (DOD) range which increase the loss of active material and reform the solid electrolyte interphase (SEI) at the surface of the electrode, hence resulting in an increase in the internal impedance and minimizing the capacity of the battery [46–48]. In addition, researchers recommended avoiding overcharge and over-discharge of the battery, which can cause unwanted heating inside the battery, therefore cracking the SEI and loss of active area inside the lithium-ion battery, and minimizing the number of ions participating in the electrochemical reaction, respectively [49,50]. Consequently, the efficiently designed and high-quality charging protocol not only reduces the charging time but will also improve the performance of the battery, energy conversion efficiency, lifespan, and reduce energy loss.

This paper delineates the main fast-charging protocols for lithium-ion batteries, as expressed in Figure 2. The protocols can be split into power management, which depends on the topology of applying the voltage and current during the charging process; thermal management, which manipulates the temperature of the lithium-ion battery while charging; and the material aspects which pertain to the electrolyte modifications (concentrated electrolyte and low viscosity additives). The most up-to-date articles in each category are discussed in the following sections.

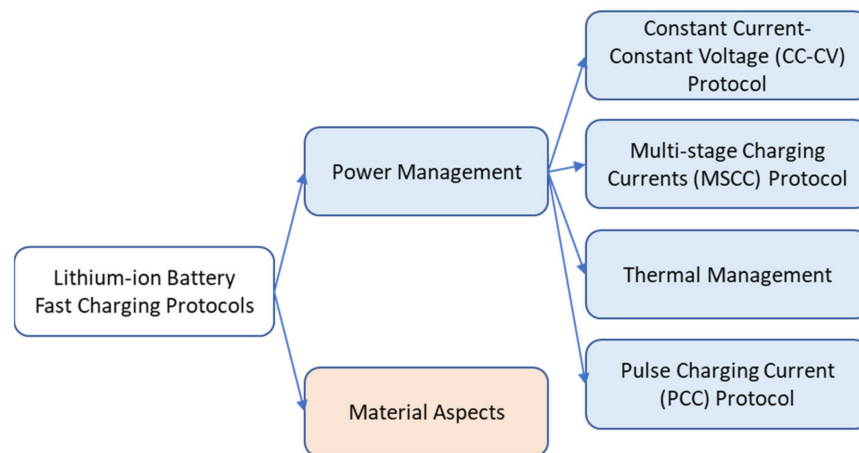


Figure 2. Main fast-charging protocols of the Lithium-ion battery.

### 3. Power Management Charging Protocol

The power-management charging protocol is based on charging the lithium-ion battery with various current and voltage topologies to ensure fast charging, minimum charging loss, high efficiency, and increased lifespan. An investigation for each protocol is introduced in the following sections.

#### 3.1. Constant Current Constant Voltage (CC-CV) Protocol

CC-CV is considered to be the traditional charging protocol for lithium-ion batteries. CC-CV methodology is based on charging the battery by a constant rated charging current until the voltage reaches the cut-off value and then the voltage is held constant while the current decays to the minimum value as expressed in Figure 3. This protocol is efficient with a battery management system (BMS) [51], easy to implement, has simple requirements, and avoids overcharging due to the constant voltage mode. In addition, CC-CV is considered as the main contributor in the centralized electric-vehicle charging stations in minimizing the queuing delay per EV, especially during peak hours [51]. However, it is conservative because of the long charging time while gradually reducing the current density to 0.1 C where the C-rate is a measure of the rate at which a battery is charged/discharged relative to its maximum capacity [52], low efficiency, and short battery runtime [53,54]. The authors in [55] revealed that the CV charging stage can cause server degradation whenever the voltage exceeds the cutoff voltage.

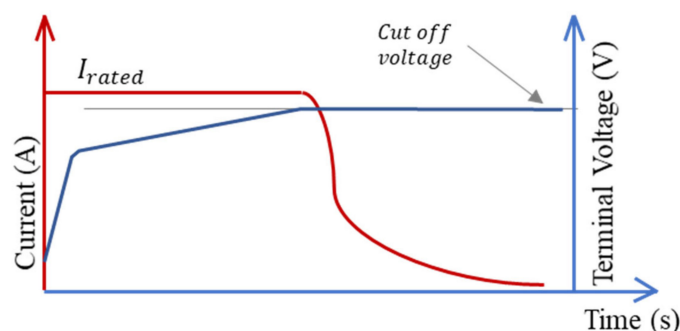


Figure 3. Schematic diagram of the Constant Current Constant Voltage (CC-CV) Protocol.

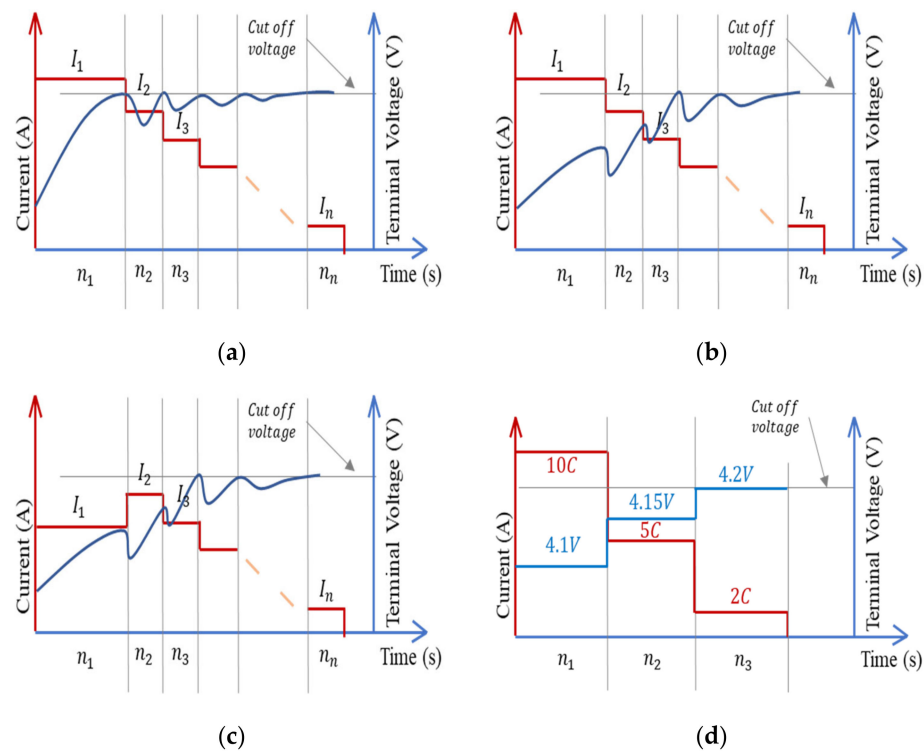
#### 3.2. Multi-Stage Charging Currents (MSCC) Protocol

Researchers are seeking protocols to reduce the charging time and degradation compared to the CC-CV methodology. In the multi-stage charging currents protocol, the battery is charged by a multi-stage application of different currents and the lifetime extends without degradation impact. Many algorithms and techniques have been implemented for

multi-stage constant current charging of the lithium-ion battery to reduce the charging time, reduce the energy loss and improve the charging efficiency. However, it is time-consuming to find the optimal charging strategy by means of charging and discharging experiments.

The charging process in [56] is split into  $n$  stages of constant current (CC) [ $I_1, I_2, \dots, I_n$ ], which are combined with  $n$  voltage thresholds [ $V_1, V_2, \dots, V_n$ ], which control the end of each CC stage. An optimization algorithm is formulated by the `fmincon` MATLAB function to estimate the parameters of the MSCC protocol, where the number of stages is set to  $n = 10$ . MSCC is investigated at different chosen temperatures of 5 °C, 25 °C, and 45 °C representing a cold, mild, and hot climate, respectively. The comparison between the MSCC and CC-CV is implemented via five main scenarios, as presented in Table 2 below. The proposed scenarios successfully reduced the degradation compared to CC-CV references.

An optimal charging pattern is implemented in [57], of five MSCC, where the Grey Wolf Optimization algorithm (GWOA) is used to find the optimal charging current for each stage. An improvement in the charging time, maximum temperature rise, and charging efficiency are ensured in this article. The advantages of the GWOA include few parameters, easy implementation, and a special capability to strike the balance between exploration and exploitation during the searching process. The charging current stage using GWOA changes whenever the battery voltage reaches the cut-off voltage and these procedures are repeatable until the change in voltage is minimized as shown in Figure 4a.



**Figure 4.** Schematic diagram of the Multi-Stage Charging Current (MSCC) Protocol where (a) The charging current stage changes whenever the battery voltage reaches the cut-off voltage, (b) the Hierarchical technique (HT), (c) the Conditional random technique (CRT), and (d) multilevel multistage constant current-constant voltage superfast charging (ML MCC-CV) methodology.

A multistage constant current-constant voltage protocol (MCCCV), based on the particle swarm optimization algorithm, is proposed in [58], where the following three strategies are proposed: a fast charging for motorway driving (aging loss of the battery is not considered  $\beta = 1$ ), minimum aging charging for family use ( $\beta = 0$ ), and a balanced charging for daily use which is expressed using a Pareto frontier boundaries plot. In MCCCV procedures, the battery is first charged at a constant current until the voltage reaches a cut-off voltage, then a new set of charging currents is applied accordingly, until



the SOC of the battery reaches  $\geq 90\%$ , at which point it reaches the constant voltage stage. Additionally, the authors in [59] used the Particle Swarm Optimisation (PSO) algorithm with strategies presented in [58].

The Taguchi-orthogonal method was employed in [60] to search for an optimal fast charging five stage pattern. The Taguchi method is based on experimental analysis, so as to avoid complicating the modeling of the lithium-ion battery.

In [61], the Taguchi-orthogonal-based particle swarm optimization (TPSO) algorithm was utilized, using four MSCC protocols and the results were compared with five MSCC protocols. It was concluded that four or five MSCCs do not have a significant impact on the charging time and efficiency. However, the battery cycle life decreased when using four MSCC protocols with respect to the CC-CV protocol.

The multi-objective particle swarm optimization (MOPSO) method based on the Pareto front was employed in [62]. The optimum solution is selected using the technique for order of preferences by similarity to ideal solution (TOPSIS).

In [34,63] a meta-heuristic algorithm based on the Cuckoo Optimization Algorithm was utilized in the fast charging of a lithium-polymer ion battery. COA is applied via two main techniques: The Hierarchical technique (HT) and the Conditional random technique (CRT) as shown in Figure 4b,c respectively. The HT was obtained by applying hierarchical stepping-down variable constant currents during the charging process, while the CRT was based on the conditional randomness of the cuckoo optimization algorithm which chooses the values of the stage currently lying within the boundaries.

To prevent the voltage from rising to the cut-off voltage level during the charging process, multilevel multistage constant current-constant voltage superfast charging (ML MCC-CV) methodology was implemented in [64]. The initial charge mode, in this model, is set to trickle mode to avoid battery damage. When the voltage of the battery is within the normal operating range ( $\geq 3$  V) ML MCC-CV charging starts as shown in Figure 4d, where the charging voltage and current are set to be 4.1 V and 10 C, respectively. Whenever the battery voltage reaches  $\geq 4.1$  V, a charge voltage of 4.15 V and CC of 5 C are applied. Finally, when the voltage reaches  $\geq 4.15$  V, a charging voltage of 4.2 V and CC of 2 C is implemented until the end of charging.

Researchers use various methodologies to study the charging process with different models to represent the dynamic behaviour of the lithium-ion battery, where the output of each research paper can be represented in the charging time, energy consumption, charging efficiency performance, maximum applied current, cycling, and temperature rise, which are summarized in Table 2.

In [65] a large-scale EV battery with a capacity of 50 kw was charged from 20% to 90% SOC using the constant power constant voltage (CPCV) methodology and the results were compared with the conventional CC-CV charging protocol. It was concluded that the optimal power charging can reduce the energy loss and 9% of the cost compared to the existing conventional fast-charging mode.

Such power management approaches based on MSCC are often motivated by reducing heat generation, avoiding lithium plating, avoiding overcharging, and reducing mechanical stresses when the diffusion of  $\text{Li}^+$  ions is constrained [66]. However, the MSCC protocol requires a full estimation of all the internal equivalent parameters of the electric circuit used in modelling [34,67].

**Table 2.** Comparison between algorithms presented in the literature survey using the Multi-stage charging current (MSCC) protocol, and Thermal Management Protocol.

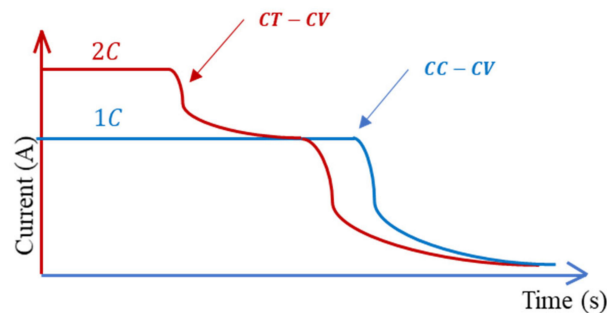
Type		Battery	Circuit	Charging Time (min)	Maximum Charging Current (A)	No of Stages	SOC <sub>t</sub> (%)	Charging Efficiency (%)	Charging Loss (J)	Cycling	Temperature Rise (°C)
Numerical optimization [56]	Case A 25 °C	CC-CV	INR18650HG2 from LG, 3 Ah	61	1.33 C	---	96.2	N/A	N/A	330	N/A
		MSCC		65	1.917 C	10	96.8	N/A	N/A	700–800	N/A
	Case B 25 °C	CC-CV		43	1.66 C	---	96.2	N/A	N/A	330	N/A
		MSCC		52	3 C	10	93.5	N/A	N/A	450	N/A
	Case C 25 °C	CC-CV		46	1.67 C	---	83.3	N/A	N/A	600	N/A
		MSCC		37	3 C	5	78.4	N/A	N/A	1200	N/A
	Case D 5 °C	CC-CV		66	1.33 C	---	91.4	N/A	N/A	100	N/A
	MSCC	91	1.167 C	10	90.4	N/A	N/A	400	N/A		
	Case E 45 °C	CC-CV	53	1.33 C	---	97.8	N/A	N/A	900–1000	N/A	
		MSCC	44	2.33 C	10	95.1	N/A	N/A	1200	N/A	
Grey Wolf optimization algorithm [57]	2C-CC-CV	SAMSUNG INR18650-25R Li-Ion Battery	Thevenin equivalent circuit	66	2 C	---	98.43	98.31	N/A	N/A	+2 K
	1C-CC-CV			97	1 C	---	100	98.4	1363.04	167	+1.75 K
	Case-1			92	0.8292 C	5	98.45	98.87	1133.91	300	+1.75 K
	Case-2			93	0.832 C	5	98.46	98.82	1142.4	N/A	+1.75 K
	Case-3			85	1 C	5	98.79	98.69	1334.99	N/A	+2.1 K
	Case-4			89	0.9092 C	5	98.48	98.7	1239.26	N/A	+2 K
	Case-5			91	0.8692 C	5	98.01	98.79	1175.86	N/A	+1.9 K
Case-6	93	0.822 C	5	98.46	98.81	1132.1	N/A	+1.75 K			
Adaptive MSCC [58]	Fast Charging (β = 1)	CC-CV	NCR18650B battery	52.7	1 C	---	N/A	N/A	N/A	N/A	+5.1 °C
		CC-CV		68.383	0.75 C	---	N/A	N/A	N/A	N/A	+3 °C
	Minimum-aging (β = 0)	MCCCV		52.7	1 C	NA	N/A	N/A	N/A	N/A	+5.1 °C
	Balanced charging (β = 0.014)	MCCCV		200	0.25 C	NA	N/A	N/A	N/A	N/A	+0.35 °C
		CC-CV	58	0.7836 C	NA	99.013	N/A	N/A	N/A	+3.5 °C	
		CC-CV	102.77	0.5 C	---	N/A	N/A	N/A	N/A	+1.5 °C	
Taguchi-orthogonal based Particle Swarm Optimisation (TPSO) [61]	CC-CV	Sanyo UR14500P	N/A	119	0.7 C	0	99.5	99.10	N/A	280	+2.75 °C
	ECCCV	840 mAh		114	0.8036 C	0	98.7	98.93	N/A	N/A	+1.5 °C
	MCCCV	Sanyo UR14500P		67	1.262 C	4	94.7	98.97	N/A	190	+3.5 °C
	MSCC	2200 mAh		51	1.44 C	5	98.91	98.91	N/A	N/A	N/A
	CC-CV	2200 mAh		118	1.44 C	0	98.54	98.54	N/A	N/A	N/A
Multi-objective particle swarm optimisation (MOPSO) [62]	MSCC	LiFePO <sub>4</sub> battery 8 Ah and 3.2 V	1RC transient	25.567	4.925 C	8	N/A	N/A	N/A	N/A	+4.1 °C
Taguchi-orthogonal method [60]	CC-CV_0.1C	3150 mAh	1 Resistor + 1 Impedance	59.4	1.55 C	---	94.1	93.3	N/A	N/A	+20.3 °C
	CC-CV_0.2C			49.37	1.55 C	---	92.3	93	N/A	N/A	NA
	MSCC_1			54.22	1.55 C	5	93	93.9	N/A	N/A	+19.2 °C
	MSCC_2			55.47	2 C	5	93.1	91.1	N/A	N/A	+28.5 °C
	1C-CC-CV			50	1 C	N/A	N/A	N/A	N/A	N/A	N/A
Particle Swarm Optimisation (PSO) [59]	2C-CC-CV	Panasonic 18,650 LI-ION CELLS	1RC transient	-29.2	2 C	N/A	N/A	N/A	N/A	N/A	+18 °C
	Minimum charging time (β = 1)			27.43	2 C	N/A	N/A	N/A	N/A	Decays 0.8%	+18 °C
	Minimum Aging charging (β = 0)			-60	0.077 C	N/A	N/A	N/A	N/A	Decays 0.5576%	+0.04 °C
	Balanced charging (β = 0.0113)			51.832	0.89 C	N/A	N/A	N/A	N/A	Decays 0.6276%	+4 °C
Cuckoo Optimisation Algorithm (COA) [34,63]	CC-CV	Lithium Polymer ion battery 1000 mAh	2RC transient	118.33	1 C	---	100	NA	1127.667	N/A	N/A
	The hierarchical technique (HT)			96.92	1 C	5	100	CC-CV + 8%	1039.9	N/A	N/A
	The conditional random technique (CRT)			91.767	1 C	5	100	CC-CV + 14.1%	1010.3	N/A	N/A
Constant Temperature Constant Voltage (CT-CV) protocol [68]	CC-CV	Samsung INR18650-25R cylindrical cell	Thevenin model + Second-order thermal model	85	1 C	---	100	N/A	N/A	N/A	+7.5 °C
	CT-CV			69.5	2 C	---	100	N/A	N/A	N/A	+7.5 °C
Pontryagin's Minimum Principle (PMP) [69]	Real time PMP	Panasonic NCR18650PF	Thermal Dynamics	18	5 C	---	20 to 70	N/A	N/A	N/A	+46 °C
	CC-CV			16	1.61 C	---	20 to 70	N/A	N/A	N/A	+5.5 °C
Genetic Algorithm (GA) optimal charging strategy [70]	CC	LiNMC, 5 Ah, 3.6 V	1RC transient	40.05	0.5 C	---	95.34	N/A	0.77	N/A	+2.13 °C
	Optimal Improvement			36.1	0.5 C	---	95.34	N/A	0.7	N/A	+1.91 °C
Two Stage Constant Current (2SCC) [71]	High-low profile	A123 26,650 LiFePO <sub>4</sub> graphite cylindrical battery cell	N/A	30	2.6 C to 0.6 C	2	80	98.1	6.62	N/A	+8 °C
	Low high profile			30	0.6 C to 2.6 C	2	80	95.1	6.83	N/A	+8.5 °C

### 3.3. Thermal Management Protocol

Thermal management charging protocol depends on the control of the ambient and cell (battery) temperatures during the charging process. Due to battery temperature being considered a key degradation metric, a new fast-charging constant temperature constant voltage (CT-CV) protocol was presented in [68] and is represented in Figure 5. The CT-CV protocol is based on applying an initial current until 2 C of the battery is reached, then an exponentially decaying current profile until 1 C; once the battery voltage reaches 4.2 V, the current starts decaying until 0.1 C, as shown in Figure 5. To maintain a constant



temperature, the Proportional-Integral-Derivative (PID) conventional controller is utilized with the aid of a feed-forward term.



**Figure 5.** Schematic diagram of the Constant Temperature Constant Voltage (CT-CV) Protocol.

In [69], Pontryagin's Minimum Principle (PMP) was implemented in fast charging to solve the optimal control framework to minimize the charging time and ohmic heat generation. In [70], a 1 RC transient equivalent circuit, power loss model, and thermal model were built. The integrated fitness function was formulated to minimize the energy loss and temperature increment during the charging process where the parameters were estimated by a genetic algorithm (GA).

In [71], a two-stage constant current (2SCC) charging protocol without constant voltage (CV) charge was introduced. The 2SCC is based on applying different levels of currents and combinations to a pseudo-two-dimensional (P2D) electro-chemical-thermal coupled model. The proposed protocol studied the thermal behaviour and energy efficiency of a lithium-ion battery for a 30 min charging with 80% rated capacity.

To limit the degradation of the battery, it is recommended in [56] to limit the temperature to a maximum of 50 °C, the surface temperature should not rise more than 15 °C, and the current charging level should not exceed 3 C capacity of the battery.

Ultrafast charging is proposed for 209 Wh/kg pouch cells lithium-ion battery in [72] using the asymmetric temperature modulation (ATM) method. The battery is charged with an initial 5% SOC to 88% SOC within almost 5 min, retaining 97.7% capacity after 1000 cycles. In addition, the ATM method prevents lithium plating within the range of 30–90% SOC and slows down capacity fade by raising the usable capacity by 10%.

The aging behaviour of cycled Li-ion batteries within a wide temperature range –20 °C to 70 °C was investigated in [73]. In this temperature range of –20 °C to 25 °C, the aging rate increases with a decrease in temperature from its nominal value. In the other range of 25 °C to 70 °C, the aging rate increases with an increase in temperature from its nominal operable value. The influence of low ambient temperatures on lithium-ion battery performance was examined in [74,75], where a drop in activity and amount of useable active material, as well as an increase in resistance, resulted in a decrease in the operating voltage and energy supplied.

The articles that used thermal management protocol are summarized with the MSCC protocol from the perspective of the charging time, energy consumption, charging efficiency performance, maximum applied current, cycling, and temperature rise, as shown in Table 2.

It is concluded that temperature is one of the main critical barriers in the fast-charging process, wherein Li-ion batteries are strongly impacted by the temperature change. The acceptable temperature range of thermal management, performance, and safety of the li-ion batteries is from 20 °C to 60 °C [76]. Battery Kinetics is sluggish at low temperatures, while aging accelerates at high temperatures [77]. Charging at low ambient temperatures leads to lithium plating [78,79]. Therefore, enhancing the cold-climate charging ability by pre-heating the batteries is recommended, as demonstrated in [77]. In addition, a multilayer nickel foil is embedded into the battery and used as a heater and sensor where the SOC reaches 80% within 15 min at –50 °C, with the preheating process derived from the 9.5 Ah pouch cell, from –50 °C to room temperature, 25 °C, within 1 min. In contrast,

high temperatures accelerate the side reactions and electrode degradation [80]. Hence, the thermal-management system is mandatory during charging, otherwise the battery could reach abuse conditions and trigger an uncontrollable release of heat due to exothermic reactions and catastrophic hazards [81,82].

3.4. Pulse Charging Current (PCC) Protocol

As an alternative to the CC-CV and MSCC protocols, periodically changed current protocols, which are called pulse charging current (PCC) protocols, have been utilized in the charging process of lithium-ion batteries. PCC depends on the control parameters of duty cycle, frequency, and peak amplitude of the charging current pulses. PCC is implemented on the charging process of the lithium-ion to speed up the charging rate, heating the battery at low-temperature conditions, and inhibiting the growth of lithium dendrites [52]. The reason is to eliminate concentration polarization, increase the power transfer rate, and remove the constant voltage mode [83].

PCC can be categorized as a positive pulsed charging current protocol (PPCC), negative pulsed charging current protocol (NPCC), or a Bidirectional Pulsed Charging Current Protocol (BPCC), as described in Figure 6.

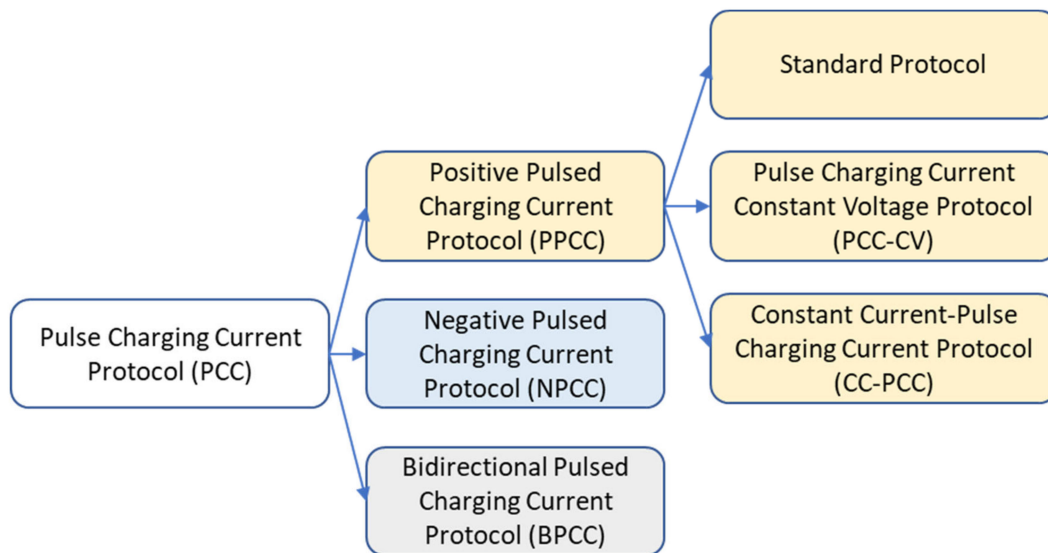


Figure 6. Overall schematic diagram of the Pulse Charging Current (PCC) Protocol.

In the next subsection, we can firstly discuss the positive pulsed charging current protocol (PPCC) and all its branches.

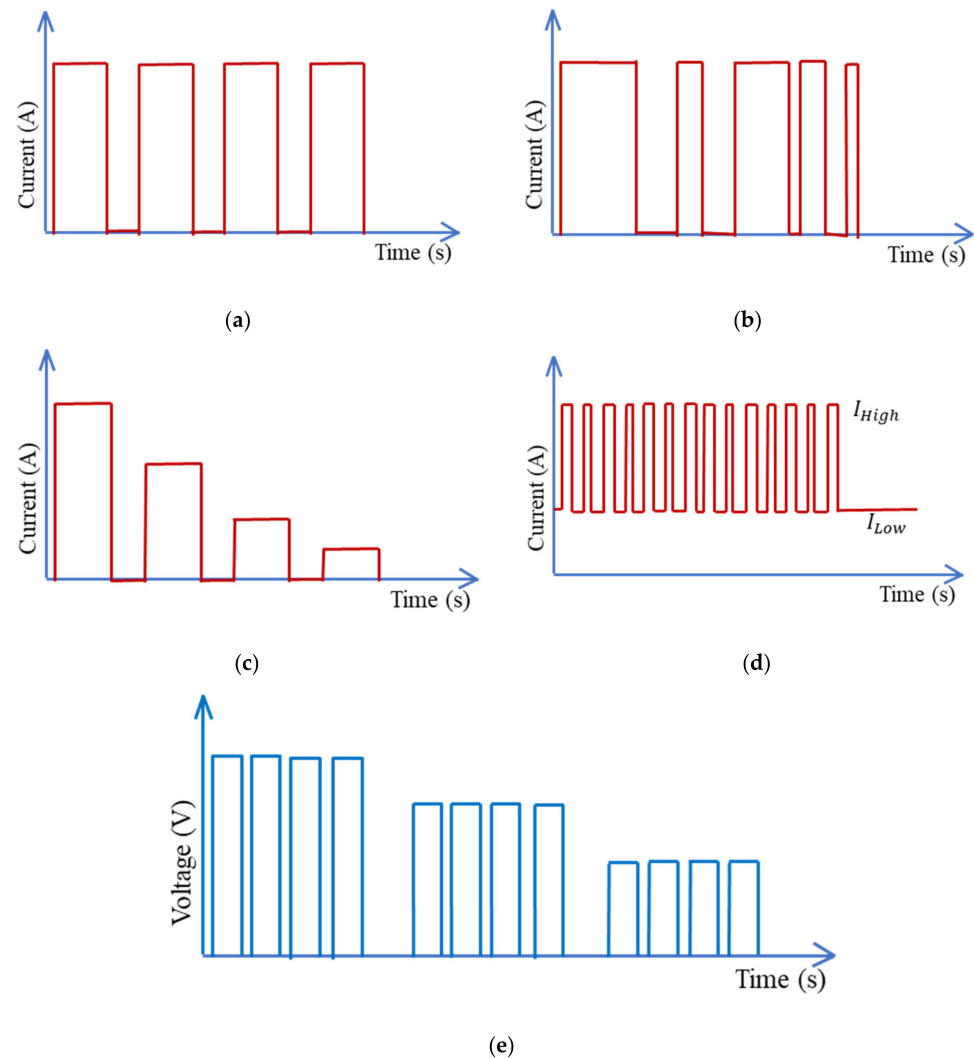
3.4.1. The Positive Pulsed Charging Current (PPCC) Protocol

- Standard PCC Protocol

The standard PCC protocol depends on the charging current pulses, and alternates with high and low current values, frequency, and duty cycle. The impact of charging using this protocol is a reduction in the diffusion resistance, better active material utilization, improved cycle life, and reduced charging time as the constant voltage phase becomes redundant [83,84]. Standard PCC is categorized into constant rest periods with constant amplitude current pulses, where  $I_{Low} = 0$  A, as expressed in Figure 7a, with constant current pulses with different rest periods as in Figure 7b, decaying current pulses with constant rest periods as in Figure 7c, current pulses consisting of two different charge steps varies between predetermined currents  $I_{High}$  and  $I_{Low}$  as in Figure 7d, and different pulse charge voltages [84,85] as shown in Figure 7e. The mentioned methodologies of the standard PCC protocol allow the lithium surface concentration to reach high levels early in the charging cycle [84].

It is stated that the capacity and power density decrease simultaneously while energy efficiency drops as overpotential increases [85]. Consequently, the decrease in the capacity of the cell leads to performance degradation. In [53], the performance of the lithium-ion battery was investigated throughout various duty cycles of 20%, 50%, and 80%, at different frequencies, of 0.1 kHz, 1 kHz, 6 kHz, 12 kHz, 50 kHz, and 100 kHz. The orthogonal arrays (OA) method was used to solve the large experimental domain to find the optimal parameters combination. The remaining battery capacity after 400 full cycles (charge/discharge) at room temperature, using this methodology, is almost 81%, and 75% for both the pulsed charging current and CC-CV protocols, respectively.

It is concluded that at a 50% duty cycle, a better energy efficiency is obtained and a 25% less efficiency is obtained at a 20% duty cycle. In addition, frequencies of less than 6 kHz and greater than 50 kHz produced longer charge times, and energy losses were minimized especially at 12 kHz, thereby resulting in improved performance with an increase in the cycle life compared to the CC-CV protocol. Additionally, it was observed that the higher the peak current, the faster the charging time obtained, with safety circuits implemented to prevent overcharging and overvoltage conditions, and a good cooling system should be applied due to the increase in battery surface temperature.



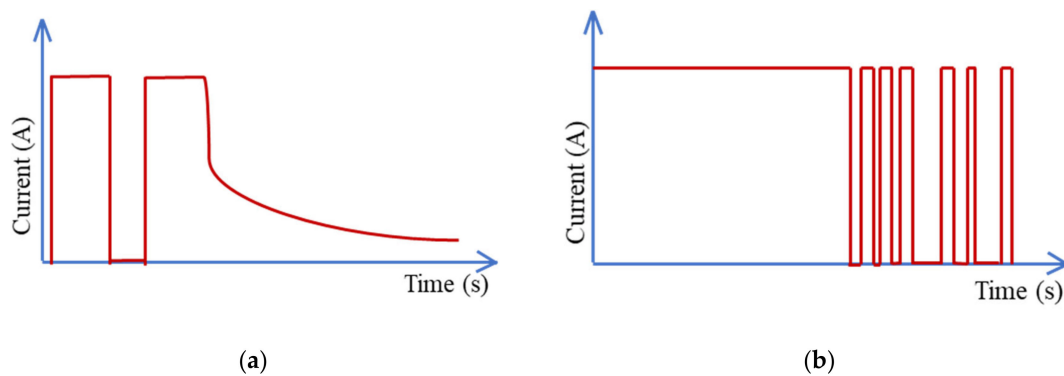
**Figure 7.** Types of the Standard Positive Pulsed Charging Current (PPCC) Protocol; (a) standard protocol with equal duty cycle, (b) standard protocol with various duty cycle, (c) standard protocol with decaying current, (d) standard protocol with upper and lower current limit, and (e) different pulse-charge voltages.

- Pulse Charging Current-Constant Voltage (PCC-CV) Protocol

PCC-CV protocol depends on a sequence of pulse charging currents for a specific interval time which is followed by a constant voltage stage until full charging capacity is reached, as shown in Figure 8a. The PCC-CV was proposed in [86] to study the capacity fading and service life of lithium-ion batteries under different charging–discharging strategies, which reflects the growth of solid electrolyte interphase (SEI). Compared with the CC-CV protocol, the PCC-CV revealed better cyclic performances because of the smaller average currents.

- Constant Current-Pulse Charging Current (CC-PCC) Protocol

In this protocol, the lithium-ion battery is charged using a constant current (CC) mode until a predetermined voltage level is reached, then the CC mode is switched to pulsating charging current mode as shown in Figure 8b. In [31], the Constant Current-Pulse Charging Current (CC-PCC) protocol was proposed. Rectangular current pulses with a constant duty cycle of 50% were specified and utilized to avoid distortions due to different mean charging currents, reflected by reducing the charging current or increasing the pause lengths. However, It is concluded that the CC-PCC protocol leads to a longer charging time than the CC-CV protocol.



**Figure 8.** (a) Pulse Charging Current-Constant Voltage (PCC-CV) protocol, and (b) Constant Current-Pulse Charging Current (CC-PCC) protocol.

A comparison between the different categories of the positive pulsed charging current (PPCC) protocol is presented in Table 3. Herein, it is concluded that all the proposed methodologies of the PPCC protocol have almost the same effect on the cycle life while used in the charging process.

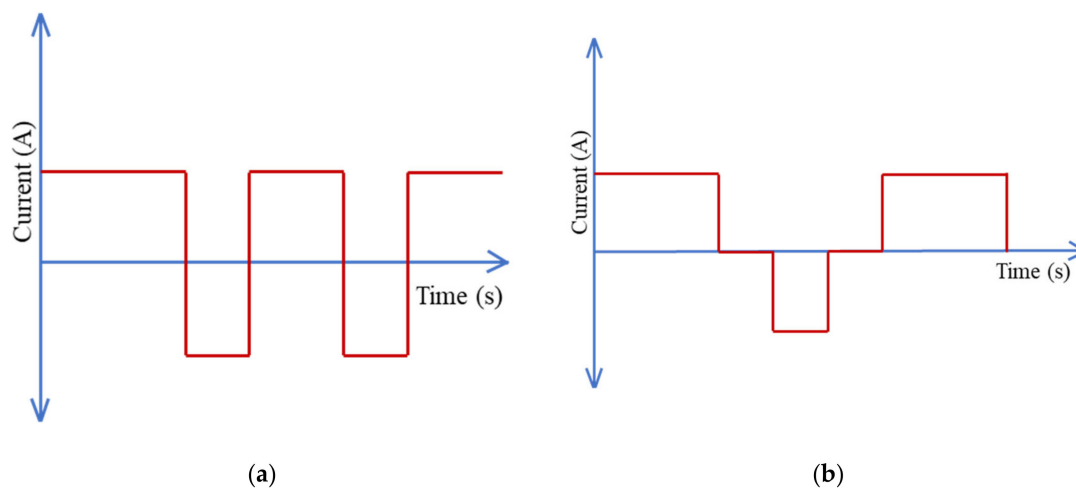
**Table 3.** Comparison between different types of Positive Pulsed Charging Current (PPCC) Protocol.

Protocol Type	Duty Cycle	Frequency	Compared with	Impact
Standard PCC based on Orthogonal arrays [31]	50%	12 kHz	CC-CV	+100 cycle life
Standard PCC [87]	50%	25 Hz	CC-CV	Same cycle life
	50%	1 Hz		Same cycle life, only a somewhat faster capacity fade can be observed
Pulse charging current constant voltage (PCC-CV) [86]	50%	0.02 Hz	CC-CV	Same cycle life
Constant Current-Pulse Charging Current (CC-PCC) [31]	50%	2.5 Hz	CC-CV	Same cycle life

### 3.4.2. Bidirectional Pulsed Charging Current (BPCC) Protocol

Low-temperature charging is considered a major challenge for lithium-ion batteries due to the degradation and cycle life [83]. Charging at low temperatures increases polarization, affecting capacity, causing an internal short circuit, and presenting the possibility of lithium plating. Herein, Joule heat is used to generate self-heating via the internal resistance of the battery and eliminate heat loss from any external heating equipment [83]. The PCC protocol is used to warm the battery from  $-10\text{ }^{\circ}\text{C}$  to  $3\text{ }^{\circ}\text{C}$  firstly, and then the charging is switched to the CC-CV protocol [83].

Furthermore, the bidirectional pulsed current is proposed to obtain the main data of the thermal action to comprehensively analyze heat-generation characteristics and the thermoelectric coupling model based on the second-order RC circuit to verify the basic principle [88]. The bidirectional pulsed current increases the heating speed, consequently decreasing the risk of lithium plating and ensuring safety. It is concluded that whenever the bidirectional pulsed current methodology is implemented, at a low temperature and a high current rate, overcharge or discharge will not significantly affect the life span or increase the safety risk of lithium-ion batteries. BPCC protocol has different implementation types as shown in Figure 9, based on the existing interval time between the positive and negative pulses [88]. Normally, the negative current helps in reducing the polarization voltage caused by the positive pulses and polarizes it in the opposite direction, as stated in [89].



**Figure 9.** Different types of the ideal bidirectional pulsed charging current (BPCC) where (a) the standard normal operation, and (b) Operation while having a relaxing interval time between the positive and negative pulses.

### 3.4.3. Negative Pulsed Charging Current

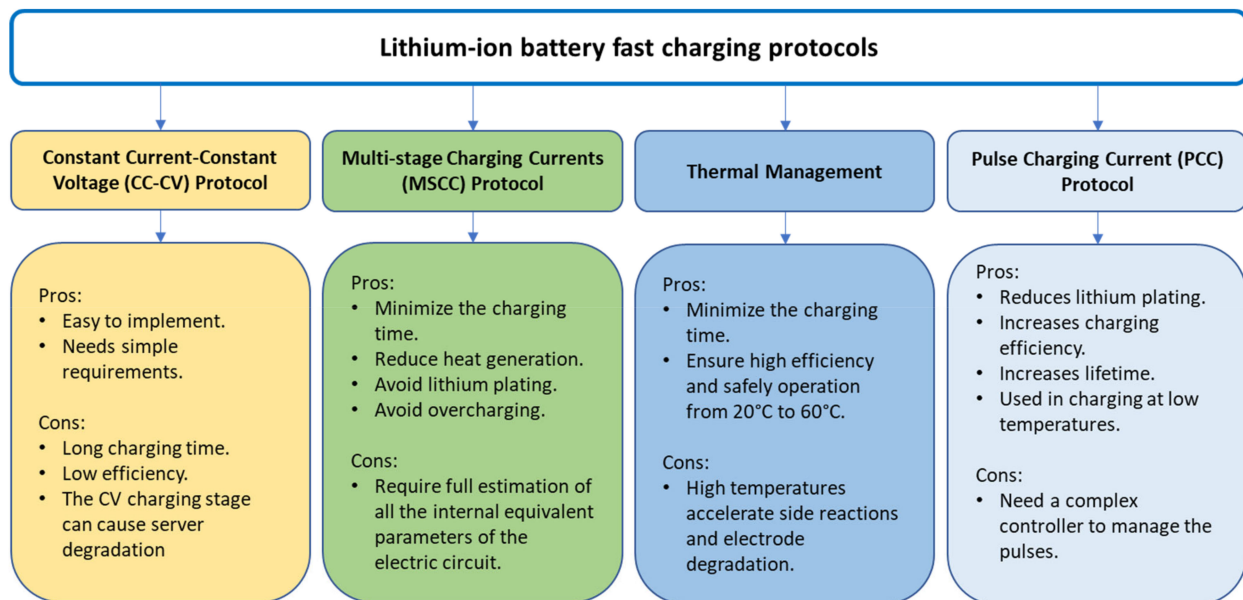
The negative pulse fast charging method (FCNP) was analyzed in [90], and ensured ion recovery from metallic lithium, hence the capacity loss was minimized; however, the same charging speed as the CC charging protocol was obtained. In addition, FCNP limits side reaction during anode potential, terminal cut-off voltage, and side reaction rate by incorporating it into a reduced-order electrochemical model (ROM) with an extended Kalman filter. A full comparison between the CC-CV at different capacities and FCNP is implemented on the pouch-type lithium-ion battery cell, freshly charged and after various cycles, as expressed in Table 4. The charging time for up to 100% SOC by FCNP is longer than that of the 3C CC-CV charging protocol, however, it becomes shorter as degradation is in progress, particularly after 40 cycles. On the other hand, the capacity loss by FCNP is comparable with that of the 2C CC-CV charging protocol, which is approximately 23% less than that of the 3C CC-CV charging protocol after 60 cycles.

**Table 4.** A Comparison between the negative pulsed charging current and CC-CV protocol.

	Up to 80% SOC Fresh Cell	Up to 100% SOC Fresh Cell	Up to 100% SOC after 20 Cycles	Up to 100% SOC after 60 Cycles
3C CC-CV	15.7 min	44 min	47.3 min	55.2 min
2C CC-CV	22.8 min	56 min	56.1 min	59.2 min
FCNP	16.6 min	49 min	51.1 min	52 min

The Pulse Charging Current Protocol, with all its proposed categories, reduces the risk of lithium plating, reduces the charging time, increases charging efficiency and battery lifespan [91], leads to low heating and the low degradation of materials [15]. In addition, the risk arising from charging batteries at low temperatures can be alleviated using this protocol. However, the main drawback is the complexity of the controller.

We can summarize the previous findings and the current challenges of the power management protocol with all its methodologies by stating their advantages and disadvantages, which are as presented in Figure 10.



**Figure 10.** The pros and cons of the power management protocol with all its categories.

#### 4. Material Aspects Charging Protocol

Recently, researchers have directed their attention to the Extreme Fast Charging (XFC) which mandates a charging rate equal to or greater than 6 C [92]. XFC leads to cathode particle cracking, low active material utilization, electrolyte–electrode side reactions, and lithium plating at the anode. The mentioned cons can be summarized as electrode variability [92,93].

In [92], the cathode particle cracking and electrolyte modification (concentrated electrolyte and low viscosity additives) limitations have been identified to ensure safety and stability problems. In [94], an electrolyte additive trimethylsilyl isothiocyanate (TMSNCS), based on amino silane with a high electron-donating ability that can scavenge HF and PF<sub>5</sub> has been proposed to solve the detrimental effects of LiPF<sub>6</sub>.

The authors in [95] investigated the XFC performance for a cell with a low loading of 1.5 mAh.cm<sup>-2</sup> and moderate loading of 2.5 mAh.cm<sup>-2</sup>. It is concluded that the combination of increasing the battery temperature, reduction in the electrode tortuosity, and enhancement of the ion transport in the electrolyte are required to facilitate the CFC for high-energy lithium-ion batteries. Lithium bis (fluor sulfonyl) imide (LFDI) was utilized



in [96] to provide a fast charging capability of high energy density because of its high conductivity and high lithium-ion transference number compared to  $\text{LiPF}_6$  salt. In addition, a physical–chemical model is introduced in [97], which improved the discharge-rate capability of the lithium-ion cells via the laser-structured graphite anodes.

Fast charging protocols based on the material modification are interesting and require a detailed and clear description as well as a comparison between different physical, material aspects, and chemical structures of the lithium-ion batteries to evaluate and summarize the extremely fast charging protocol, such as that mentioned in the review papers [92,93,98,99].

## 5. Conclusions

This paper reviews the current up-to-date status and implementation of the lithium-ion battery fast charging protocols. The fast-charging protocols are divided into power and thermal management protocols, which depend on the electrical charging current, voltage, and cell temperature. Power and thermal management protocols are categorized as constant current constant voltage (CC-CV), multi-stage charging current (MSCC), thermal management, and pulse charging current protocols. In addition, fast charging protocols based on material modification, physics, structures, and aspects were reviewed. This paper reveals the full comparison between the sub charging methods of each charging protocol and the impact on the charging time, efficiency, lifetime, cell temperature, and energy loss of the lithium-ion batteries. In addition, we presented up-to-date charging strategies that are not mentioned in other literature reviews and stated the pros and cons of each charging protocol to improve the existing protocols and initiate novel research. Importantly, there is a direct need to enhance the charging process at different temperatures and at a relative humidity for applicability worldwide and during different seasons. Therefore, artificial intelligence (AI) has to be applied in proposing a dynamic charging protocol and improving the modelling of the lithium-ion battery at various ambient circumstances to ensure a safe charging process with a minimal charging current, maximum efficiency, and increased lifespan.

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