A Survey on Efficient Charger Design for Modern Electric Vehicles

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Abstract

The demand for charging facilities in electrical vehicle is very high. In the implementation and development of electric vehicles or plug-in hybrid electric vehicles, the efficient charger design is a critical and essential step. The battery performance depends on the design of the modules and application of the charged. This paper presents various surveys on efficient designs of batteries for electric vehicles, and they have their advantages and limitations. Researches proved that batteries have various optimal factors for charging and discharging performance. Only various battery technologies affect battery performance, how the battery will be used and how it will be charged also greatly affects battery performance.

Keywords: Electric Vehicle, Charger Design, Battery Performance, Environmental Impact.

1 Introduction

The first practical electric vehicle was built by Thomas Davenport in 1835 (motor patented: February 25, 1837). Although diesel and gasoline vehicles were introduced by 1900, the internal combustion engines they used were not perfect yet and steam engines had their own limitations. Hence, Ferdinand Porshe (first 1898 model: Lohner Porshe) and Thomas Edison set out to build and popularize electric vehicles, which were being seen as the future of mobility [1].

By 1914, Henry Ford had introduced an efficient assembly line for mass production of gasoline vehicles that brought down the price to $260 as compared to an Electric Roadster costing $1750. Additionally, the invention of the automatic starter combined with the superior range of petrol cars impacted the viability of electric vehicles. The battery technology just was not there.

By 2000, with the development of light-weight and high energy density lithium-ion batteries, soaring oil prices and environmental pollution, EVs began gaining popularity again. Tesla Motors and other car manufacturers have pledged to shift towards electric for a greener future [2, 3].

1.1 Why is EV the New Buzzword?

More often than not, whenever change happens, it is just history repeating itself. The EV segment of the automobile industry has shown a similar trend: from about 40% in 1900, to almost nil by 1935, and sharply increasing again as we approach 2020. Predicted to be the next disruptive market force for transportation, EVs have the potential to revolutionize how energy is used, created and redirected [4].

Benefits of Going Electric

Fights Global Warming: One of the primary reasons for the introduction of electric cars into the market is the concern over greenhouse gas emissions and their contribution to global warming. Elimination of the exhaust pipe in electric cars promotes sustainable mobility.

Better Energy Efficiency: EVs are 75% efficient at turning input energy into kinetic energy, while gas-powered vehicles with internal combustion engines (ICE) are only 25%.

Low Maintenance Costs: An average driver could save approximately $ 860 a year on gas costs when they switch to an electric car. A 50 kWh battery has a range of 220 miles and charging it fully costs about $ 5.5, whereas fuel costs about $21 for the same range.

In the future, it is likely that all cars will be electric. In fact, there are already pledges in place by many car manufacturers to have a full electric fleet in only a couple decades. It's time to embrace the change and look towards our future.

1.2 Why is the Charger Design so Important?

The charging infrastructure plays a vital role in the EV market. One of the prime reasons why EVs are not able to penetrate certain market segments is the "charging anxiety". Simply put, it takes a lot of time to charge an EV, making it a problem for emergencies. For a typical EV, the time taken to add 100 miles of range varies from 26 hours for the slowest AC charger, to 6 minutes for the fastest DCFC (Direct Current Fast Charger) – still far slower than the 300 miles/minute enjoyed by a 30 mile/gallon ICE [5].

Faster charging implies a more powerful charger, which in turn implies higher operating current levels and hence demands an efficient power electronic design. Several protection and communication features are also vital while charg-

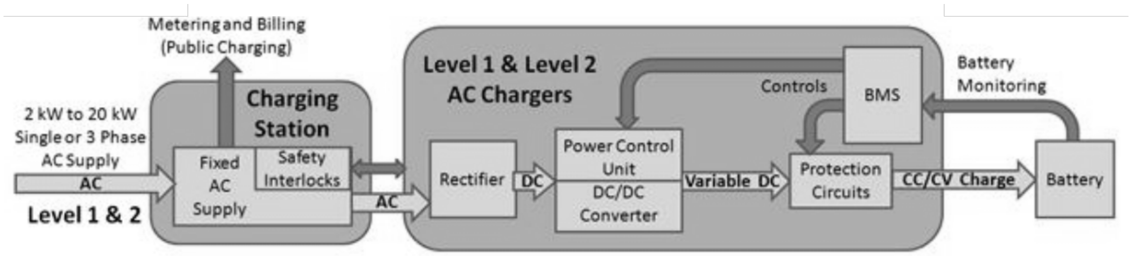

Figure 1: Electric Vehicle Supply Equipment

ing, thus arising the need of the commonly known Electric Vehicle Supply Equipment (EVSE) as presented in Figure 1, a protocol to help keep the user and the electric vehicle safe while charging.

2 Environmental Impact of Electric Vehicles

Research has shown that electric cars are better for the environment. They emit fewer greenhouse gases and air pollutants than petrol or diesel cars. And this takes into account their production and electricity generation to keep them running [6].

The major benefit of electric cars is the contribution that they can make towards improving air quality in towns and cities. With no tailpipe, pure electric cars produce no carbon dioxide emissions when driving. This reduces air pollution considerably. Put simply, electric cars give us cleaner streets making our towns and cities a better place to be for pedestrians and cyclists. In over a year, just one electric car on the roads can save an average 1.5 million grams of CO_2 [7, 8].

Well-to-wheel efficiency of electric cars are considering the enormous worldwide increase of mobility expected for the future, the reduction of automobile energy. demand is one of the most important challenges. In order to evaluate the technologies available, energy consumption is divided into the well-to-tank (WTT) and the tank-towheel (TTW) demands. WTT refers to the stage from the extraction of feed-stock until the delivery of fuel to the vehicle tank. TTW quantifies the performance of the drive-train. Together, both result in the overall well-to-wheel (WTW) efficiency. The WTW evaluation allows estimation of the overall energy and efficiency of automobiles powered by different propulsion technologies [9, 10].

However, making electric cars does use a lot of energy. Even after taking battery manufacture into account, electric cars are still a greener option. This is because of the reduction in emissions created over the vehicle's lifetime.

The emissions created during the production of an electric car tend to be higher than a conventional car. This is due to the manufacture of lithium ion batteries which are an essential part of an electric car. More than a third of the lifetime CO_2 emissions from an electric car come from the energy used to make the car itself. As technology advances, this is changing for the better [11–13].

Reusing and recycling batteries is also a growing market. Research into the use of second-hand batteries is looking at ways to reuse batteries in new technologies such as electricity storage. One day we could all have batteries in our homes being used to store our own energy. Opportunities like this will reduce the lifetime environmental impact of battery manufacture [14–17].

2.1 Other Issues in Electric Vehicles

The other issues for using electric vehicles are as follows (Figure 2):

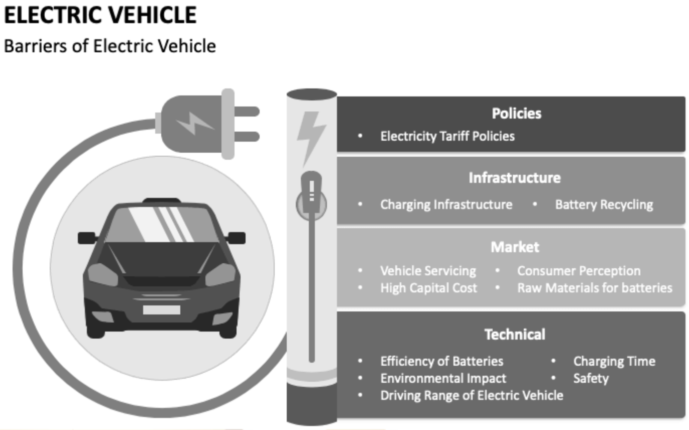

Figure 2: Issues in Electric Vehicles

- Policies
  - Electricity tariff policies
- Infrastructure
  - Charging infrastructure
  - Battery recycling
- Market
  - Vehicle servicing
  - Consumer perception

  - High capital cost
  - Raw materials for batteries
- Technical
  - Efficiency of batteries
  - Charging time
  - Environmental impact
  - Safety
  - Driving range of electric vehicles

3 Related Work

The demand of charging facilities in electrical vehicle (EV) is very high. The charger design plays an important role in the development of electric vehicles (EVs) or plug-in hybrid electric vehicles (PHEVs). The performance of battery modules depends not only on the design of the modules but on how the modules are used and charged as well.

3.1 A Controllable Bidirectional Battery Charger for Electric Vehicles with Vehicle-to-Grid Capability

Melo *et al.* [18] proposed a simple and functional bidirectional PEV (or stationary battery) charger topology, which allows enhancing the capabilities of a joint operation of storage and an autonomous EMS in a residential setting, with potential benefits for end-users and utilities/system operator. The PEV role as load or power supplier is also emphasized. This charger is adjustable for charging or discharging operations using a power level provided by the EMS, instead of minimizing the charging time by using only the maximum power level.

3.2 Design and Control of Battery Charger for Electric Vehicles using Modular Multilevel Converters

Quraan *et al.* [19] proposes a new battery charger for electric vehicles based on modular multilevel converters. The converter produces an extremely low distortion of the output voltage, with direct benefits for the operations as a battery charger. For this reason, the grid filter can be eliminated with benefits on the hardware costs. The proposed charger integrates the battery management system (BMS) in the power converter control and eliminates the need for additional balancing circuits. The state of charges of all battery cells are managed by SOC balancing controllers without affecting the grid voltage and current. The battery cells are charged from the utility grid and the charging operation is controlled via a proportional resonant current controller with a phase-locked loop to charge the cells at unity power factor.

3.3 Efficient AC-DC Power Factor Corrected Boost Converter Design for Battery Charger in Electric Vehicles

Turksoy *et al.* [20] proposed an efficient AC-DC power factor corrected (PFC) boost converter with active snubber cell (ASC) for battery chargers in electric vehicles. The developed active snubber cell (ASC) provides zero voltage transition (ZVT) operation for the turn-on and zero current transition (ZCT) operation for the turn-off of the converter switch. It has been provided that other switching elements are operated under soft-switching conditions. With the help of the ASC, energy efficiency has been increased by minimizing switching losses. The current and voltage stresses have not been observed on any element in the main converter and ASC circuits that cause the size of the circuit components to increase. With the proposed converter, high power density was achieved with less cost and smaller size. The performance of the proposed converter has been tested according to the load conditions in European efficiency standards and different input voltage levels. The peak efficiency of the proposed converter is measured as 97.82% in 220 V rms input voltage and 3.3 kW output power. Also, the unity power factor is achieved in all load conditions and all voltage levels.

Boost circuit inductor value is calculated based on parameters such as maximum duty cycle, inductor ripple current, lowest input voltage and maximum load current as given in following equations [21, 22]:

$$D_{\max} = \frac{V_{\text{out}} - V_{rect.in(\min)}}{V_{\text{out}}} \tag{1}$$

$$V_{rect.in(\min)} = \sqrt{2} V_{in(\min)} \tag{2}$$

$$I_{in(\max)} = \frac{2P_{\text{out}}}{\sqrt{2} \times V_{in(\min)}} \tag{3}$$

$$\Delta I_{in} = I_{in(\max)} \times k_d \tag{4}$$

$$L_1 \geq \frac{V_{rect.in(\min)} T_{sw} D_{\max}}{\Delta I_{in}} \tag{5}$$

where $D_{\max}$ is the maximum duty cycle of the S_1, V_{out} is the output voltage, $V_{rect.in(\min)}$ is the minimum rectified input voltage, $I_{in(\max)}$ is the maximum input current, P_{out} is the nominal output power, $V_{in(\min)}$ is the minimum input voltage, k_d is the ripple ratio, T_{sw} is the switching period, ΔI_{in} is the inductor ripple current.

3.4 Sinusoidal-Ripple Current Control in Battery Charger of Electric Vehicles

Bayati *et al.* [23] proposed electric vehicle (EV) battery charger (BC) with its precisely designed control system that can successfully implement sinusoidal-ripple-current (SRC) charging-discharging method. It is true to state that it can implement even other methods such as constant-current constant-voltage (CC-CV), pulse-current, and Reflex because the reference commands are defined in general forms.

Also, an innovative effective solution to resolve the power quality problem was suggested so that it is able to participate in V2G technology and exchange active and reactive power without fluctuation. The proposed DC-DC stage can be separately utilized in charging stations and DC distribution networks providing services for EVs. Moreover, it can generate the SRC or step signals, suitable for advanced online electrochemical impedance spectroscopy (EIS) algorithms, in a controlled way.

3.4.1 Charging and Discharging System

Figure 3 depicts complete AC-impedance model of Li-ion battery. From the viewpoint of electrical circuit, different charging-discharging frequencies change its magnitude and phase such that it has a minimum magnitude at a particular frequency. To make SRC method, the reference command of the battery current must be defined for the control system as [24, 25]:

$$i_B^* = i_{\mathrm{DC}}^* + i_{\mathrm{AC}}^* \quad (6)$$
$$= I_0 + I_1 \cos(2\pi f_c t) \quad (7)$$

The superscript * denotes the reference command. I_0 and I_1 are constant amplitudes. I_0 is positive in charging mode and negative in discharging mode. The instantaneous power is calculated as:

$$P_B = v_B \times i_B^* \quad (8)$$
$$= v_B \left(I_0 + I_1 \cos(2\pi f_c t)\right) \quad (9)$$

Fourier series of the periodic waveform of i_B in Equation 7 consists of two components, a zero frequency component and a cosine component with the frequency f_c. These components also appear in Fourier series of P_B in Equation 9. f_c is tuned in practice [26, 27].

3.5 High-Efficiency Single-Stage On-Board Charger for Electrical Vehicles

Zinchenko *et al.* [28] presented an isolated single-stage onboard electric vehicle charger without an intermediate DC-link. Based on an isolated current-source topology, the converter features soft-switching in semiconductors regardless of load variation for the full AC line voltage range. Moreover, it requires no external snubber or clamp circuits. The power factor correction and voltage regulation are provided by a relatively simple phase shift modulation, while the amount of circulating energy is kept at minimum. The charger is distinguished by its efficiency characteristic – the maximum is achieved in the constant power charging mode. The control method, component stresses, and design constraints of the topology are analyzed. The concept is verified using a 3 kW experimental SiC-based prototype, which reaches a peak efficiency of 96.4%.

3.6 An Isolated Bidirectional Integrated Plug-in Hybrid Electric Vehicle Battery Charger with Resonant Converters

Ebrahimi *et al.* [29] proposed a new three-phase bidirectional isolated soft-switched PHEV battery charger that benefits a series resonant DC/DC converter. A switching method is also proposed so that all switches of the proposed topology benefit soft-switching operation, minimizing switching losses. The conventional bulky capacitor of the DC link is eliminated as well. Moreover, their proposed structure is an integrated charger that can share the hardware of the traction mode with contactors; contrary to common battery chargers, no bulky reactive component is needed in the proposed structure, and the leakage inductance of the small high-frequency transformer can be used as the reactive element of this topology.

3.7 An Isolated High-Power Integrated Charger in Electrified-Vehicle Applications

Haghbin *et al.* [30] proposed an isolated high-power integrated charger based on a split winding ac motor can yield a charging power of half the traction power. The electric motor stator windings were reconfigured for the traction and charging modes through a relay-based switching device, which, together with a clutch, were the only extra components needed to yield a very cost-effective compact onboard three-phase isolated charger with unity power factor capability. The mathematical model of the electric machine in the charging mode has been presented in detail. Furthermore, the system's functional description and controllers have been explained for grid synchronization and charge control. To verify the system operation for the modeled integrated charger, the simulation results for a practically designed system have been presented, showing that the system has good operation performance.

3.8 Integrated Single-Phase PFC Charger for Electric Vehicles

Truntič *et al.* [31] presented a method which is an interesting approach to reduce the number of electric and magnetic components. It has been shown in the research, that by simply adding an electromechanical relay to the appropriate point in the converter it is possible to use the classical DC-AC inverter, which is normally applied for the control of the electric motor in the power-train, also for the purpose of charging batteries. Even more, the windings of the motor could be used as the power inductor in battery charging mode. It has been proved theoretically and experimentally that it is possible to design a single PI controller for controlling the grid current in both buck and boost, operating modes of the discussed battery charger. By adapting the

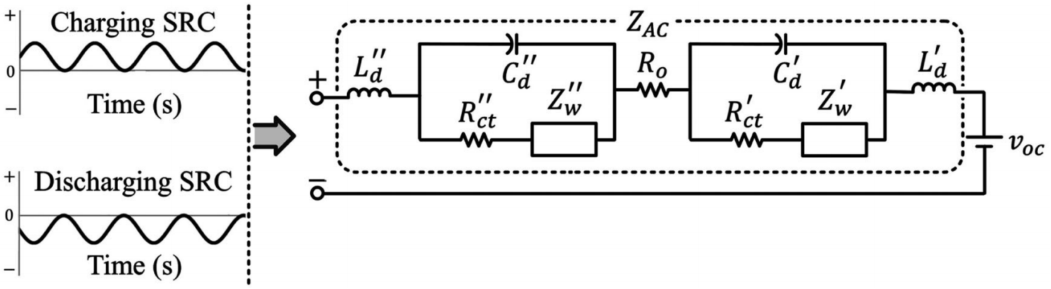

Figure 3: Complete AC-Impedance Model of Li-ion Battery

input current reference as described in this article, smooth operating mode transitions can be achieved.

3.9 Multi-Functional On-Board Battery Charger for Plug-in Electric Vehicles

Kim and Kang [32] proposed a multi-functional battery charging system for plug-in electric vehicles. The proposed charger works for three tasks; on-board charger (OBC) grid-to-vehicle (G2V), inverting vehicle-to-grid (V2G), and low voltage DC-to-DC converter (LDC). Theoretical analysis and design procedures have been described and explained in detail. The validity of the proposed charger was verified by simulation and experiment. For the practical application, voltage rating and average current on switches are investigated in p.u. values. The volume and weight of the proposed charger are compared with individual OBC and LDC.

3.10 Design Methodology of A 3-Phase 4-Wire EV Charger Operated at the Autonomous Mode

Fu *et al.* [33] provided a design methodology of controllers in a three-phase four-wire voltage-source inverter. A neutral leg with split DC-link capacitors provides a stable neutral point, even with extremely unbalanced loads. As the output voltage quality is vulnerable under the autonomous mode with nonlinear load, a voltage controller with a harmonics compensator and virtual resistance is presented to address this problem. The optimized design method of controller is comprehensively analyzed in the frequency domain, and analytical formulas were given with the time delay considered. Thanks to the stabilized neutral point, three-phase legs could be controlled independently. At last, the simulation and experiment are carried out on a bidirectional EV battery charger, which is capable of grid-to-vehicle (G2V), vehicle-to-grid (V2G) and vehicle-to-load (V2L) to investigate the performance of designed controllers in both steady states and transient states.

3.11 High Efficiency Bridgeless Single Power Conversion Battery Charger for Electric Vehicle

Ramya *et al.* [34] proposed a single-power-conversion battery charger without a bridge made up of a boost AC-DC converter that is isolated and with a circuit having resonance in series to suit this need. The circuit with a series resonance decreases by offering zero current switching, you may reduce output diode recovery losses, while conduction losses associated with the input diode rectifier are reduced by using a bridgeless arrangement. Furthermore, injection of current by direct and series-resonance allows the transformer to excite the core in both directions, providing for high power capabilities. In conversion of power using single stage, the feedback linearization-derived control algorithm is also built, allowing the suggested charger for power factor correction and output power regulation.

3.12 Modified Repetitive Control Design for Two Stage off Board Electric Vehicle Charger

Seth and Singh [35] designed and implemented a three-phase, two stage, bidirectional off board plug-in Electric Vehicle (PEV) charger controller in real time. The proposed PEV charger is able to work in all four quadrants in active–reactivepower plane. Generally, power electronics converters are controlled by PI regulators in $d-q$ reference frame, where the signals to be regulated are inherently DC in nature. These controllers are implemented in two loops i.e., Slow (outer) control loop and fast (inner) control loop. Setting the gains of outer loops are little bit easier in comparison to fast acting inner loops besides the involvement of decoupling terms to have independent operation of active and reactive current components. Therefore, a repetitive controller (RC) is designed to regulate the inner sinusoidal reference current having both active–reactive components as per the control requirement without involving any decoupling terms.

3.13 Design of Single-Inductor Double-Input Double-Output DC-DC Converter for Electric Vehicle Charger

To meet out this demand, Ramanathan *et al.* [36] proposed dual input and dual output DC-DC converter for charging system in the EV charging technology. This proposed system consists of two inputs, two outputs and a single inductor in its architecture. It works in boost condition for both the given inputs. Here, one source is used for boost condition and other source is also utilized in boost condition, with these conditions its importance is established in the new systems of this filed. This is possible because of the constant current control at input in which the sources are controlled by duty cycles. The output is controlled in different method that any change in one of the outputs do not affect the other. It has the feature of DC-DC converter to regulate the noises and high frequency-based switching help them to put switching losses to minimum and reason to adapt for boost condition is to reduce the diode losses as in most systems. This system also uses only few components than most converter-based systems.

3.14 Unidirectional Voltage Converter for Battery Electric Vehicle Ultrafast Charger

Szymanski *et al.* [37] demonstrated the possibility of adapting drive frequency converters (FCs) to the needs of electric vehicle batteries charging. After using a rectifier attached to the drive inverter, a DC voltage source with adjustable value was obtained in such a way that a constant current of battery charging was ensured. The software functions of drive FCs are used here to shape the inverter voltage characteristics and thus the value and quality of the rectified voltage. The use of rectification and inverter implemented in the one power integrated circuit eliminates the negative side effects of the inverter CM voltage.

3.15 An Isolated Bridgeless Cuk–SEPIC Converter-Fed Electric Vehicle Charger

Kushwaha *et al.* [38] developed a single-stage electric vehicle (EV) battery charger with an isolated bridgeless (BL) Cuk–single-ended primary-inductor converter (SEPIC) converter. The design of proposed charger is ensured in discontinuous conduction mode with intrinsic power factor correction (PFC) at ac mains. Compared to the BL Cuk converter topology when used for both positive and negative cycles, the proposed topology has reduced number of components with improved efficiency. This is due to integration of Cuk and SEPIC converters during the individual half cycle. The presence of output inductor at Cuk converter side also smoothens the output current, as compared to SEPIC converter used for both cycles. A high power quality (PQ) operation of new BL isolated PFC converter with an EV battery load of 48 V/100 Ah is verified using single-phase PQ analyzer. A laboratory prototype of proposed charger is developed and validated to corroborate the efficient performance during two charging profiles. Test results are shown under steady state as well as over extreme load and line conditions. Different performance indices such as displacement power factor (PF), ac mains PF, and mains current distortion are recorded, which comply the IEC 61000-3-2 standard.

3.16 Burst Mode Elimination in High Power *LLC* Resonant Battery Charger for Electric Vehicles

Shafiei *et al.* [39] introduced a special *LLC* tank design method driven by both Variable Frequency (VF) and Phase Shift (PS) to achieve all the regulation requirements for battery charging (from recovery, bulk, equalization, to finish). The design procedure was based on multivariate design methodology and resulted in advantageous extreme regulation in the converter and the elimination of detrimental burst mode operation. The complete analysis of the resonant converter (higher order including leakage inductance), along with mathematical equations, were presented in order to optimize and select the normalized parameters of the LLC resonant converter. The main advantage of the LLC resonant con verter with the proposed modulation strategy is its ability to regulate the output voltage from close to zero up to 1.5 times the nominal voltage in continuous conduction mode with low switching frequency variation, while providing soft switching conditions for semiconductor devices in all operating conditions.

4 Proposed Approach

Based on survey presented in this paper the following work can be approached as:

- The phase-shifted full bridge (PSFB) converter can be tested along with the power factor correction (PFC).
- Components of electric vehicles sizing can be done more efficiently to reduce the overall size and weight.
- Heat sink design and fabrication can also be looked for overheating issues.
- A central software can also be looked into that will control battery management system and charger simultaneously and it will improve according to the utilization of the user.

5 Conclusion

This paper presents various surveys on efficient designs of batteries for electric vehicles, and they have their advantages and limitations. There are many environmental benefits of using electric vehicles. The proper policies, infrastructures, market strategies and technological aspects are required to be implemented.

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