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Design Of Fast Cycloconverter-Based Battery-Charging Circuit For HighPenetration Of Electric Vehicles

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Abstract. There have been growing concerns involving the penetration of Electric Vehicles (EVs) due to the time required by its battery to attain full charge. Interests in EVs had recently experienced a dramatic turn down due to mileage limitation on full battery charge amidst the cost ofpurchase, but most notably due to the absence of quick chargers that can keep the vehicle on the road within few minutes of arriving at the charging station. Researchers had proposed different charging schemes such as level II ac charging, dc charging, and in some cases, wireless charging schemes that later appear to be inefficient. The use of dynamic or simply road-way powered electricvehicles was also proposed in the literature. However, the proposed cycloconverter-based circuit was simulated in Simulink, and the results obtained proved that the rate of charge increased when compared to the conventional EV charging circuit. Also, the focus is on battery charging technologyand battery modeling for application in an electric vehicle.

Keywords: battery; cycloconverter; electric vehicle; rectification; state-of-charge.

Introduction

To meet future mobility needs, decrease gas and toxic emissions, and eliminate dependence on fossil fuels, automotive technologies need to be substituted by further effective, efficient, and clean environmentally-friendly alternative energy sources. On the evolution of a sustainable society, proficient mobility technologies are mainly desirable worldwide. Electric vehicles have been recognized as being such a technology. In parallel, some nations, like Denmark, Germany, and Sweden have agreed to replace electricity production from fossil fuel to renewable energy sources [1], hence, further advancing sustainability and viability of electric vehicles when compared with internal combustion engine vehicles. Most notably, plug-in hybrid electric vehicles (PHEV) are becoming increasingly popular. This type of vehicle carries both a conventional gasoline engine along with a battery and an electric motor. The battery can be charged by plugging into an outlet ora charging station. As such, the PHEV attempts to use the best of two worlds: The long driving range is provided by the conventional gasoline engine, while the electric power train makes the vehicle efficient and clean. In combination with these reasons, some countries are not offering tax deductions on hybrid cars, while EVs are often fiscally incentivized [2]. While hybrid and gasoline vehicle relies on a rather complex power train, an electric vehicle is, on the other hand, quitesimple. It consists of mainly three electric power components: an electric motor with a gearbox, battery, and power electronics for driving the motor and charging. An EV often uses a fixed-ratio transmission because the motor can run at many speeds and still provide its maximum torque and power [3].

Few frictional parts are between the motor and wheels which cause electric vehicles to require less maintenance. The frictional parts are the motor bearings, the single gear in the gearbox and the wheels drive shafts. One of the reasons for adequate research in fast charging is its potential for mitigating range anxiety, which is the major impeding factor to high penetration of EVs in the transportation market. If drivers can charge their vehicles in less than 20 minutes, then longer trips are made possible because EVs can be charged without inconvenient waiting times. This makes it possible to travel any distance, and potentially also serving the users that require up to 1000 km of driving a day or more. Thus, fast charging technologies are paramount in increasing the rate of EV penetration and consumer acceptance. With the growing research on wireless charging [4], EVshave the potential to upset the transportation market soon due to the improved safety feature and convenience of this type of charging system.

DC Charging. With DC charging stations, the AC-DC conversion takes place in the station itself, off-board the vehicle. In contrast, AC charging station transfer grid AC power directly to the vehicle's on-board converter. Many DC charging stations weigh between 300kg and 800kg, requiring elaborate planning and several people for installation. Hence, this increases installation costs [2].

Level 1 and 2 AC Charging. Level 1 and level 2 AC charging are assumed to be the normal charging levels, which will take place where the vehicle will be idle for a substantial amount of time, such as home or office. However, the disadvantage of charging a vehicle with these normal charging levels is that it can take 4 to 20 hours depending on available power, battery size, and SOCof the battery, and this is not a viable option when long travel distances are considered [3].

The Level III Charger. This is the most interesting and practical one for the installations in public places like commercial areas since it enables easier integration of PHEVs and EVs into the market. For this reason, many developed countries are planning on using the level III, off-board quick chargers, especially in western Europe. With this charging method, EVs can be charged between 10 to 30 minutes [5].

Fast Charging Outcomes. The need for fast charging is highly indispensable. As such, we need an intelligent charger that will charge the electric vehicle within 10 to 30 minutes. Besides charging a battery car to 80% of its SOC is typically 15minutes, fast charging also decreases and increases productivity in two ways.

- Fast chargers are known to be more efficient than conventional chargers and charging with less overcharging increases than battery efficiency.
- Fast charging technology increases vehicle speed.

The main issues in fast charging reside in the four main failure mechanisms of industrial batteries. They are listed below:

- Positive active material shedding
- Imbalance among battery cells
- Corrosion of the positive plate grid
- Suffocation of negative plates.

Conventional Charging System. In constant current / constant voltage (CCCV) mode, the batteryis first charged in constant current mode to 70% SOC, then it is charged in constant voltage mode. To implement fast charging, several algorithms and methods have been found, and among them is a fully digitized smart method involving a combination of a high continuous constant chargingcurrent and some charging pulse current. Such techniques consider the actual charge state of the battery and battery previous charges and discharges. The level III fast charging provides DC power via DC connector by drawing power from AC or DC sources. The conversion from AC to DC and vice versa and among them is done through converters such as AC controller (AC to AC), Chopper (DC to DC), Rectifier (AC to DC), Inverter (DC to AC).

Battery Modelling. The charging process can be facilitated if the battery system is well defined and understood. For this reason, the battery must be modeled into a system whose physical response canbe simulated and analyzed. Given the complex nature of electrochemical energy storage devices, several approaches for predicting their voltage behavior have been adopted [6]. Method 1 (steady- state modeling) uses the charge and discharge curves provided by battery manufacturers to estimate the relevant battery parameters. This method is sufficient for estimating the steady-state (constant current) characteristics of a battery cell but is limited under conditions of dynamic loadings. Method2 (dynamic modeling) uses an equivalent circuit model to capture the dynamic behavior of the battery cell. This is the most common modeling technique. Method 3 (electrochemical modeling) models the behavior of the battery cell from first principles. This approach requires a good understanding of materials, electrochemistry, thermodynamics, and chemical reaction kinetics.

Cycloconverters. A cycloconverter is a direct-frequency changer that converts AC power at one frequency to AC power at another frequency by AC-AC conversion. Cycloconverters are used in high power applications driving synchronous and induction motor. They are usually phase- controlled, and they use thyristors due to their ease of natural (phase) commutation [7].

Methodology

A source voltage, AC with a peak value of 380V and a frequency of 60Hz, also consisting of a single-phase full-wave rectifier circuit consisting of four diodes. This utilizes the Constant Voltage Constant Current (CVCC) charging method with an average value of the charging current (constant)as shown in Figure 1. In contrast, the charging voltage is the source voltage. The battery nominal voltage is 360V, and it is slightly less than that of the charging source, as shown in Figures 2 and 3, respectively. The rated capacity is chosen to be 167Ah, which mimics the actual value of a practicalEV battery. This value is carefully calculated and chosen based on the real parameters of EVs in themarket. For example, the Tesla Model S has a capacity of 60 kWh, dividing this value by thebattery nominal voltage should give an approximate value of 167Ah.

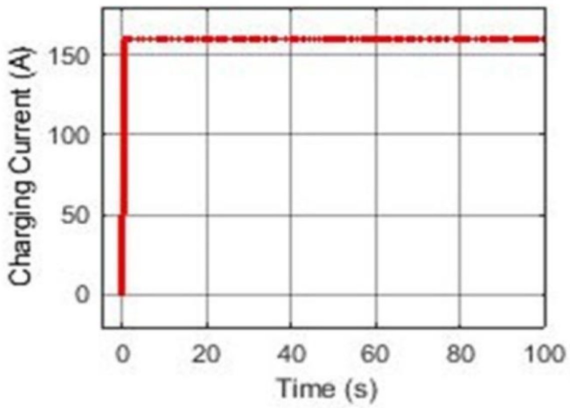

Figure 1: Charging Current against Time

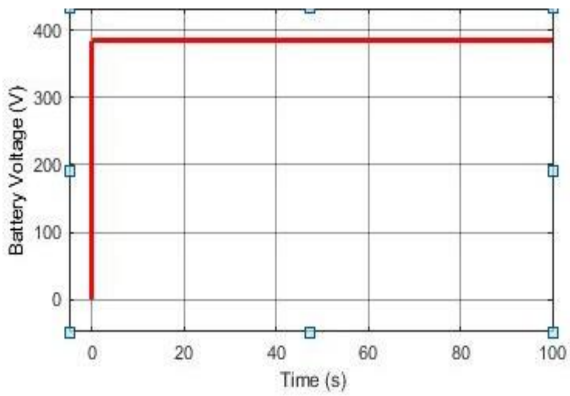

Figure 2: Battery Voltage against Time

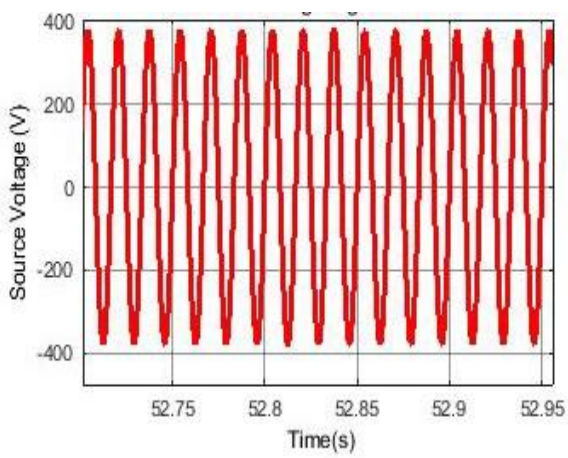

Figure 3: Source Voltage against Time

The current capacity is derived using equation (1), also to derive the source voltage from equation (2) using the nominal voltage, which is rated at 360V.

(1) $$I = \frac{EV_{capacity}}{nominal\ voltage}$$

(2) $$\frac{N_2}{N_1} = \frac{V_2}{V_2}$$

The full-wave rectifier allows the input AC source to complete its current flow circuit in both positive and negative half of the AC cycle. The initial state of charge (SOC) is also 30% (0.3), as it is not advisable to drain your battery to 0%. The blocking diode in the circuit is used to block the current so that the battery does not discharge; instead, it receives current from the source. In so doing, the discharge current is made to be zero, as shown in Figure 4.

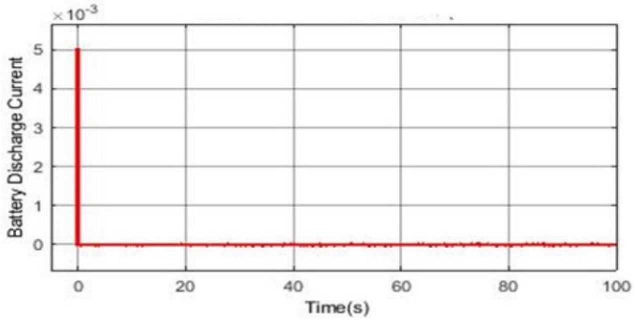

Figure 4: Battery Discharge Current against Time

Furthermore, the cycloconverter is integrated between the AC source and the rectifier, the main function of the cycloconverter, between the source and the rectifier, is to attain a higher SOC slope. For this design, a starting frequency of 50 Hz was employed, which was then stepped down to the desired frequency of 25 Hz, followed by rectification to DC, which will eventually charge the battery then drive the load, Electric Vehicle. The efficiency of cycloconverters is the range of other power electronics devices, i.e., 94 - 98% [8], with the losses owing to conduction and switching activities. The conduction losses are a function of the internal resistances of the system components. The overall block diagram for the EV charge model and the cycloconverter-based circuit is shownin Figure 5.

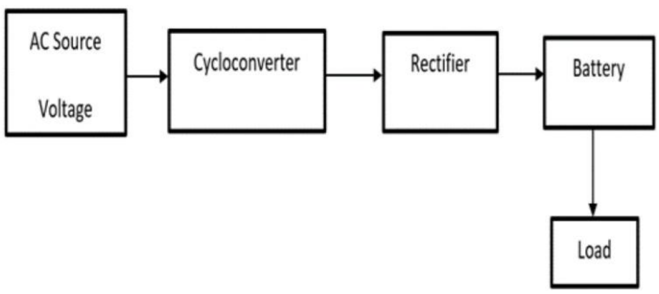

Figure 5: The overall Block Diagram for the EV Charge Model

Results and Discussion

The results showed in Figures 6, and 7 depict that the state of charge (SOC) increases when charging the battery. This will lead to a corresponding battery voltage value that is slightly higher than the nominal when the battery is fully charged. The simulation ran for 100 seconds. Consideringthat EVs must be charged faster for a maximum time of 10 minutes, very high charging current will be required to charge EVs at this rate. The battery discharge current for the EV is expected to be zero. Deep- discharge cycles are not needed for lithium batteries, unlike NiCad batteries. So, there should not be a simultaneous charging and discharging going on as the case may be insteadreceiving current from the source.

It was observed that the SOC rate as a result of using the cycloconverter is higher as compared to when a cycloconverter was not used. The SOC for both cases is shown in Figures 6 and 7,respectively. The SOC reached about 50% in 100 seconds, which was about 1.7 times faster. The cycloconverter reduces the frequency to half the original nominal frequency. The effect of a higher SOC of the EV battery is that it will enhance the fast charging of the electric vehicle within an acceptable waiting time.

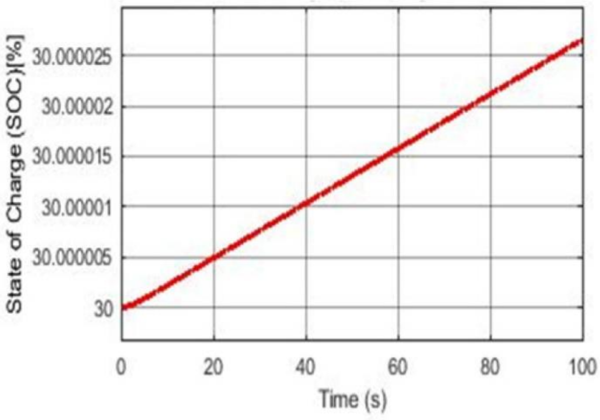

Figure 6: State-of-Charge (SOC) against Time

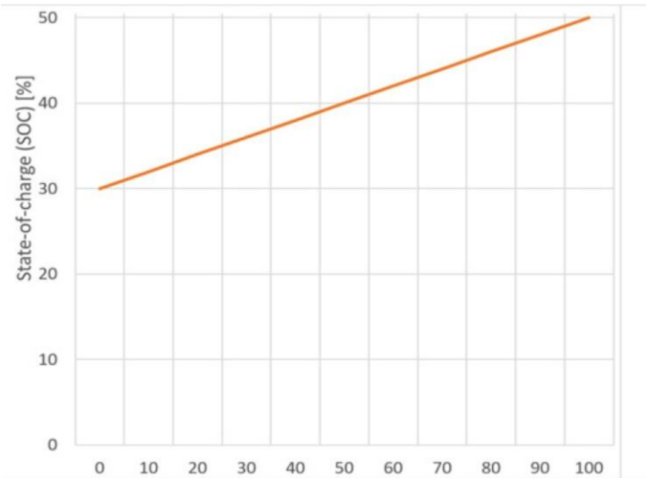

Figure 7. The Improved State-of-Charge against Time

Summary

In this work, it was observed that a higher amount of current is needed to fast charge the EV batteries. More concentration was on the battery SOC. A higher SOC of the EV battery will enhance the fast charging of the electric vehicle within a short time, say a maximum of 5-10 minutes. As such, a good number of electric vehicles can be charged within a short time, which will mitigate range anxiety. Hence, the proposed method has proven to be a reliable method for fast charging of EVs. However, an intelligent battery management system that would monitor the SOC and gradually reduce the energy taken from the battery to prevent continuous operation at a low state of charge has to be implemented to improve the efficiency of the system.

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