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Rectifier based Electric Vehicle Charger with High Frequency Isolation

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***Abstract*: The scarcity of fossil fuel and the increased pollution leads the use of Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV) instead of conventional Internal Combustion (IC) engine vehicles. An Electric Vehicle requires an on-board charger (OBC) to charge the propulsion battery. The objective of the paper is to design a multifunctional on-board charger that can charge the propulsion battery when the Electric Vehicle (EV) connected to the grid. In this case, the OBC plays an AC-DC converter. The surplus energy of the propulsion battery can be supplied to the grid. In this case, the OBC plays as an inverter. The OBC plays like a low voltage DC-DC converter (LDC). An OBC is designed with Boost PFC converter at the first stage to obtain unity power factor with low Total Harmonic Distortion (THD) and a Bi-directional DC-DC converter to regulate the charging voltage and current of the propulsion battery. The battery is a Li-Ion battery with a nominal voltage of 360 V and can be charged from depleted voltage of 320 V to a fully charged condition of 420 V. The function of the second stage DC-DC converter is to charge the battery in a Constant Current and Constant Voltage manner. While in driving condition of the battery the OBC operates as an LDC to charge the Auxiliary battery of the vehicle whose voltage is around.**

***Keywords*: AC to DC converter, Battery, on-board charger, Total Harmonic Distortion, Transformer**

1. Introduction

Recently, the automobile transportation sector has seen an increased production and sales of plug-in electric (PEV) and electric vehicles (EV). In fact, one goal of the United States is to have one million EVs on the roads by the end of 2015. The success of this goal is dependent upon improvements in battery technology, electric drive train systems and battery charging infrastructure. Furthermore, mass adoption of this technology is dependent upon alleviating public concerns such as range anxiety and charging times. A strategy to alleviate such concerns is the deployment of a public charging infrastructure with Level 3 DC battery fast chargers. Such DC fast chargers, which add 60 to 80 miles of driving range with a 20 minute charge, must include the following features: high efficiency, high input current quality, high power density, and cost-effectiveness. A conventional unidirectional topology for EV DC Fast Charging employs a 3-phase diode rectifier at the input various topologies with improved power factor are presented in but often employ a large active switch count and require complex control and modulation strategies. Matrix converter based topologies are proposed for bidirectional battery fast chargers in Although these topologies have good input current quality and have the capability of vehicle-to-grid operation, they also use a relatively high number of active semiconductor devices and require complex control strategies. The DC battery fast charger proposed in this seminar with addresses the existing drawbacks by introducing a push-pull based topology with a reduced active switch count and simple control strategy.

2. Overview

A. Electric Vehicle vs. Hybrid Electric Vehicle

Electric vehicles have only one source of energy i.e. the on-board battery bank and by utilizing the stored energy, they drive the vehicle. The battery bank can be charged by taking electricity from either conventional or non-conventional sources. The schematic shows the block diagram of an electric vehicle. As shown in the Fig. 1, the power electronic converter matches the electrical ratings of the battery bank and the motor. The motor can be a DC motor or AC motor, depending on the motor the converter can be a DC-DC converter or DC-AC converter. Large charging time and limited range of driving due to the limited capacity of the on-board battery pack are the challenges that can be considered.

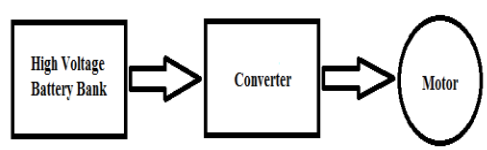

Fig. 1. Block Diagram of Electric Vehicle

Unlike EVs hybrid electric vehicles (HEV) have two or more sources of energy. The sources can be a battery bank and a fuel cell or an IC engine along with a battery bank. Fig. 2 shows the block diagram of an HEV. It can be observed from the block diagram that both the IC engine and the Battery bank van be utilized to drive the vehicle hence by improving the range of the vehicle. Fig. 1, Block diagram of EV charger The charger can be unidirectional i.e. can only charge the EV battery from the grid or bidirectional i.e. can charge the battery from the grid in charging mode and can pump the surplus amount of power of

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the battery into the grid. Both isolated and non-isolated topologies can be employed for the charger. The details of each stage are thoroughly described in subsequent chapters.

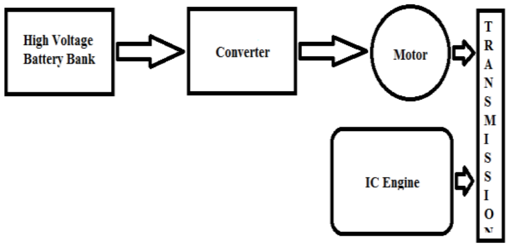

Fig. 2. Block Diagram of Hybrid Electric Vehicle

B. *Battery Chargers for Plug-In Electric Vehicles*

In order to utilize the battery to its maximum capacity the battery charger plays a crucial role. The remarkable features of a battery charger are efficiency and reliability, weight and cost, charging time and power density. The characteristics of the charger depend on the components, switching strategies, control algorithms. This control algorithm can be implemented digitally using micro-controller. The charger can be unidirectional i.e. can only charge the EV battery from the grid or bidirectional i.e. can charge the battery from the grid in charging mode and can pump the surplus amount of power of the battery into the grid. Both isolated and non-isolated topologies can be employed for the charger. The details of each stage are thoroughly described in subsequent chapters.

1) *Battery study*

The very first step of designing an Electric Vehicle (EV) or Hybrid Electric Vehicle (HEV) is to design the suitable propulsion battery which is responsible for driving the motor. The battery must be able to satisfy the electric specifications such as operating voltage, power, power and energy densities and long working cycle and life. Presently Lithium-Ion battery is the most commonly used in automobile industries. The advantages are:

- The energy density of Li-Ion battery is around twice of Ni-Cd battery and the load characteristics are almost similar as Ni-Cd battery.
- A single cell of Li-Ion battery is of 3.6 volts where it is 1.2 volts and 2 volts in the case of Ni-Cd and Lead Acid battery respectively.
- The discharge rate of the battery is fairly flat i.e. it delivers a constant power over 80% of the discharge cycle.
- The weight of Li-ion battery pack is much less than Ni-Cd. For example, 20kWh Li-ion battery pack weights around 160 kg while Ni-Cd weights around 275-300 kg for the same ratings.

With above advantages, Li-ion batteries also have some major drawbacks which are the battery is very costly, flammable and the life cycle is limited between 400 and 700 cycles. The safety issue can be eliminated by using Lithium ion phosphate batteries which life cycle is around 1000 cycles**.**

2) *Electrical model of li-ion battery*

The main objective to model a battery is to represent the battery operation via a mathematical equation or equivalent circuit or both. Equivalent circuit model is convenient for power system simulations as it can be modeled with basic electrical components such as voltage source, resistor, and capacitors.

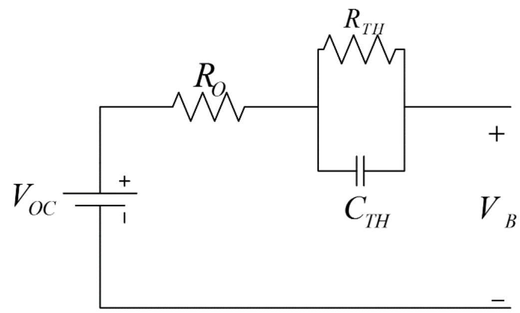

Fig. 3. Equivalent Model of Li-Ion Battery

The above Fig. 3 shows the Thevenin's equivalent model of a Li-Ion battery. The open circuit voltage is Voc. Both Ohmic resistance Ro and polarization resistance RTh are accounted for internal resistance and the transient response during charging are discharging are modeled by an equivalent capacitanceCTh. VB represents the effective battery voltage.

3. Circuit description

The circuit diagram of electric vehicle charger based on rectifier with high frequency isolation is as shown in Fig. 4.

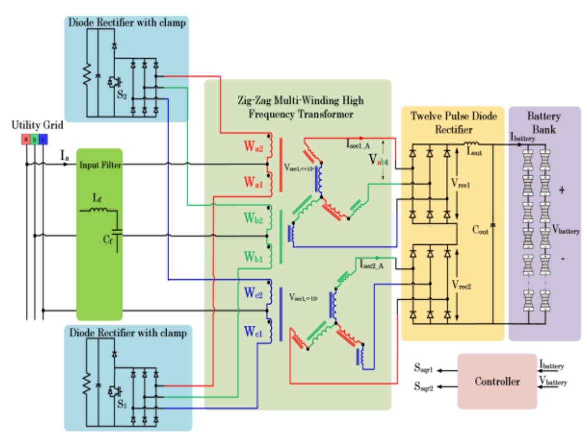

Fig. 4. Circuit Diagram of AC to DC Charger

(Proposed push-pull based topology with high frequency isolation for EV DC fast charging).

A. *Proposed Electric Vehicle Charger with High Frequency Isolation*

The push-pull based topology with high frequency isolation for EV DC fast charging is shown in Fig. 3. The operation of the system can be divided into the following subsections:

- Diode
- Rectifiers with clamp circuit,

- High frequency zig-zag transformer,
- Twelve pulse diode rectifier and
- Modulation and control scheme.

1) Diode Rectifier with Clamp Circuit

The creation of the 3-phase AC link across the transformer windings is achieved by switching S1 and S2 The primary windings of the zig-zag transformer can be divided into two sets that are 180° phase shifted in magnetic coupling, namely windings (Wa1, Wb1, Wc1) and windings (Wa2, Wb2, Wc2). The center tap of each primary winding is connected to the utility grid through an input filter. In addition, the switching terminals of windings (Wa1, Wb1, Wc1) are connected to a diode rectifier whose output is in turn connected to S1. Similarly, the switching terminals of windings (Wa2, Wb2, Wc2) are connected to a diode rectifier whose output is in turn connected to S2. The active devices S1 and S2 operate with simple square wave modulation. The switching function of S2 has a 180° phase shift compared to the switching function of S1. When S1 is gated ON, the switching terminals of windings (Wa1, Wb1, Wc1) are shorted through the diode rectifier. In essence, the switching terminals are shorted to the neutral point as shown in Fig. 3.1.1 (a). At this instant, the line-to-neutral voltages Van, Vbn, and Vcn appear across windings Wa1, Wb1, and Wc1 respectively. The switching terminals of the other set of windings (Wa2, Wb2, Wc2) are open and the energy stored in their leakage inductance is dissipated through the capacitor and bleeding resistor. The voltages across windings (Wa2, Wb2, Wc2) have the opposite polarity compared to the voltages across windings (Wa1, Wb1, Wc1) because they are 180° in magnetic coupling. Meanwhile, the induced voltages on the secondary side have the same polarity as the voltages across windings (Wa1, Wb1, Wc1).

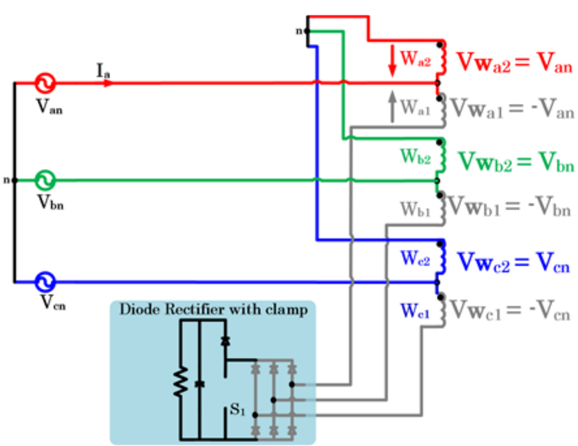

Fig. 5. Switching Operation switch S2

(Operation when S1 is gated OFF and S2 is gated ON. The switching terminals of Wa2, Wb2, Wc2 are shorted while the switching terminals of Wa1, Wb1, Wc1 are open).

When S2 is gated ON, the switching terminals of windings (Wa2, Wb2, Wc2) are shorted and connected to the neutral point. At this instant, the line-to-neutral voltages Van, Vbn, and Vcn appear across windings Wa2, Wb2, and Wc2 respectively. The switching terminals of the other set of windings (Wa1, Wb1, Wc1) are open and the energy stored in their leakage inductance is dissipated through the capacitor and bleeding resistor. Now the voltages across windings (Wa1, Wb1, Wc1) and the induced voltages on the secondary side have opposite polarity compared to the utility grid line-to-neutral voltages. It can be noted that the voltage polarity across each winding changes as S1 and S2 are switched. By switching S1 and S2 at HF a 3-phaseAC link is created.

2) High Frequency Zig-Zag Transformer

The operation of a medium frequency zig-zag transformer is described in. For this EV charging application, a HF transformer zig-zag arrangement is considered. As in the switching frequency of S1 and S2 determines the transformer's frequency of operation. Operating the transformer at HF reduces its core size, thus increasing the system's power density. Due to its relative low losses at the kHz switching frequency range, a ferrite core material is envisioned for the HF transformer. The zig-zag multi-winding transformer can be built using three 1-phase multi-winding transformers or it can be built using a single 3-phase multi-winding transformer. To achieve a more compact design, a single 3-phase, 5-limb, transformer is proposed for this system as shown in Fig. 3.1.2 (a). The primary and secondary windings are wound around the interior three limbs of the transformer. The outer limbs provide a magnetic path for any residual flux in the transformer which helps to avoid magnetic core saturation.

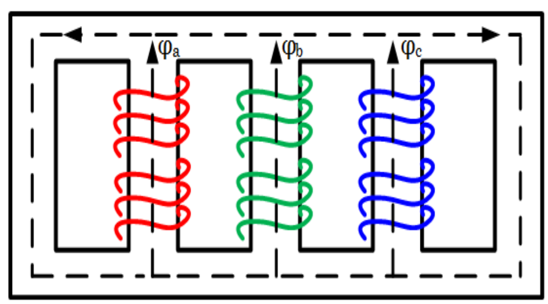

Fig. 6. Multi-winding 3-phase, 5-limb, transformer

In conventional 12-pulse operation, multi-winding transformers in star-delta connection are often employed to create a 30° phase shift. In order for the two output diode rectifiers to process the same amount of power, the delta connected windings must have a higher number of turns compared to the star connected windings. This difference in turns ratio creates different leakage inductances on the secondary side. To mitigate this problem, the secondary side of the HF transformer in the proposed system is connected in zig-zag. With zig-zag arrangement the leakage inductances on the secondary side are balanced. The secondary side windings are connected in such a way that two sets of 3-phase voltages with a net 30° phase difference are fed to the 12-pulse diode rectifier. One set of 3-phase voltages is displaced by +15° with respect to the primary windings, while the second set of 3- phase voltages is displaced by -15° with respect to the primary windings.

4. Conclusion

The basic difference between EV and HEV is stated of this seminar. A brief explanation of two stage EV charger with the power converters required for each stage is described. New era EVs and HEVs use high voltage Lithium Ion battery pack for driving purpose. The various advantages of Li-ion battery and the charging profile i.e. CC/CV mode charging which is suggested by the battery manufacturers and the equivalent electrical model of the battery are thoroughly explained. Section describes different classifications of EV charger based on the power levels and power flow capability i.e. unidirectional and bidirectional. In previous work regarding EV charger and the converters associated with the charger has been stated. As the first stage of an OBC is the AC-DC converter, hence, the AC-DC converter topology is explained in seminar.

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