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Design of Level Two On-board Charger for Plug-In Electric Vehicle using ANFIS

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***Abstract*— This paper presents the design and analysis of an onboard charger for Electric Vehicles (EVs) employing advanced power conversion techniques. The proposed system features an AC-DC conversion stage using a Totem-pole Power Factor Correction (PFC) converter and a DC-DC conversion stage with an LLC resonant converter, optimized using an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller.The proposed OBC system is aimed at improving the efficiency, power density, and reliability of EV charging systems. The Totem-Pole AC-DC converter is employed to rectify the AC input with minimal switching losses, leveraging its inherent ability to operate in continuous conduction mode (CCM) and reduce reverse recovery issues in diodes. Following the rectification, the LLC resonant DC-DC converter efficiently steps up the DC voltage to the appropriate battery charging level, offering zero-voltage switching (ZVS) and zero-current switching (ZCS) to enhance overall efficiency. The ANFIS controller combines the strengths of fuzzy logic and neural networks, offering superior adaptability and control precision under varying operational conditions. Simulation results indicate significant improvements in efficiency, power factor, and transient response with ANFIS. Experimental validation confirms the superiority of the ANFIS-based system, establishing it as a viable solution for contemporary EV charging applications.**

***Index Terms*- On-board charger(OBC),Power factor correction (PFC),Electric vehicles(EVs),Adaptive Neuro-Fuzzy Inference System(ANFIS).**

I. INTRODUCTION

Plug-in hybrid EVs and exclusively battery-powered EVs are the two types of electric cars (EVs). Because they offer a viable means of transportation with low carbon emissions, EVs are becoming more and more popular worldwide. With significant investments and incentives, several nations are attempting to expand the EV industry. As a consequence, there will be more than 16.5 million EVs on the road in 2021—a threefold increase in only three years—when just light-duty passenger cars are taken into account.

This research focuses on the development of an onboard plug-in electric vehicle charger incorporating a Totem-Pole Power Factor Correction (PFC) converter as the AC-DC stage and an LLC resonant converter for the DC-DC stage. The Totem-Pole PFC has emerged as an attractive topology for onboard chargers due to its high efficiency and ability to achieve near-unity power factor. It minimizes conduction losses by using fast-switching semiconductors, making it a superior choice compared to traditional boost converters in EV applications.

The DC-DC conversion stage employs the LLC resonant converter, known for its high efficiency, soft-switching capabilities, and ability to operate over a wide range of output voltages. The combination of the Totem-Pole PFC and LLC resonant converter creates an integrated solution that offers enhanced power efficiency, reduced size, and improved thermal performance—key parameters in the design of compact and high-performance OBCs.

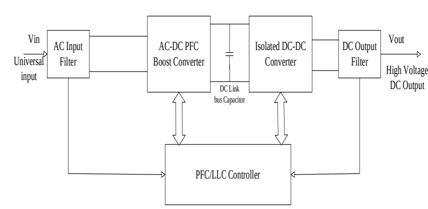

Figure 1 Block diagram of the proposed on-board charger

The design and development of OBCs also directly impact the range and cost of EVs, as more efficient chargers reduce energy consumption and allow for smaller, lighter batteries, which can reduce vehicle weight and extend driving range. Thus, improving OBC technology can help accelerate EV adoption by

addressing consumer concerns related to range anxiety, charging infrastructure, and charging times.
Design considerations, modeling, and implementation of the Totem-Pole PFC and LLC resonant converter for an onboard EV charger. Simulation results, experimental validation, and performance analysis are presented to demonstrate the advantages of this combined approach in improving efficiency, power density, and overall charger performance.

II. DEVELOPED OBC AND IT'S OPERATION

Onboard charger for electric vehicles (EVs) comprises two primary power conversion stages: the AC-DC conversion using a Totem-pole Power Factor Correction (PFC) converter and the DC-DC conversion utilizing an LLC resonant converter. These converters, in conjunction with advanced control strategies such as Proportional-Integral (PI) and Adaptive Neuro-Fuzzy Inference System (ANFIS), ensure efficient power delivery from the grid to the EV battery. The working principles of both conversion stages and control strategies are detailed below.

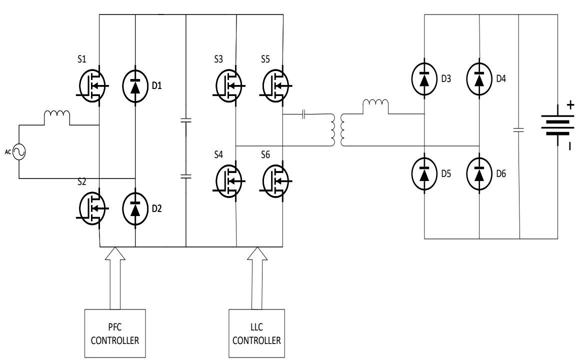

Figure 2 schematic of the proposed on-board charger

Circuit details of on-board charger is shown in fig 2. the main principle of the proposed OBC is ac input rectification and filtering, power factor correction,DC-DC conversion and Battery charging.

The OBC firstly rectify the ac supply into dc supply using the totem pole converter and the capacitor C_f is used as filtering capacitor smooth the rectified DC voltage to remove ripples. PFC is used to adjust the current waveform to match with voltage waveform, minimizing harmonics distortion and improve's the power factor.

Then the back-end DC-DC converter i.e LLC resonant converter operates near to the resonant frequency to achieve zero-voltage switching (ZVS) and high efficiency. The resonant tank circuit (composed of inductor and capacitor) determines the frequency and impedance characteristics.

The proposed OBC is composed of an front-end converter with($S_1 - S_2, D_1 - D_2$),and back-end converter of one full bridge circuit($S_3 - S_4$ and $S_5 - S_6$), with rectifier diodes ($D_3 - D_4$ *and* $D_5 - D_6$) and a high frequency transformer.In this the front-end converter can work as an AC-DC converter, and PFC controller

The isolated converter is used as the back-end converter which can work as an DC-DC converter.
On-board charger is consists two part's

1. AC to DC Converter
2. DC to DC Converter

A. Design of AC to DC Converter:
Circuit configuration of proposed OBC consists of totem pole pfc converter as AC to DC Converter to maintain the high power factor and minimizing harmonic distortion of the source.

The Two Active Switches (S1 and S2) are used as High-speed MOSFET, responsible for the AC-DC conversion.the Diodes (D1 and D2) are Used for rectification of the AC input.Input Inductor (L_{in}) Used to store and transfer energy and it plays a very key role in shaping the input current to follow the input voltage waveform and ensuring the high power factor.Control Circuit is to regulates the duty cycle of the switches to achieve power factor correction and output regulation.

In this the PR Controller is used for Voltage regulation and the PI controller is used for Current regulation.
For an AC input Voltage with an amplitude of V_{in_peak} , and the time-varying input voltage $V_{in}(t)$ is

$V_{in}(t) = V_{in\_peak}$ *sin(ωt) (1)

$I_{in}(t) = I_{in\_peak}$ *sin(ωt) (2)

Where $V_{in}$and I_{in} are the rms value of the gird voltage and the current,respectively, and ω is the angular frequency.

The inductor voltage $V_l(t)$ *is given by*:

$V_l(t)$=L$\frac{dI_l(t)}{dt}$ (3)

The inductor current during the switch period Ts can be

$$I_l(t)=I_{l\_min} + \frac{V_{in}(t)*D*Ts}{L} \quad (4)$$

The PI controller adjust the duty cycle D(t) to minimize the error is given by

$$D(t)= K_p * e(t) + K_i * \int e(t)dt \quad (5)$$

Where

e(t)=$V_{ref} - V_{output}$

K_i and K_p are the proportional and integral gains, respectively.

The supply side inductor (L_{in}**)** is used to determine the current ripple of the supply,the inductor L_{in} is calculated by using

$$L_{in} = \frac{V_o}{4f_{sw}\Delta i_{L_{in}}} \quad (6)$$

Control Strategy

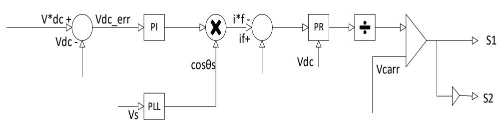

Figure 3 Control Strategy of Totem Pole Converter

Fig 3 shows the control scheme is composed of two loops - an outer voltage loop and an inner current loop. The error signal obtained by comparing the measured output voltage (DC) against a voltage set point is given to the outer loop proportional-integral (PI) controller for voltage compensation. The voltage loop output is multiplied by the input voltage signal (AC) to generate the current reference. The inner loop proportional-resonant (PR) controller controls the input current to follow the current reference. The resulting value is provided to a modulator for PWM generation.

B. Design of DC to DC Converter:

Since the dc-link voltage is kept constant and while the HV battery needs to operating in a wide voltage rang, the dc-dc converter has to be able to cover the rang. The dc-dc converter consists of four MOSFET switch and an isolated transformer which will use to convert the low frequency ac to high frequency ac to obtain the soft switch and reduce the switching losses and then an rectifier circuit with four diode(($D_3 - D_4$ and $D_5 - D_6$) are used the capacitor C_L is used as the filter.

LLC resonant converter as the DC-DC converter. The topology of the LLC resonant converter can be divided into three main networks: the inverter network, the resonant network, and the rectifier filter network**.**Inverter Network**:** Comprises switching transistors (MOSFET).Resonant Network**:** Includes the resonant capacitor (Cr), resonant inductance (Lr), and excitation inductance (Lm). The resonant capacitor (Cr) also serves to block the DC component of the square wave generator's output voltage from flowing to the transformer, while balancing the magnetic flux to prevent magnetic circuit saturation.Rectifier Filter Network**:** Consists of a double half-wave rectifier with a center tap on the secondary side of the transformer.

Resonance**:** The switching frequency is set close to the resonant frequency of the tank circuit, minimizing the voltage across the switch at turn-on, which results in Zero Voltage Switching (ZVS).

Power Transfer**:** Power is transferred from the primary side to the secondary side through a high-frequency transformer, which adjusts the voltage up or down according to the application requirements.

Load Regulation**:** The output voltage is regulated by controlling the switching frequency. The converter can operate either below or above the resonant frequency to maintain efficient operation while regulating the output voltage

The LLC converter as two resonant frequency,first resonant frequency f_r and the second resonant frequency f_m.

$$f_r= \frac{1}{2pi\sqrt{L_r C_r}} \quad (7)$$

$$f_m= \frac{1}{2pi\sqrt{(L_r+L_m)C_r}} \quad (8)$$

The equivalent resistance to the primary side is given by

$$R_{ac} = n^2 R_e = \frac{8n^2}{\pi^2} R_L \quad (9)$$

Where n is the primary to secondary turns.

The ratio of the transformer's secondary voltage to the primary voltage can be expressed as

$$M = \frac{nV_o}{V_{in}} = \frac{nV_{sec}}{V_{ab1}} \quad (10)$$

Where V_{ab1} is the input voltage of the resonant circuit after the conversion and nV_{sec} is the output voltage of the resonant circuit after the conversion.

The quality factor is given by

$$Q = \frac{\sqrt{L_r C_r}}{R_{ac}} \quad (11)$$

III. PROPOSED CONTROLLER ONBOARD CHARGER

ANFIS combine's fuzzy logic with the neural networks to create a more adaptive and flexible control system. It utilizes fuzzy rule's and membership functions to handle uncertainties and non-linearities in the control process:

Description	Values
Grid Voltage(V_{in})	240V rms
Grid Frequency(f_{in})	60 Hz
Switching Frequency	110 -150kHz
DC-link Voltage	350V-400V
HV battery Voltage	400V
Power output	7.2kW

A.Benefits of ANFIS

Adaptive Control**:** ANFIS adjusts to varying operating conditions and system dynamics, delivering enhanced performance across diverse scenarios.

Non-Linearity Handling**:** ANFIS effectively manages the non-linear behaviors typical in LLC converters, resulting in more precise control.

Faster Response**:** ANFIS controllers offer quicker response times and reduced overshoot compared to traditional PI controllers.

B.Implementation in LLC Converters the following steps are typically involved:

Modeling the System: Develop a fuzzy logic model of the LLC converter's dynamics and establish membership functions and fuzzy rules.

Training the ANFIS: Use training algorithms to optimize the parameters of the fuzzy rules and membership functions based on the system's operating data.

Integration: Integrate the trained ANFIS controller into the LLC converter's control loop, replacing the conventional PI controller.

C. Performance Comparison:

Voltage Regulation**:** ANFIS controllers achieved superior voltage regulation with reduced deviation from the reference voltage compared to PI controllers.

Transient Response**:** ANFIS demonstrated a faster transient response and lower overshoot during sudden load changes.

Efficiency**:** Overall efficiency was enhanced due to better handling of non-linearities and improved dynamic control.

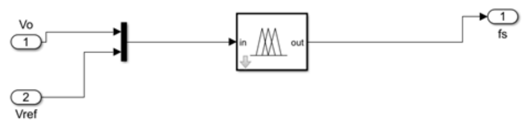

Fig 4 Simulation Diagram of ANFIS Controller

IV. SIMULATION RESULTS OF PROPOSED ONBOARD CHARGER

The proposed Onboard charger is simulated using the matlab software.the specifications of the OBC is mention on table.1,the input voltage ,output voltage and output power of the OBC is given in it.

Table 1 Specifications of OBC

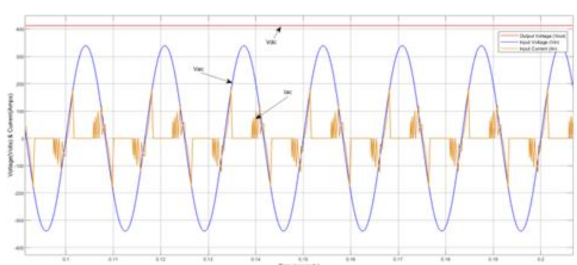

Fig 5 Input voltage ,Input current and Output voltage without PFC controller

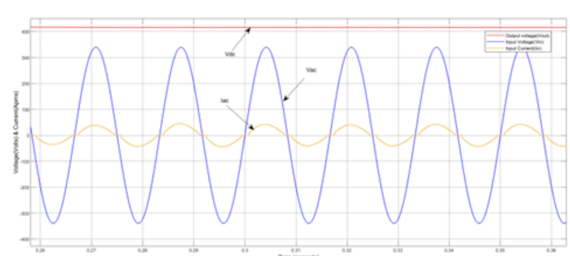

Fig 6 Input Voltage ,Input Current and Output Voltage with PFC controller

Fig 5 shows the circuit without a PFC (Power Factor Correction) controller, highlighting the variation in the current waveform due to a lower power factor Fig 6. presents the circuit with a PFC controller, where the power factor is corrected to unity.In both cases, the input voltage is 240V RMS, and the current drawn is 18A from an AC supply. This AC supply is converted into DC, with the output voltage at 410V DC.

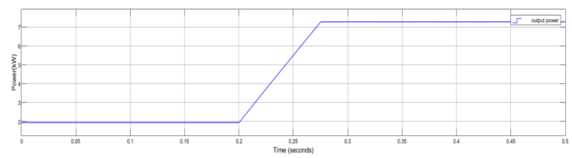

Fig 7 Output Power of Proposed OBC

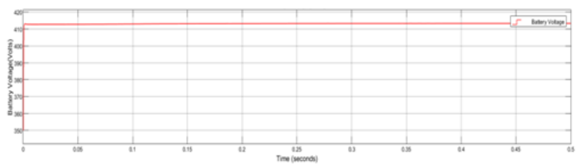

Fig 8 Battery Voltage

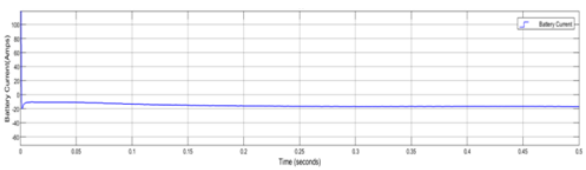

Fig 9 Battery Current

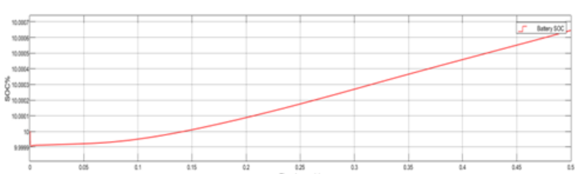

Fig 10 Soc of the Battery

The analysis presents various performance of the onboard charging system, including output power, battery voltage, current, and state of charge (SOC).Fig 7 illustrates the output power of the onboard charger rated with 7.2 kW. Fig 8 displays the battery voltage**,** measured at 410 V. Fig 9 shows the battery current for the 7.2 kW onboard charger, where the current value increases to 17 A.Finally, Fig 10 depicts the **s**tate of charge (SOC) of the battery. The battery's initial SoC is set at 10%, with a response time of 1 second and a capacity rating of 40 Ah**.**

CONCLUSION

A new circuit topology for an on-board charger is introduced. In grid-connected mode, it facilitates Grid-to-Vehicle (G2V) power transfer. The Power Factor Correction (PFC) circuit is integrated with a Totem-pole circuit. Detailed operation and design aspects of the circuit are presented. A 7.2 kW onboard charger is designed and simulated in grid-connected mode. Simulation results demonstrate that the LLC can support Zero Voltage Switching (ZVS) operation. The front-end PFC, along with the Totem-pole circuit in grid-connected mode, allows the use of wide band-gap devices, enabling switching frequencies around 120 Hz. Since all switches of the LLC resonant are soft-switched, their switching frequency can range from 100 to 150 kHz. Current stress analysis on the switches and inductors is conducted. The proposed circuit for Onboard Electric Vehicle Charger (OBEVC) achieves significant improvements in power density, reliability, and cost savings.

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