Design And Analysis of Fuzzy Logic Control-Based Half-Bridge Resonant LLC Converter

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***Abstract*—This paper presents the design, simulation, and hardware implementation of a half-bridge LLC resonant DC–DC converter regulated by a fuzzy logic controller (FLC). The converter achieves soft switching through zero-voltage and zero-current conditions, thereby reducing switching losses and improving efficiency. A MATLAB/Simulink model validated the design with a resonant frequency of 65kHz and an efficiency of 94.6%. A hardware prototype using an Arduino-based FLC and TLP250 driver demonstrated stable 15V output from a 12V input with 93.75% efficiency. Results confirm that integrating fuzzy logic control with the LLC topology provides robust voltage regulation and high efficiency suitable for renewable-energy interfaces and electric-vehicle chargers.**

Keywords—Half-Bridge LLC, Fuzzy Logic Controller, Resonant Converter, Soft Switching, High Efficiency.

I. Introduction

The growing demand for compact, high-efficiency DC–DC converters in renewable-energy systems, electric-vehicle chargers, and advanced power supplies has exposed the limits of conventional pulse-width-modulated (PWM) topologies, which incur significant switching losses at high frequencies. To address this challenge, resonant converter architectures have gained prominence. Among them, the half-bridge LLC resonant converter is particularly attractive because its resonant tank enables both zero-voltage and zero-current switching, thereby reducing conduction and switching losses and achieving high power density [2], [4].

Various control strategies for the half-bridge LLC topology have been reported. Proportional–integral–derivative (PID) control provides basic voltage regulation but relies on accurate modeling and offers only moderate disturbance rejection [1]. Other approaches including extended asymmetrical half-bridge control [2], variable magnetizing-inductance schemes for hold-up-time improvement [3], and hybrid or digitally controlled LLC converters [4]–[6] enhance efficiency and transient performance but often require intricate implementation or precise system parameters.

Fuzzy logic control (FLC) presents a compelling alternative because it operates without an exact mathematical model and can accommodate nonlinearities and parameter variations. By continuously adjusting the switching frequency in response to output-voltage error and its rate of change, FLC improves transient response and maintains stable operation over a wide range of input and load conditions. Building on the control concepts and resonant-design principles established in prior research [1]–[6], this work details the design, simulation, and hardware realization of a fuzzy-logic-controlled half-bridge LLC resonant converter, demonstrating high efficiency and robust voltage regulation.

II. Methodology

Fig. 1 shows the basic configuration of the proposed fuzzy-logic-controlled half-bridge LLC resonant converter. A regulated DC source supplies power to the half-bridge LLC converter, which contains the resonant tank elements to enable soft-switching and high-efficiency energy transfer. The converter's output stage provides a stable DC voltage that drives the connected load. Output voltage is continuously monitored and fed to a fuzzy logic controller, which computes the error between the reference and measured voltages and adjusts the switching frequency of the half-bridge to maintain tight regulation under varying input or load conditions. This closed-loop control strategy ensures improved dynamic response and high conversion efficiency.

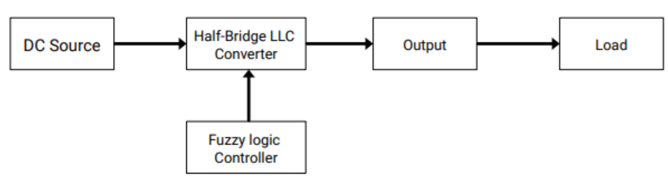

Fig. 1 Block diagram of proposed topology

A. Resonant LLC Converter

Fig. 2 shows the schematic of a half-bridge LLC resonant converter comprising four key sections: the power switches, resonant tank, high-frequency transformer, and diode rectifier.

A DC input V_{IN} feeds the half-bridge leg formed by MOSFETs S_1 and S_2, which alternately generate a high-frequency square-wave voltage. This drives the resonant network composed of the series resonant inductor L_R, resonant capacitor C_R, and the transformer magnetizing inductance L_M, producing a sinusoidal current that enables zero-voltage and zero-current switching. The high-frequency transformer, with a turns ratio of n:1,

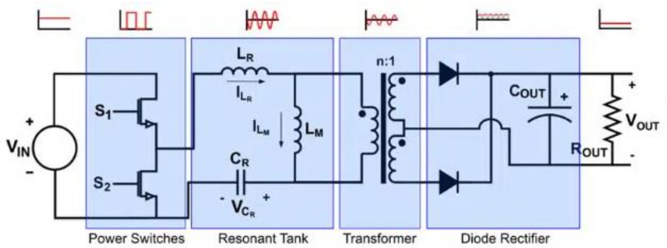

Fig. 2 Schematic diagram of Resonant LLC Converter

provides galvanic isolation and steps the voltage to the required level. On the secondary side, a full-wave diode rectifier converts the AC output to DC, while the output filter capacitor C_{OUT} smooths the voltage supplied to the load R_{OUT}. This topology achieves high efficiency and low electromagnetic interference by maintaining soft-switching operation across a wide load range.

III. CONTROL STRATEGY OF THE PROPOSED MODEL

In the proposed system, the DC–DC converter switches are driven by precisely controlled gate pulses. The reference output voltage V^*_{DC} is continuously compared with the measured output voltage V_{DC} to produce an error signal V_E, expressed as

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$$V_E=V^*_{DC}-V_{DC}.$$

This error signal is processed by the controller, which, based on the control law and the discrete sampling interval k, generates a reference control voltage V_C.

Gate pulses for the converter are then synthesized by comparing V_C with a high-frequency carrier signal, M_C. The switching logic is defined as follows:

- When $M_C < V_C$, the gate pulse is turned ON.
- When $M_C \geq V_C$, the gate pulse is turned OFF.

This modulation scheme ensures accurate timing of the switching devices and stable regulation of the DC output voltage.

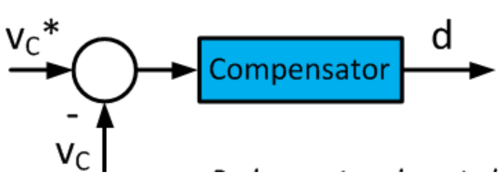

Fig. 3 Control loop of DC-DC Converter

A. FUUZY LOGIC CONTROL

The fuzzy logic control (FLC) system shown above operates by processing real-world signals through a sequence of clearly defined stages to generate a precise control action without requiring an exact mathematical model of the plant.

Fig. 4 illustrates the flowchart of the fuzzy logic–based control strategy used to determine the duty cycle of the converter switches. Initially, the fuzzy inference system (FIS) data, including the membership functions and fuzzy rules, are loaded. The DC bus voltage is then measured and processed as the input variable for decision-making.

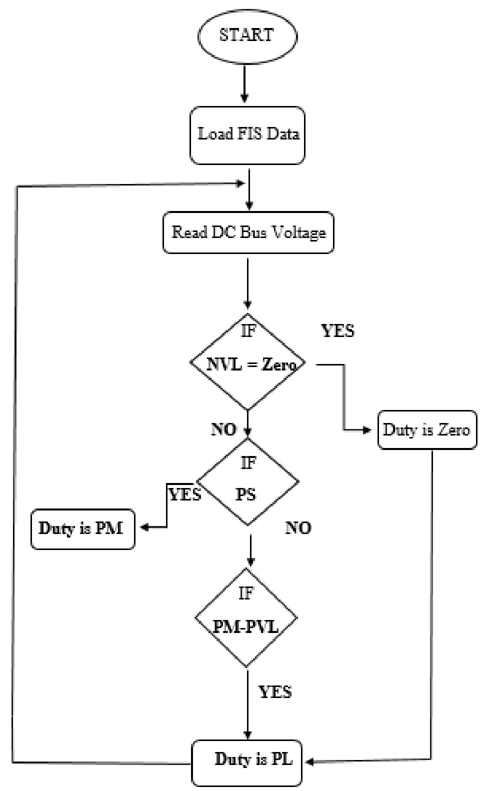

Fig. 4 Flow Chart for the control flow of Fuzzy Control

If the normalized voltage level (NVL) is zero, the system assigns the duty cycle as zero to ensure protection and prevent switching during abnormal conditions. When NVL is nonzero, the controller evaluates the "Power Stable" (PS) condition. If the PS condition is satisfied, the duty cycle is set to PM (Positive Medium), ensuring a stable operation point. If the PS condition is not met, the controller further evaluates the PM–PVL relationship, where PVL (Positive Voltage Low) indicates a low-voltage fuzzy region. Under this condition, the duty cycle is assigned as PL (Positive Low).

This closed-loop decision-making process ensures that the duty cycle is continuously updated based on real-time feedback of the DC bus voltage, providing adaptive regulation, smooth dynamic response, and inherent protection during abnormal or unstable operating States.

Table I. Rules Table for the flow chart of Fuzzy Control for the half-bridge LLC converter

Rule No.	Condition (IF)	Action (THEN – Duty Cycle Output)
R1	NVL = Zero	Duty = Zero (Converter OFF for protection)
R2	NVL ≠ Zero AND PS = True	Duty = PM (Positive Medium)
R3	NVL ≠ Zero AND PS = False AND PM = PVL	Duty = PL (Positive Low)

IV. SIMULATION AND RESULTS

Table II. Simulation Parameters

Parameters		Values
Load Voltage (in volts)		30V
Load Power (in kilowatts)		30KW
PROPOSED LLC CONVERTER	Lr	0.2mH
	Cr	110µF
	Lm	24mH
Switching Frequency		65 KHz
Input Voltage		300V

The proposed half-bridge resonant LLC converter is simulated using MATLAB/Simulink software. The Simulation parameters are shown in Table II. The Simulation is done with R-Load, and its value is 100Ω. The resonant Inductance Lr (0.2mH) and resonant capacitors Cr (110µF) are connected in series, and the magnetizing inductor Lm (24mH) is taken in the Transformer. It is connected to the diode rectifier connected to the R-Load.

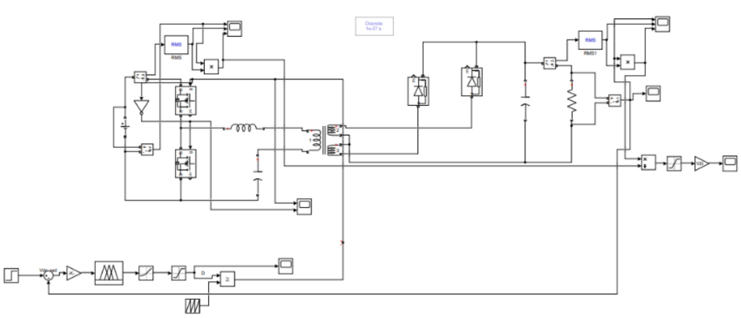

Fig. 5 Simulation on fuzzy logic control-based half-bridge resonant converter

The output voltage, current, and power (with LLC converter) are provided in Fig. 6.

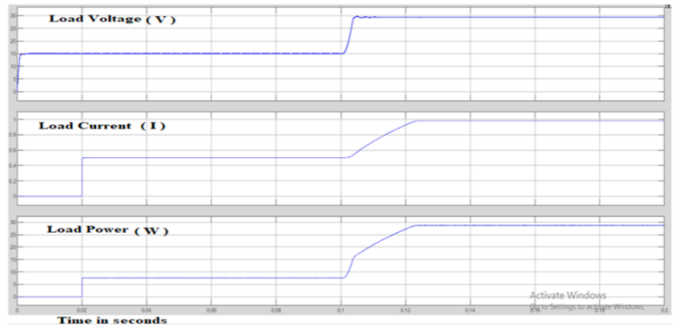

Fig. 6 Simulation Waveform of Voltage, Current, Power

Simulation results confirm that the half-bridge LLC resonant converter maintains stable regulation under dynamic conditions. The output voltage rises rapidly to about 12V, then after a disturbance at 0.1s, smoothly reaches 24V with only ~ 0.24V ripple (≈ 0.75% of rated), while the output current tracks the load, increasing from 0.4A to 1A as the voltage steps up. Correspondingly, output power transitions steadily from roughly 12W to 24W without overshoot, demonstrating the fuzzy controller's ability to deliver efficient, stable operation.

The efficiency of the LLC converter with the FLC controller is provided below in Fig. 7:

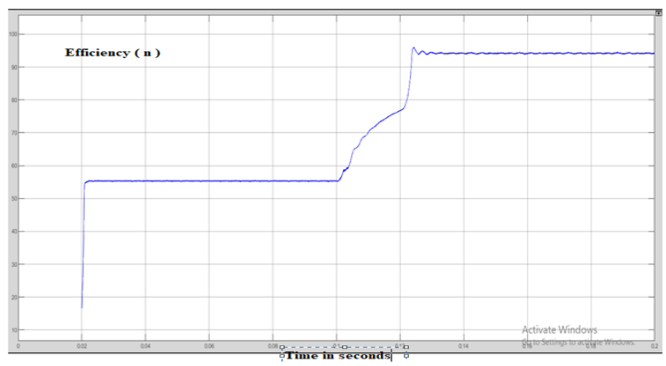

Fig. 7 Efficiency Waveform for Half-Bridge LLC Converter using FLC Controller

In the simulation of the LLC Converter Using a Fuzzy Logic Controller, the output initially stabilizes at about 40% and then, after a step change around 0.12-0.14s, smoothly improves the efficiency to the range of 94.6%.

The FLC effectively regulates the converter by adjusting the switching frequency, providing a stable response with minimal overshoot and oscillations. This demonstrates that FLC enhances the dynamic performance, ensures soft-switching, and maintains efficient voltage under load conditions.

V. EXPERIMENTAL RESULTS AND ANALYSIS

A. HARDWARE DESIGN AND IMPLEMENTATION

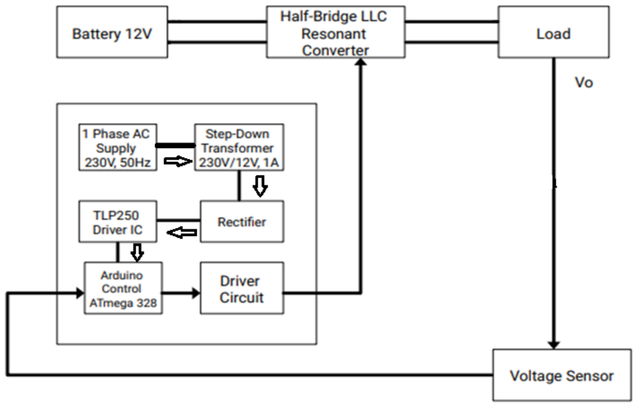

Fig. 8 Block diagram of proposed model

B. HARDWARE CALCULATION

Calculation of Efficiency by using Hardware Results

Table III. Experimental Results

Parameters	Output Specifications
Vin	12V
Vo	14.96V
Io	0.015A
Fs	200kHz

In a half-bridge topology:

$$D = T_{on} / T_s$$

If the MOSFET conducts for 6μs in a switching period of 12μs,

So the ideal duty ratio for a half-bridge resonant converter is usually:

$$D = 0.5 \quad (1)$$

Calculate output power (Po):

$$Po = Vo * Io \quad (2)$$

Estimate input current (Iin)

$$Pin \approx Po \Longrightarrow Iin = Po / Vin \quad (3)$$

$$Pin = Vin * Iin \quad (4)$$

Efficiency:

$$n = (Po/Pin) * 100 \quad (5)$$

The hardware measurements indicate that the half-bridge LLC converter achieves high conversion efficiency at the tested light-load condition.

With an input voltage of 12V and an output of 15V at 0.015A given in Table II, the output power is approximately 0.225W by using equation 2. The corresponding input power is about 0.24W using equation 4, giving an overall efficiency of roughly 93.8% using equation 5.

C. HARDWARE IMPLEMENTATION

The hardware prototype employs key components to achieve efficient and reliable operation of the half-bridge LLC resonant converter. Two IRF250N MOSFETs act as high-speed switches, driven by a TLP250 driver for precise high-frequency control. A 12V, 1A transformer with a 1000µF input capacitor provides isolation and filtering, while a 100 Ω resistor limits inrush current. The resonant tank comprising a 0.225 mH inductor and a 1 µF, 240 V capacitor enables soft switching. Output rectification and smoothing are handled by an IN4007 diode and 100 µF capacitor. An Arduino Uno executes the fuzzy-logic control, powered by a 12 V, 1.3 Ah battery, and a 100 Ω load, which allows accurate performance testing under varying conditions.

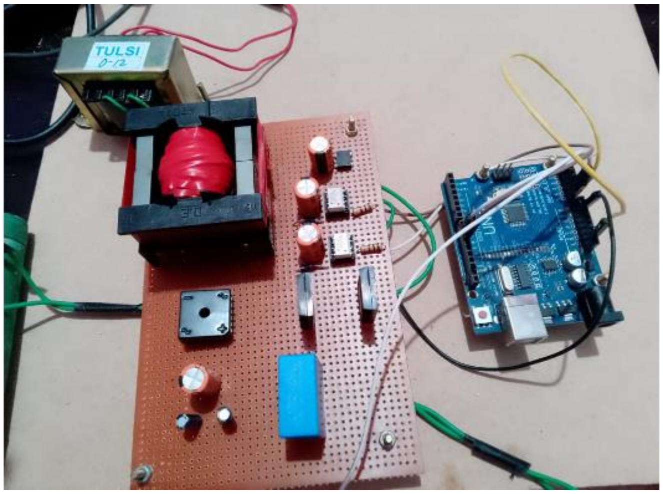

Fig. 9 Hardware implementation of Half-bridge LLC Resonant Converter

The output waveform of MOSFET's Gate Pulses for Half Bridge LLC Resonant Converter is shown in Fig. 10

The switching waveform shows a stable operation of the half-bridge resonant LLC converter at a frequency of 25kHz.The gate pulse on CH2 has a measured value of Vrms = 10.80V, while the output response on CH1 is Vrms = 1.04V.

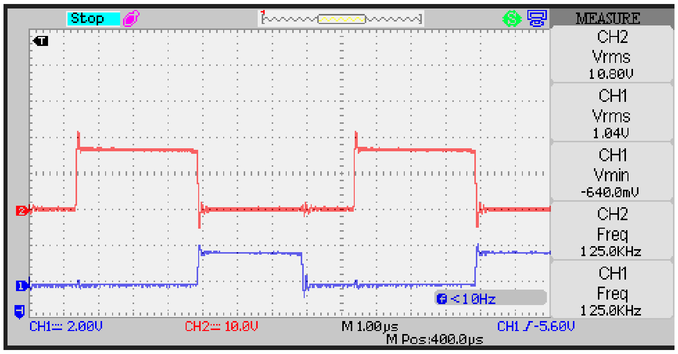

Fig. 10 MOSFET's Gate Pulses

The output voltage waveform for the Half Bridge LLC Resonant is shown in Fig. 10

In Fig. 11, the switching waveform shows a stable operation of the half-bridge resonant LLC converter at a frequency of 369kHz. The Output Voltage is 14.98V For Vin = 12V

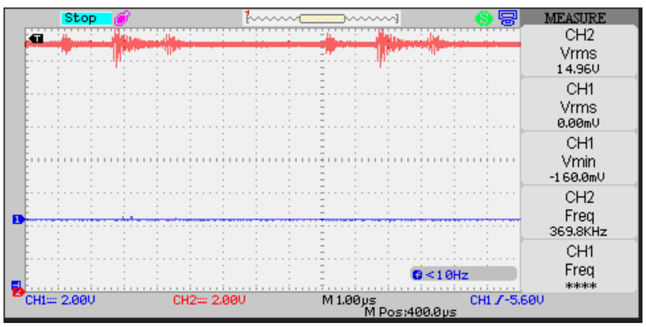

Fig. 11 Output Voltage Waveform

VI. Comparative Study

Table IV shows the comparison between paper [1] and the proposed paper

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Parameters	[1]	Proposed-Model
Control-Method	PID Controller	Fuzzy Logic Controller
Input Voltage (V_{in})	375 – 400V_{DC}	300V_{DC}
Output Voltage (V_o)	12V	30V
Output Power (P_o)	30W	30kW
Switching frequency (f_r)	50-70kHz	65-200kHz
Voltage Ripple	1.5% of rated voltage	0.75% of rated Voltage
Efficiency	92%	94.6%

Table V. shows the comparison between the Simulation and Hardware of the proposed model.

Table V. Comparison between Hardware and Simulation of Half-Bridge Resonant LLC Converter using FLC Technique

Parameters	Simulation	Hardware
Input Voltage (V_{in})	300V_{DC} (designed input)	12V_{DC} (Battery, 1.3Ah)
Output Voltage (V_o)	Stable at 30V (after Regulation)	14.96V
Output Current (I_o)	1000A	0.015A (By Calculation)
Output Power (P_o)	30kW	0.225W (By Calculation)
Switching Frequency (f_s)	65kHz	200-369kHz
Control	FLC Control	Arduino Uno running FLC with TLP250 driver
Soft-Switching	ZVS and ZCS both achieved	ZVS achieved
Efficiency	94.6%	93.75%

VII. Conclusion

The project successfully demonstrates the design, simulation, and hardware implementation of a fuzzy logic controlled half-bridge LLC resonant DC–DC converter that delivers high efficiency, stable voltage regulation, and low switching losses. By combining a resonant tank with zero-voltage and zero-current soft-switching and an adaptive fuzzy logic controller, the system achieved simulation efficiency of about 94.6 % and hardware efficiency 93.75 %, while maintaining a regulated output despite input or load variations. MATLAB/Simulink studies confirmed smooth transients with minimal ripple around 30 V, and the cost-effective hardware prototype, built with IRF250N MOSFETs, TLP250 gate drivers, and an Arduino-based fuzzy controller, verified the design's practicality, providing a compact, robust, and intelligent power-conversion solution suitable for renewable-energy systems, battery chargers, and electric-vehicle power modules.

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