High Power DC-DC Converter Design and Dynamic Control Using Ann Methodology

Pikki Ramu, Prof. P.Mallikarjuna Rao, D.Rajesh
Department of Electrical Engineering, Andhra University college of Engineering, Visakhapatnam, India

Abstract— The project thoroughly discusses efficiency-oriented design considerations based on the operation-mode analysis of the LLC converter, taking into account the characteristics of charging profiles. The precise time-domain model provides mode boundaries and distribution. The design constraints for achieving soft switching with the load varying from zero up to the maximum are clearly outlined. Additionally, a charging trajectory design methodology is proposed and rigorously validated through experiments, demonstrating a peak efficiency of 97% when converting 600 V from the DC power source to the battery emulator in the range of 400–500 V at 15kW.

Key words— Battery charger, DC-DC converter, Multi-resonant converter, capacitor, inductor, transformer, diodes, MOSFETs, neural network.

NOMENCLATURE

BMS	Battery management system
CC	Constant-Current
CV	Constant-Voltage
DAB	Dual Active Bridge
EV	Electric Vehicle
FHA	First Harmonic Approximation
ISR	Interrupt Service Routine
PSFB	Conventional Phase-shifted Full Bridge
ZVS	Zero Voltage Switching
ZCS	Zero Current Switching
Fr	Resonant Frequency
Fsw	Switching Frequency
Vo	Output Voltage
Io	Output Current
Po	Output Power
Vi	Input Voltage
Ii	Input Current
Vmin	Minimum Voltage
Vmax	Maximum Voltage
Lr	Resonant Inductance
Cr	Resonant Capacitor
Lm	Magnetizing Inductance
Q	Quality factor
M	Unity Gain Mode
TDA	Time-Domain Analysis

1. INTRODUCTION

The LLC resonant converter is a type of DC/DC converter widely used in applications requiring high efficiency, high power density, and reliable performance. Its unique design and operating principles make it especially suitable for challenging power conversion tasks, such as those found in electric vehicle (EV) battery chargers. The high-frequency isolated DC/DC converter of an EV ultra-fast battery charger has the fundamental role of controlling the power delivered to the battery (i.e., regulating the charging current), meanwhile providing galvanic isolation from the grid. The Introduction wide output load and voltage regulation capability, to comply with the broad range of battery Voltage and load levels during the charging process; low battery-side current ripple, which causes the premature aging of the battery itself. High conversion efficiency and power density. Notably, high power density can only be achieved by operating the converter at high switching frequencies, in order to reduce the size of the passive components. Therefore, the soft-switching operation of all semiconductor devices is a fundamental requirement, as it provides the only means to limit the converter losses and thus achieve high conversion efficiency [1]. Accordingly, hard-switching converters cannot be adopted in the present application. The development of high step-up dc–dc converters is becoming more and more important and employed widely in many applications. The LLC resonant converter stands as the epitome of DC/DC converter technology, offering unrivalled efficiency, power density, and reliability. Its innovative design and operational principles make it the unequivocal choice for demanding power conversion applications, particularly in electric vehicle (EV) battery chargers. In the realm of ultra-fast EV battery chargers, the high-frequency isolated DC/DC converter plays a pivotal role in regulating the charging current while ensuring galvanic isolation from the grid. It boasts wide output load and voltage regulation capabilities to accommodate varying battery voltages and load levels during the charging process, effectively minimizing battery-side current ripple and maximizing conversion efficiency and power density. It's imperative to note that achieving high power density hinges on operating the converter at high switching frequencies to reduce the size of passive components, thereby necessitating the soft-switching operation of all semiconductor devices. This requirement for soft-switching operation makes hard-switching converters unsuitable for this application. The demand for high step-up DC-DC converters is on the rise, as evidenced by their widespread use across various applications. The output voltage is significantly impacted by parasitic elements and equivalent series impedance in practical applications. Operating at a high duty ratio can lead to diode reverse recovery and substantial conduction losses. Ongoing research is firmly focused on topologies derived from the boost converter to definitively achieve high step-up voltage gain and conversion efficiency. It is imperative to ensure the soft operation of semiconductor devices to unequivocally minimize converter losses and achieve high efficiency. The high-frequency isolated DC/DC converter in an ultra-fast electric car battery charger indisputably plays a critical role in regulating the charging current and providing galvanic isolation. A DC-DC power converter serves as an important electronic device, enabling the conversion of DC voltage to the necessary DC output voltage. It can receive input from a battery or rectified AC line voltage, providing the option of working with regulated or unregulated input voltages. It's worth noting that linear regulators were the first DC-to-DC power converters with an output voltage lower than the input voltage.

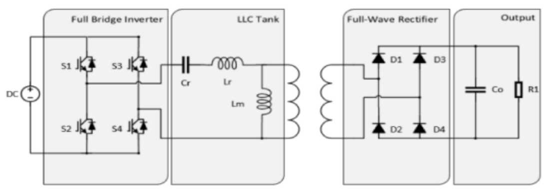

Fig.1. Full Bridge LLC resonant converter

2. TOPOLOGY OF FULL BRIDGE LLC RESONANT CONVERTER

The full-bridge LLC resonant converter is a widely used topology in high-power applications, particularly in electric vehicle (EV) charging stations, data centers, and industrial power systems. This design provides high efficiency, soft switching, and the ability to operate over a wide range of input voltages, making it ideal for applications where reliable and efficient power conversion is essential. The converter's topology is based on a full-bridge circuit, which consists of two pairs of switches on the primary side that drive a transformer with an alternating AC voltage. These switches are typically metal-oxide-semiconductor field-effect transistors (MOSFETs) or insulated-gate bipolar transistors (IGBTs) and are arranged in an H-bridge configuration. The switching of these transistors alternates between pairs, creating an AC waveform that powers the resonant tank circuit, which is the core of the LLC topology.

The resonant tank circuit of the full-bridge LLC resonant converter consists of three main components: a resonant inductor, a resonant capacitor, and a magnetizing inductor. The resonant inductor (Lr) is usually positioned in series with the primary winding of the transformer, creating a pathway for the AC voltage produced by the full-bridge switches. Alongside this inductor, the resonant capacitor (Cr) forms a resonant circuit that establishes the converter's resonant frequency. This frequency is significant as it defines the optimal operational point of the converter, where it achieves zero-voltage switching (ZVS) or zero-current switching (ZCS) to minimize switching losses. In addition, the magnetizing inductor (Lm), often formed by the leakage inductance of the transformer, plays a critical role in maintaining the converter's soft-switching characteristic, which allows efficient power transfer while minimizing heat generation and electromagnetic interference (EMI).

The transformer in the full-bridge LLC resonant converter is a crucial component, providing galvanic isolation between the input and output sides of the converter, thereby enhancing safety and enabling different input and output voltage levels. The transformer also facilitates efficient power transfer across different voltage levels by using an appropriate turn's ratio, which is important in EV charging stations and other high-power applications that require flexible voltage outputs. On the secondary side of the transformer, the output is rectified by a secondary rectifier circuit, typically consisting of fast recovery diodes or, in some designs, synchronous rectification using MOSFETs to further increase efficiency. After rectification, a filter capacitor smooths the output to deliver a stable DC voltage.

A unique aspect of the full-bridge LLC resonant converter is its ability to regulate output power by adjusting the switching frequency. At the resonant frequency, the converter achieves maximum energy transfer efficiency, and zero-voltage or zero-current switching conditions are naturally maintained. This not only improves efficiency but also reduces stress on the power components, resulting in longer lifespan and better performance under heavy loads. Operating the converter below the resonant frequency reduces the output power, enabling precise control over power delivery, especially in response to load variations. This adaptability is valuable for applications such as EV charging, where charging demands fluctuate based on battery characteristics and charging protocols.

Overall, the full-bridge LLC resonant converter's topology, which combines a full-bridge inverter, resonant tank, transformer, and rectifier, provides a reliable, high-efficiency solution for high-power applications. Its capability to switch softly, handle wide input voltage ranges, and dynamically regulate power output makes it well-suited to meet the requirements of modern power systems, especially where efficiency, reliability, and power density are crucial.

3. OPERATION OF FULL-BRIDGE LLC RESONANT CONVERTER

The full-bridge LLC resonant converter operates by converting a DC input into a high-frequency AC waveform, which is then processed through a resonant tank circuit and transformer to supply a controlled DC output. This begins with the primary side, where four switches (typically MOSFETs or IGBTs) are configured in a full-bridge or H-bridge layout. These switches are controlled in pairs, creating an alternating square-wave voltage that drives the resonant tank circuit, the core of the LLC topology. The resonant tank consists of a resonant inductor (Lr) and a capacitor (Cr), arranged in series with the primary winding of the transformer. Together, these elements set the resonant frequency of the converter, where optimal operation and soft switching—zero-voltage switching (ZVS) or zero-current switching (ZCS)—are achieved, minimizing switching losses and improving efficiency.

The resonant circuit's frequency allows the converter to operate efficiently at points where power transfer is maximized while reducing heat generation and electromagnetic interference. The transformer in this setup provides galvanic isolation between the primary and secondary sides, adding a level of safety and flexibility by allowing different voltage levels across input and output. The transformer also incorporates a magnetizing inductance (Lm) from its leakage inductance, contributing to the soft-switching capability and controlling the amount of circulating energy in the resonant tank.

On the secondary side of the transformer, an AC waveform is output and then rectified and filtered by a secondary rectifier stage, which often uses fast recovery diodes or synchronous rectification with MOSFETs to further enhance efficiency. A filter capacitor smooths the output into a stable DC voltage, ready for the load. By varying the switching frequency of the primary-side switches, the converter can regulate output power dynamically, adapting to changes in load conditions while maintaining high efficiency. This dynamic regulation and adaptability make the full-bridge LLC resonant converter especially suited for high-power applications, such as EV chargers and industrial power supplies, where efficiency, reliability, and load flexibility are paramount.

4. FULL BRIDGE LLC RESONANANTCONVERTER USING ANN CONTROLLER

In the field of machine learning, a neural network, also known as an artificial neural network (ANN) or neural net, is a computational model that draws inspiration from the structure and function of biological neural networks found in animal brains. An ANN comprises interconnected units or nodes referred to as artificial neurons, which are designed to loosely mimic the behaviour of biological neurons. These artificial neurons are linked by edges, simulating the synapses in the brain. Each artificial neuron receives signals from connected neurons, processes them, and transmits a signal to other connected neurons. The "signal" is represented by a real number, and the output of each neuron is computed using a non-linear function of the sum of its inputs, known as the activation function. The strength of the signal at each connection is determined by a weight, which is adjusted during the learning process. Neurons are typically organized into layers, with different layers carrying out various transformations on their inputs.

Signals propagate from the input layer to the output layer, potentially passing through multiple intermediate layers known as hidden layers. A neural network is categorized as a deep neural network if it consists of at least two hidden layers.
Artificial neural networks find applications in diverse tasks, such as predictive modelling, adaptive control, and addressing challenges in the field of artificial intelligence. One of the key attributes of neural networks is their ability to learn from experience and draw conclusions from complex and seemingly unrelated sets of information.

This capacity to learn and generalize from data makes neural networks a powerful tool in various domains. Since the considered design targets a full-Si converter realization, the best performing commercially available 600/650V Si MOSFETs and diodes (i.e., in a discrete package) are selected. In particular, the primary-side switches operate in ZVS conditions and should feature minimum on-state resistance Rds,on (i.e., to minimize conduction losses) and large-enough output capacitance Coss to perform the snubbing action at turn-off (i.e., to minimize switching losses)[2,3]. Si Super-junction MOSFETs are perfect candidates for this application, therefore SCT055W65G3-4AG MOSFETs (650V, 58mΩ) are selected for the full-bridge inverter [4]. On the other hand, the output rectifier diodes cannot be only optimized for conduction performance, as the turn-off di/dt values are in the range of 101 A/μs in boost-mode and unity-gain-mode and can reach 102 A/μs in buck-mode. Therefore, Vishay VS-1N1183 diodes (650V, 60A) gate driver (2EDL05x06xx) family-600 V Half Bridge Gate Driver with Integrated Bootstrap Diode (BSD) [6] are selected for the output diode bridge [5].

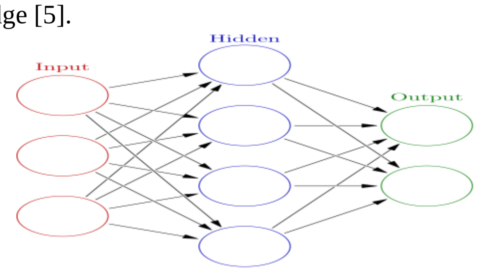

Fig.2.artificial neural network controller

A. 5. TRANSFORMER CALCULATIONS:

- Inductance ratio $\lambda = Lr/Lm$
- Primary resonance frequency frI $= 1/2\pi\sqrt{LrCr}$
- Secondary resonance frequency frII $= 1/2\pi\sqrt{(Lr + Lm)Cr}$
- Normalized switching frequency fn $=$ fsw /fr, I
- Characteristic impedance Zr $= \sqrt{Lr/Cr}$
- Output/input voltage gain M $=$ nVo/Vi
- Quality factor Q $= \pi 2/8\, Zr/n2\, Io/Vo = \pi 2/8\, Zr/n2\, 1/Ro$
- Resonant capacitor Cr $= 1/2\pi QFswRac$
- Resonant inductance Lr $= (1/2\pi QFsw)^2(1/Cr)$
- Lm $= (k + 1/k(2)r + 1) * L$ (K is the gain value 5 to 10 range)

6. DESIGN OF LLC CONVERTER

The specific design of the full bridge LLC resonant converter values is shown in Table 1.

Table 1: Specifications

S.NO	PARAMETER	VALUE
1.	$P_{O,nom}=P_{O,max}$	15kw
2.	$I_{O,nom}=I_{O,max}$	37.5A
3.	$V_{O,nom}$	400V
4.	Vo	250 - 500V
5.	Vi	325-400V
6.	η	≥97%

7. SIMULATION MODEL

The characteristics of the full-bridge LLC resonant converter used in MATLAB/SIMULINK and the sim ulation model of the PI control system are shown in Figure7 .There are 4 diodes, 4MOSFET switches. The diagram illustrates an LLC resonant converter system, a sophisticated solution for efficient DC-DC conversion with soft-switching capabilities.

The four FETs in the full-bridge converter form a robust topology, converting input DC voltage into a high-frequency AC signal. These FETs are precisely controlled by the Pulse Generator in the control system. Orchestrating Resonant Behaviour Comprised of Cr (resonant capacitor), Lr (leakage inductance), and Lm (magnetization inductance) of the transformer, the resonant tank determines the operating frequency and soft-switching conditions of the converter. It plays a pivotal role in resonating and transforming the AC signal generated by the full-bridge switches. The Voltage Maestro is the component that steps up or steps down the voltage based on the turns ratio and facilitates resonant energy transfer through its intrinsic components, namely leakage inductance (Lr) and magnetization inductance (Lm). At the Rectifier Stage, it is shaping the Output Following the resonant tank, the signal undergoes rectification through diodes to convert the AC signal back into a stable DC voltage. The output capacitor (Co) then ensures a smooth output.

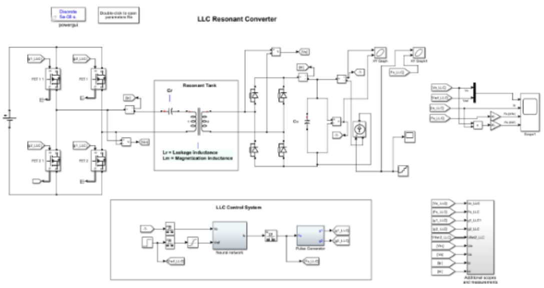

Fig.3. Full bridge LLC resonant converter with PI and NN controller

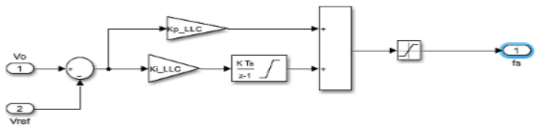

Figure .4. Subsystems of voltage regulation

The controller subsystem of the Voltage regulation is shown in Figure 3. It is then compared with the final value to control the 400V output voltage, and the signal is fed to the PI and ANN controller to control the output voltgae of the DC link capacitor.

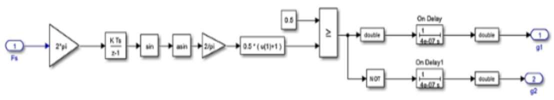

Fig .5. Subsystems of pulse generator

8. RESULTS AND DISCUSSION

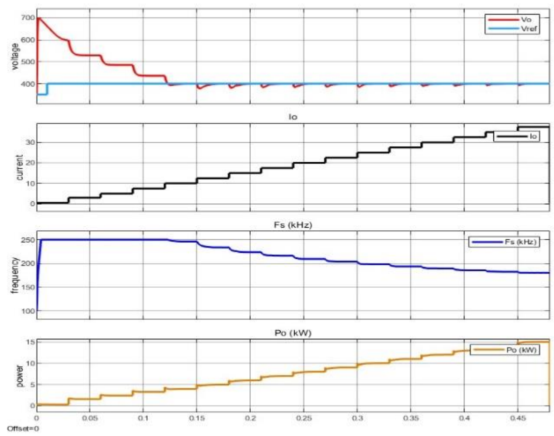

Fig.6. Output of full-bridge LLC converter using PI controller

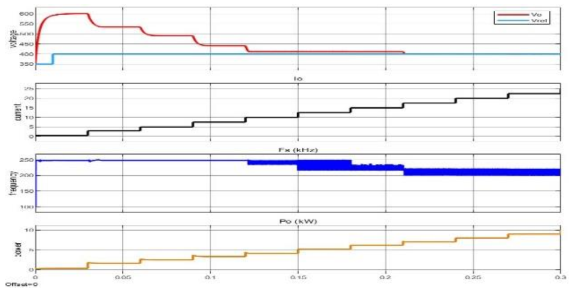

Figure.7. Output of full-bridge LLC converter using neural network controller

8. CONCLUSION

The paper presents a comprehensive overview of the design and operation of an LLC resonant converter that utilizes the leakage inductance and magnetizing inductance of the transformer as resonant components. Additionally, it extensively discusses the dual converter's capability to seamlessly transition between converter mode for charging and inverter mode for traction. It provides a detailed analysis of the increased power output achieved through the use of two inverters to effectively double the motor voltage. The paper thoroughly examines the technical intricacies of the switching scheme, emphasizing its role in mitigating harmonics and optimizing operational efficiency, particularly in facilitating charging at the rated power of the traction system, making it an ideal fit for electric vehicle charging applications. Moreover, the paper delves into the implementation of pulse current charging, providing an in-depth exploration of its impact on battery performance and longevity, and its potential implications for future applications. The integration of full-bridge and LLC resonant topologies is meticulously dissected, showcasing the multifaceted benefits it offers, including high efficiency, reduced switching losses, compact size, and inherent voltage regulation, positioning it as an optimal solution for a diverse range of applications, from server power supplies and telecommunications to electric vehicle charging systems

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