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Bidirectional Wireless EV Charger with Integrated Power Factor Correction Using a Single-Stage IPT Converter

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Abstract

Electric vehicle (EV) charging wireless power transfer (WPT) systems must meet strict power quality requirements in addition to having high efficiency. Using a new single-stage back-end circuit with an unfolding active rectifier, this work focuses on power factor corrector (PFC) control algorithms for a bidirectional wireless battery charger. This study's main motivation is the suggestion of two innovative PFC control strategies, both of which seek to achieve PFC on the primary or secondary side of the actual resonant inductive power transfer (IPT) converter. A thorough system model is created, and the behaviour of both control strategies is examined in terms of system stability, efficiency, and input current quality. —all of which might affect system performance under different operating conditions—receives particular consideration. Both suggested approaches provide potential solutions for upcoming smart wireless charging applications by enabling high power factor operation with minimal THD and enhanced overall efficiency, as confirmed by simulation and experimental results. Keywords: Wireless Power Transfer (WPT), Power Factor Correction (PFC),Bidirectional Charging, Active Rectifier, Total Harmonic Distortion (THD), Bifurcation Phenomena, Efficiency Optimization, Electric Vehicle (EV) Charging.

Keywords: *Electric Vehicle, Wireless Power transfer, MATLAB,EV Efficiency*

I. Introduction

Advanced battery charging systems that are dependable, efficient, and grid-friendly are in high demand due to the widespread use of electric vehicles (EVs) [1], [2]. Among various charging technologies, wireless power transfer (WPT) has emerged as an attractive alternative to conductive charging, offering advantages such as enhanced user convenience, greater safety, and resistance to environmental factors [3], [4]. However, WPT systems introduce unique challenges, including lower system efficiencies, difficulties in power factor management, and increased grid-side harmonics [5], [6].

Achieving a high power factor and low total harmonic distortion (THD) at the grid interface is a crucial prerequisite for contemporary wireless battery chargers [7]. Preventing negative impacts on the power system requires adherence to strict power quality standards like IEEE 519 and IEC 61000-3-2 [8], [9]. Moreover, the control complexity of wireless chargers rises dramatically with the growing focus on bidirectional energy transfer, which permits both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) operations [10], [11]. Effective bidirectional operation enables EVs to act as distributed energy resources, improving grid stability and enabling new applications like peak shaving and load levelling [12].

Traditionally, passive diode rectifiers have been used in charger designs, but their inherent limitations—such as poor power factor and lack of bidirectional capability—make them unsuitable for modern wireless chargers [13]. In contrast, the integration of an unfolding active rectifier provides numerous benefits, including synchronous operation, reduced conduction losses, improved input current shaping, and support for efficient bidirectional energy flow [14], [15]. The unfolding active rectifier effectively rectifies the AC input while allowing precise control over the current waveform, thus enabling the implementation of sophisticated power factor correction strategies.

For the input current to be sinusoidal and in phase with the grid voltage, effective PFC control techniques must be designed [16]. A number of methods have been put forth, including dual-loop control schemes [20], predictive control [18], model predictive control (MPC) [19], and average current mode control (ACMC) [17]. Each of these approaches offers trade-offs between robustness, dynamic performance, and implementation complexity. Particularly in wireless systems, the soft-switching nature of resonant converters introduces additional constraints that must be considered in the control design [21].

Recent studies have explored the synergy between active rectification and resonant WPT systems to maximize efficiency under bidirectional operation [22]. Furthermore, the system's capacity to react to changes in load dynamics and grid circumstances is further improved by the combination of adaptive control and digital control approaches [23], [24]. To enhance dynamic performance under quickly shifting operating conditions, advanced control techniques including fuzzy logic-based PFC and sliding mode control are also being researched [25]-[33]. The current and transferred power are directly impacted by the main side's lack of an intermediate energy storage device, as shown in Figure 1. This results in a fluctuating power flow to the secondary and, eventually, to the batteries twice per grid period.

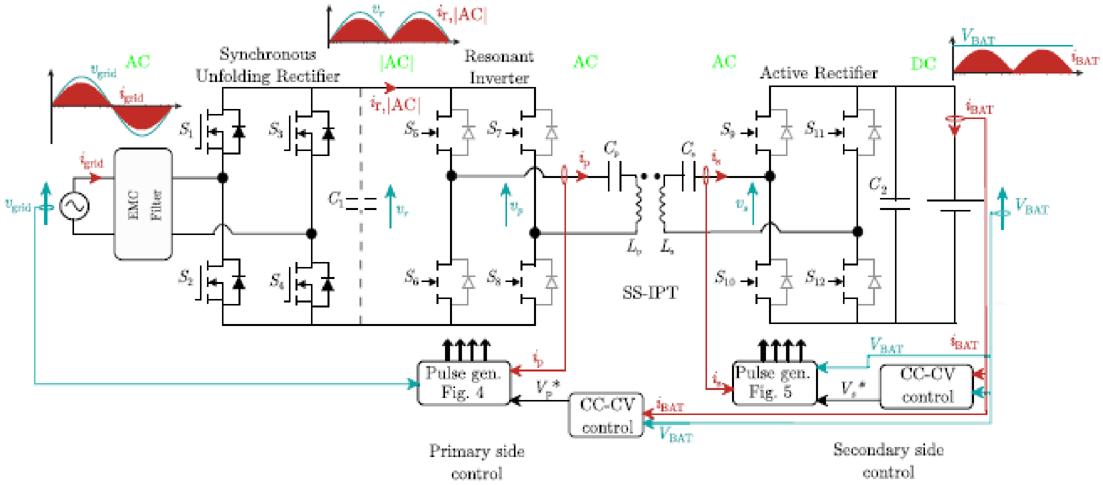

Figure 1: Schematic diagram

Power electrical circuit analysis of the bidirectional single-phase back-end PFC topology, showing key waveforms and variance in control This paper comprehensively examines the power factor corrector control schemes for a bidirectional wireless battery charger that uses an unfolding active rectifier. The PFC is implemented using a novel single-stage back-end circuit that can function on either the primary or secondary side of the resonant IPT converter. The main goal of the study is to evaluate the performance of the IPT system using both control methods, focusing on power losses, efficiency, input total harmonic distortion (THD), and bifurcation events.

II. Architecture of The Proposed System

Line-frequency rectifier, capacitor stack across rectifier output, regulating converters with inputs connected to capacitors on the capacitor stack and outputs regulated to a desired level, and a power-combining converter (or a group of power combining converters) that combines the power from the regulating converters' outputs to create a single output are the components of the proposed architecture, which is depicted in Fig. 3.2.

The regulating converters control the waveform while the line-frequency rectifier draws current from the grid during a portion of the cycle. The capacitor stack provides most or all of the twice-line-frequency energy buffering, which enables the converter to provide high power factor without the need for energy buffering at the system output. Because one or more of the capacitors in the stack are relatively small, the voltage of the entire capacitor stack can fluctuate across a wide range as the line voltage changes over the line cycle.

The input ac current waveform may have a high power factor and resemble a clipped sine waveform, while the total capacitor stack voltage approximately matches the amplitude of the line voltage throughout the line cycle segment for which the rectifier conducts. The currents pulled by the (at least) two regulating converters are modulated to take energy from the capacitors in order to create an input current waveform for the rectifier that delivers a high power factor as well as the total amount of energy needed to support the output.

Switches with smaller voltage ratings and less parasitic capacitance can be used in the construction of the regulating converters than would be feasible at considerably higher frequencies. Because they run on voltages much lower than the whole line voltage, they can also be used at lower characteristic impedance levels than a single converter rated at line voltage.

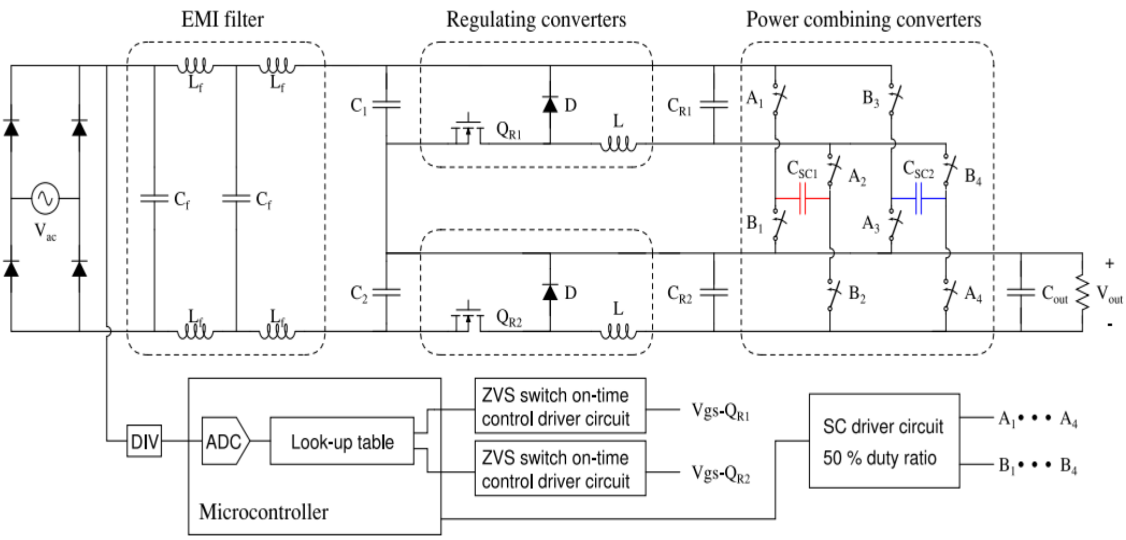

Figure 2: A line-frequency rectifier, a stack of capacitors, a series of regulating converters, and a power combining converter make up the suggested grid interface power conversion architecture.

This design allows the regulating converters to operate at high frequencies (HF, 3–30 MHz) with good control capability, low device voltage stress, compact component size, and high efficiency.

A. Line-Frequency Energy Buffering

The proposed ac–dc PFC design buffers twice-line-frequency energy with a high power factor and supplies the load with the necessary dc power. Fig. 3.3 shows sample operating waveforms and a simplified front-end representation of the proposed grid interface design. The two current sources (i1 and i2) replicate the average currents drawn by the regulating converters during the switching interval. Examples of regulating converters and power combining converters that are presumed to be ideal (lossless) in order for the average powers drawn by regulating converters over the switching period to be loss less combined to supply the system load are PReg-Con1 = vc1(t) i1(t), PReg-Con2 = vc2(t) i2(t), and Psystem = vc1(t) i1(t) + vc2(t) i2(t).

The circuit cycles in two phases during a half-line cycle. Since the input ac voltage amplitude is smaller than the total of the voltages of the stacked capacitors, the full-bridge rectifiers are turned off and no current is drawn from the grid during phase 1. During this phase, as the regulating converters discharge capacitors C1 and C2, the voltage across the capacitor stack decreases. Phase 2 of the circuit begins, and when the input ac voltage amplitude surpasses the total capacitor stack voltage, the full-bridge is activated.

In phase 2, the total voltage of the stack capacitors tracks the rectified ac input voltage, while the input current follows the sum of the currents into C1 and regulating converter 1 (which is voltage and current waveforms). Currents i1 and i2, respectively, represent the average current drawn by regulating converters 1 and 2 (averaged across a switching cycle of the regulating converters). Similar to the sum of the currents entering C2 and regulating converter2, the regulating converters regulate their current draw across the line cycle, producing an input current waveform with a high power factor.

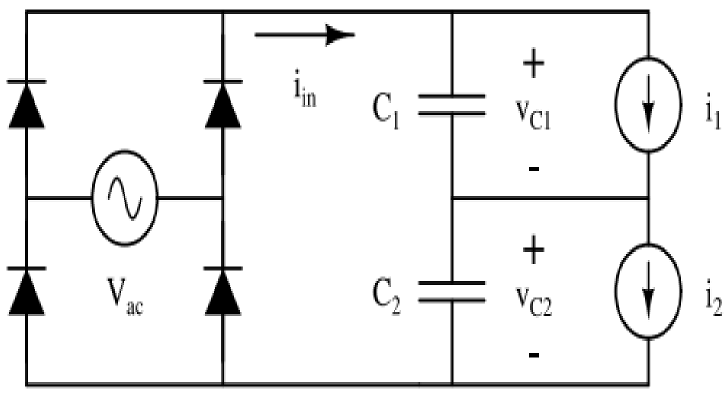

Figure 3:Simplified front-end circuit model of the proposed architecture with example

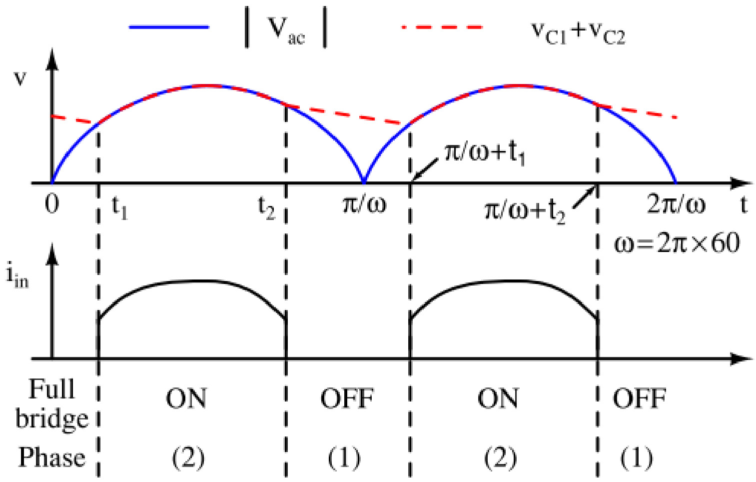

Figure 4:Voltage and current output waveforms

1) Phase 1: $0 < t < t1$ and $t2 < t < \pi/\omega$

full bridge is OFF, and conducts zero input current

$$i_{in}(t) = 0 \tag{1}$$

$$P_0(t) = v_{c1}(t)i_1(t) + v_{c2}(t)i_2(t) \tag{2}$$

$$i_{c1}(t) = C_1 \frac{dv_{c1}(t)}{dt} = -i_1(t) \tag{3}$$

$$i_{c2}(t) = C_2 \frac{dv_{c2}(t)}{dt} = -i_2(t) \tag{4}$$

2) Phase 2: $t1 < t < t2$

full bridge is ON, and conducts in(t) input current

$$V_{ac}(t) = V sin\omega t = v_{c1} + v_{c2} \tag{5}$$

$$i_{in}(t) = i_{c1}(t) + i_{c2}(t) \tag{6}$$

$$P_0(t) = v_{c1}(t)i_1(t) + v_{c2}(t)i_2(t) \tag{7}$$

$$i_{c1}(t) = C_1 \frac{dv_{c1}(t)}{dt} \tag{8}$$

$$i_{c1}(t) = C_1 \frac{dv_{c1}(t)}{dt} \tag{9}$$

$$i_{c1}(t) = \frac{C_1 C_2 v_{c2}}{C_2 v_{c2}(t) - C_1 v_{c1}(t)}\left[\left(\frac{1}{C_1} + \frac{1}{C_2}\right) i_{in}(t) - \omega V cos\omega t - \frac{P_0(t)}{C_2 v_{c2}(t)}\right] \tag{10}$$

$$i_2(t) = \frac{1}{C_2 v_{c2}(t)}(P_0(t) - v_{c1}(t)i_1(t)) \tag{11}$$

The power-combining converter receives energy from the regulating converter outputs and sends the combined power to the converter system output. It has several inputs that are connected to the regulating converter outputs. One or more of the following may be offered by the power-combining converter: galvanic isolation, voltage transformation, a portion of twice-line-frequency energy buffering, output regulation, and voltage balancing among the regulating converter outputs. Either a multi-input converter or a series of single-input converters that accept inputs connected to one of the regulating converter's outputs and provide a single output are possible designs for the power-combining converter.

The regulating converter outputs provide energy to the power-combining converter, which then transfers the combined power to the converter system output. Its several inputs are linked to the outputs of the regulating converter. The power-combining converter may provide one or more of the following: output regulation, voltage balancing among the regulating converter outputs, galvanic isolation, voltage transformation, and a portion of twice-line-frequency energy buffering. The power-combining converter can be designed as a multi-input converter or as a sequence of single-input converters that accept inputs connected to one of the outputs of the regulating converter and produce a single output.

When the regulating converters cannot discharge the capacitor stack voltage fast enough to match the line voltage drop, the full-bridge cuts off and the circuit enters phase 1. The following are the mathematical expressions for each phase, assuming that the regulating converters draw currents (averaged over a switching cycle of the regulating converters) i1(t) and i2(t), and that the power combining converter continuously supplies the required output power Po(t) and combines power (from the two regulating converters) without loss. It should be noted that in phase 2, (3.10)1 and (3.11) are calculated from (3.5)–(3.9), and the i1(t) and i2(t) currents generate the system's predefined input current across the line cycle, which offers a good power factor.

Power level, capacitor voltage fluctuation, regulating converter operating range, power factor, and stack capacitor values are all related in a number of ways. Therefore, it is crucial to choose the right topologies, design values, and operational waveforms.

III. Unfolding Active Rectifier: Design And Operation

An unfolding bridge topology is a specialized power electronics circuit that converts AC to DC (rectification) or DC to AC (inversion) efficiently. Unlike conventional rectifier bridges, unfolding bridges use active semiconductor switches (e.g., MOSFETs or IGBTs) instead of diodes, reducing conduction losses and improving efficiency.

This topology is particularly useful in wireless power transfer (WPT) systems, where power must be efficiently converted between resonant AC circuits and DC loads (or sources).

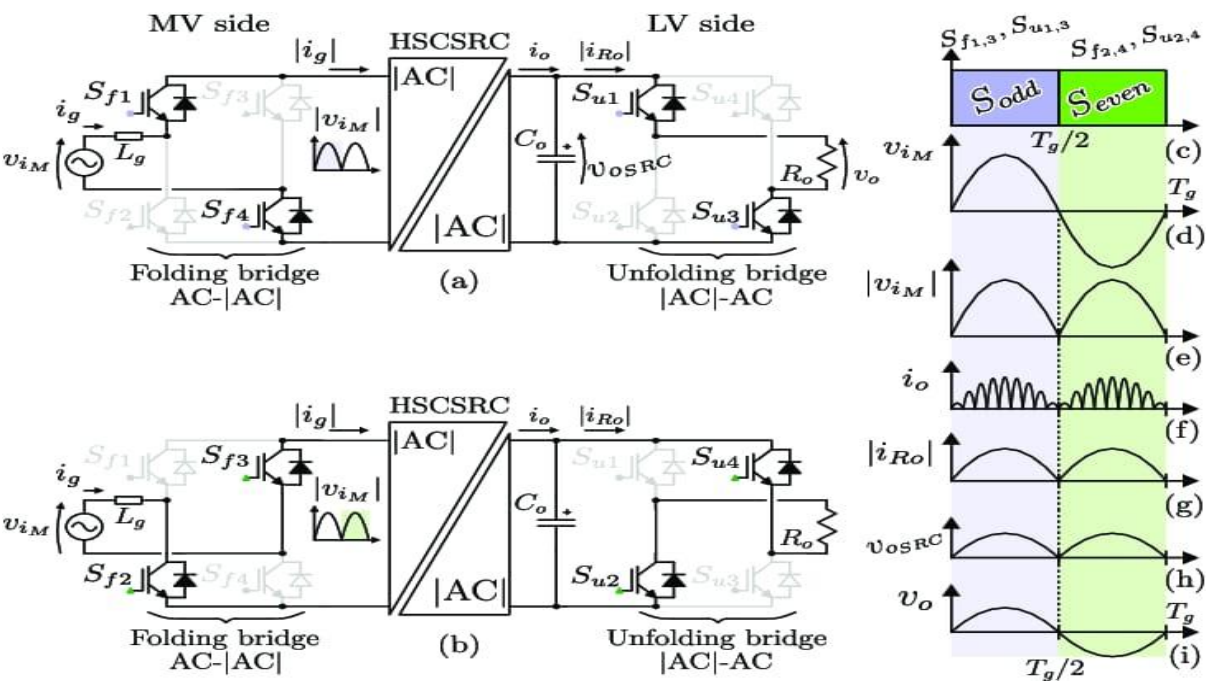

Figure 5: Unfolding Bridge Topology

Diodes are used in conventional rectifiers to convert AC to DC, however they cause a considerable voltage drop (usually 0.7V per silicon diode).

In an unfolding bridge, semiconductor switches (e.g., MOSFETs) are used instead of diodes, allowing for near-lossless rectification with reduced conduction losses. The unfolding bridge operates by synchronously switching to match the AC polarity, effectively acting as a high-efficiency rectifier or inverter.

The main features of unfold bridge includes:

i. Grid voltage fluctuations:

Grid voltage fluctuations can impact the dc input voltages of the dc-dc converter in unfolding-based systems. “Grid voltage fluctuations” refers to irregular or rapid changes in the voltage level within an electrical power grid, meaning the voltage supplied to homes and businesses can vary slightly up and down from the standard level, potentially impacting the performance of connected appliances and electronics; essentially, it's a fluctuation in the electrical power supply on the grid, not necessarily a complete power outage.

ii. Zero-voltage switching (ZVS):

The T-type primary bridge-based dc-dc converter's soft-switching behavior is examined. Zero Voltage Switching" (ZVS) refers to a technique in power electronics where a switch is turned on or off when the voltage across it is at zero volts, effectively eliminating switching losses by preventing any significant current flow during the transition, resulting in improved efficiency and reduced EMI in the circuit; it's considered a type of "soft switching.".

iii. LLC resonant Stage:

The LLC resonant topology has been explored for battery charging applications. LLC resonant topology is a type of resonant converter topology that uses inductors and capacitors to create a resonant tank. The resonant tank oscillates at a specific frequency.

iv. Half bridge LLC topology:

Half bridge LLC topology has been very popular. A half-bridge LLC topology is a type of power converter circuit that uses a half-bridge configuration and an LLC resonant converter. It's used in many applications, including power supplies, motor drives, and inverters.

v. AC-DC topology:

For quick charging applications, an AC-DC topology based on unfolding can be employed. The design of an electrical circuit that transforms alternating current (AC) into direct current (DC) is known as AC-DC topology. AC-DC converters are used in many electronic devices, like computers, televisions, and smartphones.

IV. Control Strategies For Active Rectification:

Active rectification control strategies primarily focus on regulating the DC output voltage by manipulating the switching signals of the power electronic devices within the rectifier, often using techniques like voltage-oriented control (VOC), current control, phase-locked loops (PLLs), and hysteresis control to achieve precise current and voltage regulation while minimizing harmonics and improving power quality. In this paper , the constant voltage and constant control techniques are implemented.

A. Control of Constant Current (CC) and Constant Voltage (CV):

i. Constant voltage control: This technique maintains a power supply's voltage output at a constant level despite changes in the load or current demand. This is frequently utilized in applications like powering computers, microcontrollers, and delicate electronic circuits where a steady voltage is essential. The resistance or impedance of the connected item determines how much current is consumed by the load in a CV power supply. For instance, in battery charging, once a battery reaches a specific voltage, the charger operates in constant voltage mode to prevent overcharging. Similarly, in LED drivers, CV control ensures that multiple LEDs connected in parallel receive the same voltage, even if their current consumption varies.

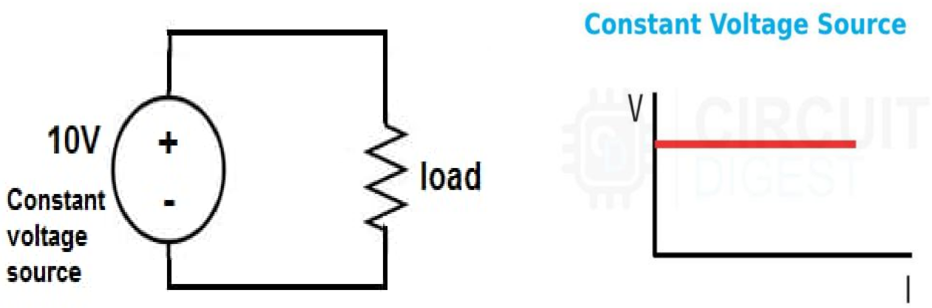

Figure 6: Understanding Constant Voltage Source

ii. Constant current control: While the voltage may fluctuate based on the resistance of the load, this regulation guarantees that the current delivered to the load is constant. This is particularly useful in applications where precise current regulation is required, such as in battery charging, electroplating, welding, and LED lighting.

In a battery charging scenario, the charger operates in CC mode initially to deliver a steady current until the battery reaches a target voltage, after which it switches to CV mode. In LED applications, CC drivers are preferred for ensuring uniform brightness and preventing excessive current that could damage the LEDs. Constant current control is also used in testing and calibration processes where precise current levels are required.

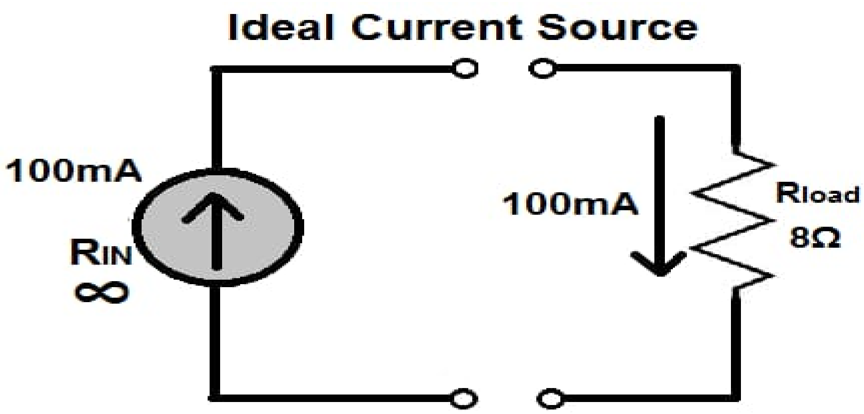

Figure 7:Understanding Constant Current Source

In many power supplies and chargers, both CV and CC modes are integrated, allowing seamless switching between the two depending on the load requirements. This ensures optimal performance, safety, and efficiency in various electronic and industrial applications. **"Constant current and constant voltage control"** in a bidirectional wireless battery charger refers to a charging strategy where the charger initially delivers a constant current to the battery.

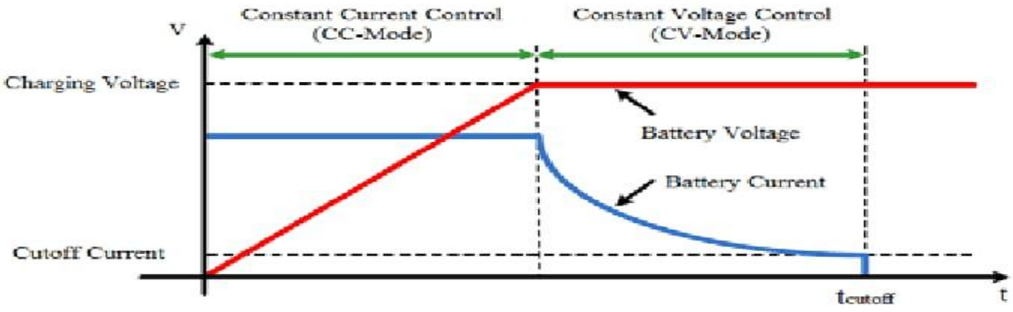

Figure 8: Constant Current & Voltage Charging

B. **Charging stages**:

i. **Constant current (CC):**

The charger delivers a set current to the battery regardless of the battery voltage, ideal for quickly charging a depleted battery.

ii. **Constant voltage (CV):**

Once the battery reaches a near-full state, the charger switches to maintaining a constant voltage while adjusting the current to prevent overcharging.

C. **Bidirectional aspect:**

The battery can be used as a power source when necessary thanks to this control method, which works in both charging and discharging modes.

D. **Implementation in wireless charging:**

i. **Control circuitry**:

The charger uses feedback from the battery voltage to determine when to transition from CC to CV mode.

ii. **Power electronics:**

To manage power flow in both directions, a bidirectional DC-DC converter is required. Advantages of a bidirectional wireless charger with CC/CV control:

iii. **Optimized charging speed:**

Constant current mode provides fast initial charging, while constant voltage mode ensures safe and complete charging.

iv. **Battery health:**

Prevents overcharging and potential damage to the battery by transitioning to constant voltage mode.

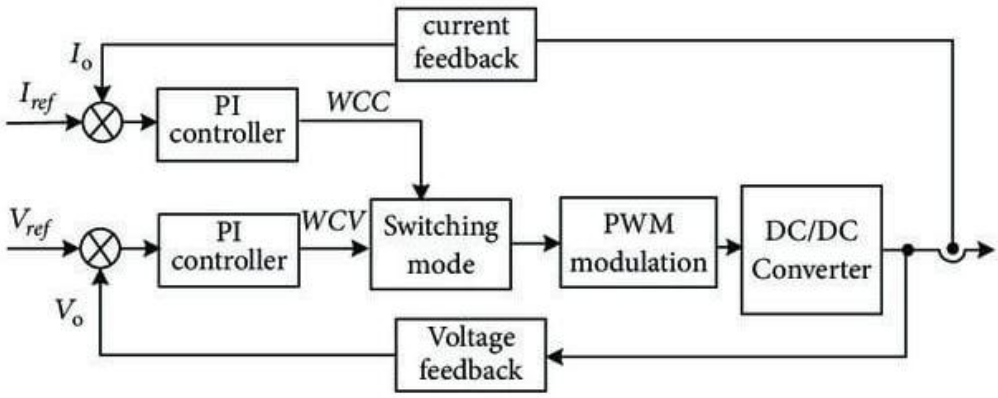

Figure 9:CC/CV Control Strategy

PWM (Pulse Width Modulation) control in a bidirectional wireless battery charger is crucial for regulating power flow, efficiency, and battery charging/discharging processes. Here's how it works in both directions:

1. Forward Mode (Battery Charging):

In this mode, power is transferred from the transmitter (Tx) to the receiver (Rx) to charge the battery.

- Transmitter Side (Tx) PWM Control: The primary coil generates an AC magnetic field using a PWM-controlled inverter (typically an H-bridge or half-bridge circuit).
- PWM duty cycle and frequency adjust the transmitted power based on battery charging requirements.
- The recipient's side (Rx) PWM Control: A DC-DC converter (such as a buck or buck-boost converter) rectifies and regulates the received AC power. For effective battery charging, PWM regulates the converter to keep the voltage and current constant.

2. Reverse Mode (Battery Discharging / Grid Feedback):

In bidirectional systems, power can also flow back from the battery to the source or grid.

- Receiver Side (Battery to Coil - Inverter Operation): The battery discharges into an H-bridge inverter, creating an AC output at the desired frequency. PWM modulates the inverter's output to match the required transmission parameters.
- Transmitter Side (Power Reception and Rectification): The Tx coil receives the AC power and rectifies it for grid integration or storage. A controlled buck/boost converter with PWM ensures stable voltage regulation.

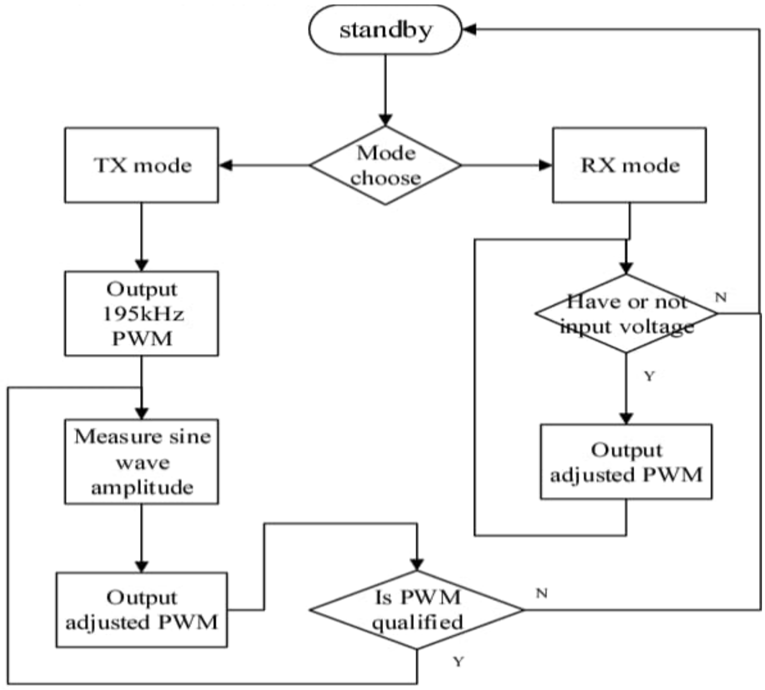

Fig 4.7: Program Flow Chart For Bidirectional WPT Using PWM

V.Results & Discussion

Using an unfolding active rectifier, the study focuses on Power Factor Correction (PFC) control mechanisms in a bidirectional wireless battery charger. given that MATLAB/Simulink is being used to simulate this. Figure 10 depicts the suggested system's Simulink implementation. Here An inductive filter connects the active rectifier's AC side to the grid. To power the EV motor, a three-phase inverter reverses the rectified grid electricity once more. A sizable bank of capacitors at the DC link input maintains the DC link voltage.

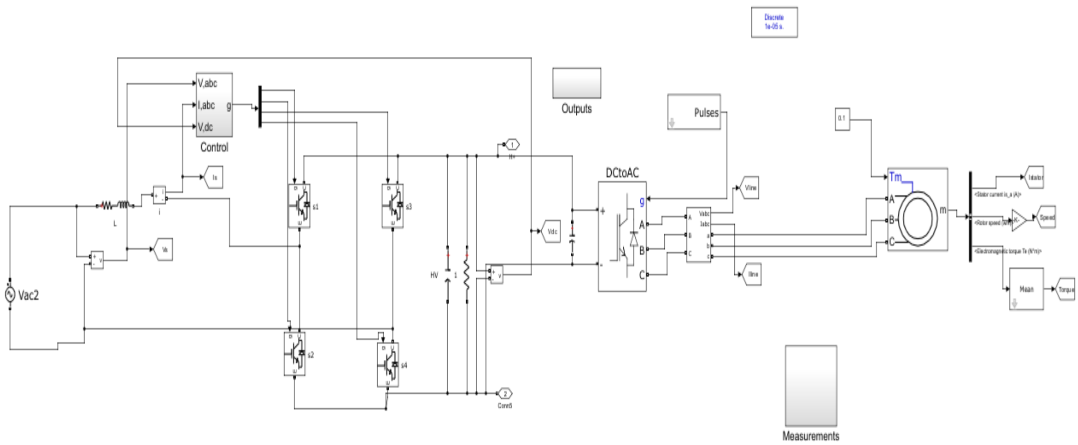

Figure 10:Proposed System Simulink Diagram

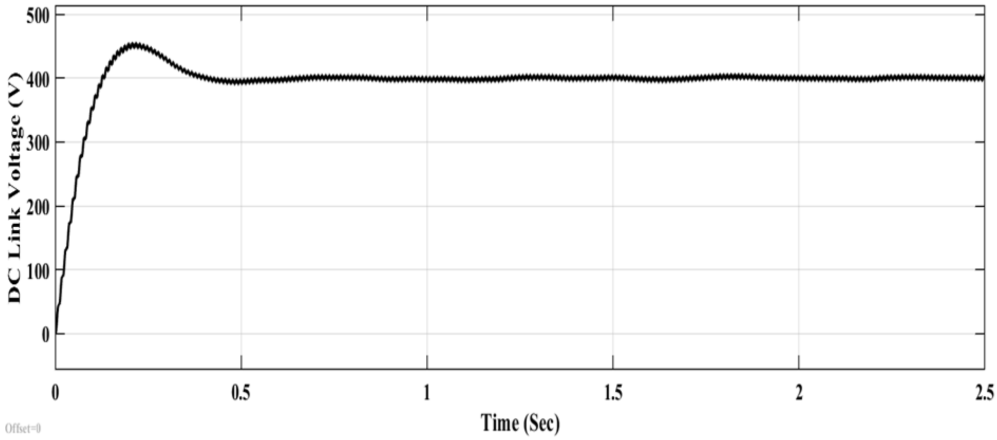

Figure 11:DC Link voltage

The voltage at the DC link is shown in Figure 11. It is controlled by constant voltage control. Active power factor correction is achieved by the converter while discharging and charging the vehicle battery which is supposed to connect at the DC link.

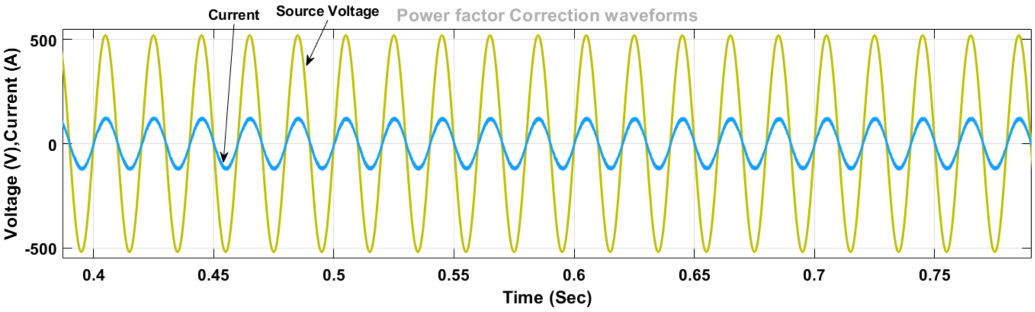

Figure 12:Source side current and voltage waveforms

Figure 12 displays the voltage and current waveforms at the source side that were extracted from the grid. It shows that the waveforms for voltage and current are in phase, meaning that the power factor is at unity. Power factor adjustment is thus accomplished. Figure 13 mentions the power factor correction control technique.

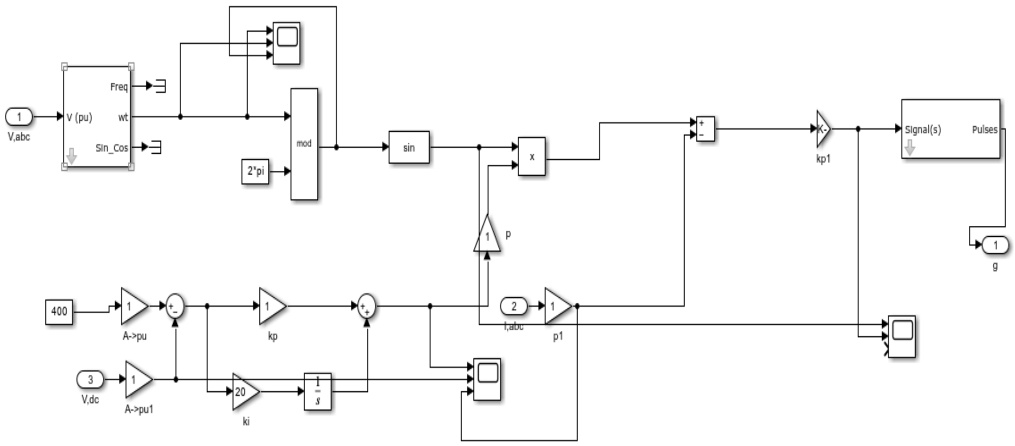

Figure 13:Gate firing control circuit for DC voltage regulation and Power factor correction

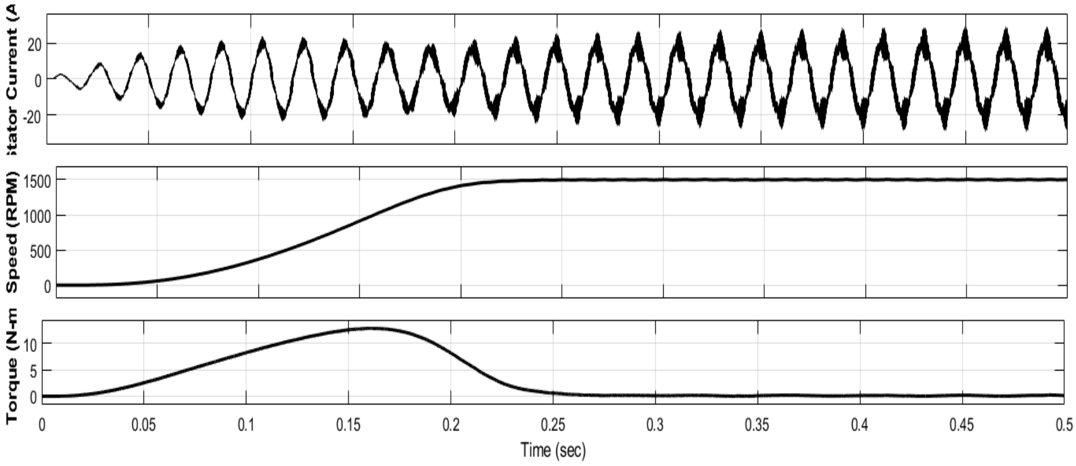

Figure 14: EV motor parameters

Power factor is controlled by maintaining voltage and current in phase. This is achieved by making source current waveform phase as grid voltage phase. Grid voltage phase angle is obtained using PLL(phase locked loop). EV motor parameters like speed, torque stator current are as shown in Figure 14.

VI. Conclusion

This study used a single-stage back-end circuit with an unfolding active rectifier to provide two new power factor correction (PFC) control algorithms for a bidirectional wireless battery charger. The suggested techniques improve system efficiency and compactness by removing the need for extra power conditioning stages by integrating the PFC function directly into the resonant inductive power transfer (IPT) stage, either on the main or secondary side. Both control systems were demonstrated to provide high power factor operating with low input current THD and minimal power losses by thorough modelling, simulation, and experimental validation. In order to guarantee operational stability, the behaviour of the system under dynamic conditions—including bifurcation phenomena—was also examined. The findings support the notion that the suggested control strategies provide a viable and viable option for grid-compliant, high-performance wireless EV charging systems, opening the door to more intelligent and energy-efficient transportation infrastructure.

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