

# A single-phase bidirectional AC-AC converter with H-bridge energy buffer for wireless power transfer applications

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## ABSTRACT

This paper introduces a single-phase bidirectional AC-AC Matrix type converter for wireless power transfer (WPT) applications. The proposed converter converts mains 50 Hz alternating current (AC) directly to high frequency 85 kHz AC without an intermediate direct current (DC) conversion stage. A minimum cost realization of only two bidirectional AC switches comprised each of two semiconductor device and one gate drive signal is employed. The converter operation modes are quantum energy injection and circulating self-oscillation. Elimination of the DC link introduces a sag in the power transfer during the zero crossing of input AC mains, which is well documented in literature. A novel H-bridge buffer structure is introduced which eliminates the power sag by storing energy during mains peak and delivering energy during the zero-crossing period. The converter operates with inherent zero current switching, thus achieving a low switching loss and electro-magnetic interference. The control feature ensures that the converter can be used for both static and dynamic wireless charging applications. The bidirectional power transfer capability ensures that the system can operate in both grid to vehicle (G2V) and vehicle to grid (V2G) power transfer modes. The proposed converter design is analyzed analytically and verified through thorough simulation study.

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## 1. INTRODUCTION

Wireless power transfer (WPT) has attracted widespread research and industry interest in recent years [1], [2]. There are two major technologies in WPT area: inductive power transfer (IPT) and capacitive power transfer (CPT). Both technologies employ high frequency excitation in order to transfer appreciable power through air. IPT is more mature technology, which employ magnetic field to transfer power. On the other hand, capacitive power transfer (CPT) employs electric field to transfer power. Although CPT is known in research community for low power consumer electronics charging applications, its employment in relatively higher power electric vehicle charging is quite recent development. CPT also requires very high frequency power electronics to enable appreciable power transfer. This paper focuses on inductive power transfer technology, and will refer to this technology while using the acronym WPT.

The fact that WPT eliminates wire gives added flexibility, enhanced reliability and higher degree of safety in hazardous environment. These benefits have made WPT an attractive technology in industrial, commercial and consumer applications. WPT is used in electric vehicle (EV) charging [3], [4], charging robots [5], material handling systems [6], biomedical implants [7], underwater vehicle charging [8], [9] and

many others. Among its many applications static and dynamic electric vehicle charging [10], [11] are most promising. Electric vehicle charging can be classified as Level 1, 2 and 3 [12]. Level 1 usually refers to low power charging taken from 120V residential outlet. Level 1 charging is suitable for plug-in hybrid vehicles and for consumers who only travel short distance each day. Level 2 Charging enables widespread EV adoption as it can charge an EV completely overnight. Level 2 source is single phase 220-240 V residential outlet available worldwide. Level 3 refers to fast chargers, which take three phase supply and is able to charge an EV from 20–80% in 20–30 minutes.

A WPT system needs high frequency current in order to transfer appreciable power from transmitter to receiver side. Compared to a tightly coupled magnetic system like transformer which has a coupling coefficient of near unity, WPT systems tend to have low coupling coefficient near 0.2. This necessitates generation of high frequency current in the order of tens of kHz. For example, SAE standard requires the WPT system to operate at 85 kHz for automotive battery charging applications. In the mains we only get 50/60 Hz AC power based on the geographical location. The mains voltage is thus converted from AC to DC and then again from DC to high frequency AC voltage in order to generate high frequency current through the coupling coils. In both primary and secondary side there is a compensation network to compensate for the coil self-inductance and to increase the power transfer capability. The high frequency AC current is conditioned in single or two stages based on the load requirements. Figure 1 gives a block diagram representation of the WPT conversion stages from the input mains to the output load.

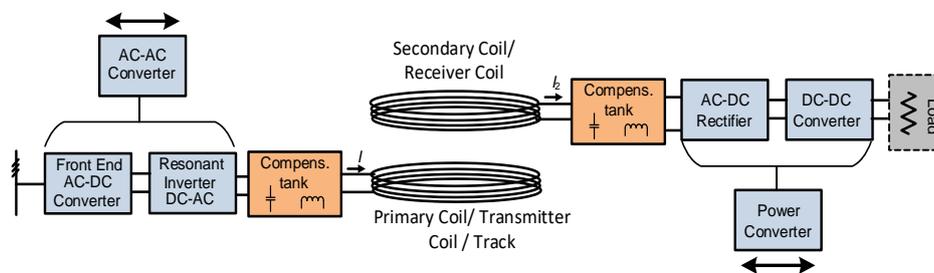


Figure 1. Block diagram of IPT system

Reduction of converter blocks and improvement in conversion capability is a constant research area in power electronics. As a more compact alternative to AC-DC-AC two stage conversion in the primary side, researchers have proposed direct AC-AC conversion without a DC link [13]–[19]. Several single and three phase matrix converter topologies have been proposed. The converter operation modes are quantum energy injection and circulating free oscillation. Although different realizations have been proposed, there is always room for an innovative low-cost realization with additional feature [20]–[23]. For single phase AC-AC conversion, these converters suffer from a current sag phenomenon during input mains zero crossing which is well documented in literature [13]–[18]. The current sag results in a drop of transmitted power even though the load is present. This is a major technical bottleneck, limiting employment of single-phase matrix converter topologies in practical products. Researchers have proposed three phase power supply as a solution to this problem [17], [18]. But single-phase wireless power transfer systems make up a major segment of wireless power transfer products, ranging from consumer battery charging to level 2 electric vehicle battery charging. Three phase solutions will require a three-phase utility connection in residential space. Three phase connection is costly as it requires the purchase of a three-phase transformer by the consumer as well. Thus, there is a need for a matrix converter which can directly convert single phase mains AC to high frequency AC suitable for exciting a wireless inductive link without any power sag. A natural extension to unidirectional wireless power transfer from grid side to electric vehicle (G2V), recent advances have explored vehicle to grid power transfer (V2G) as well. The key technology for enabling V2G power transfer is bidirectional converters. Several papers in literature discuss novel converters for bidirectional wireless charging [24]–[26].

This paper proposes a compact single phase bidirectional AC-AC converter with H-bridge energy buffer for wireless power transfer applications. The main converter is comprised of only two bidirectional AC switches. Each AC switch has two insulated gate bipolar transistor (IGBT)/metal oxide semiconductor field effect transistor (MOSFET) device with only one common gate signal. This simplifies the converter construction and control significantly. The variable frequency quantum energy injection and circulating free

oscillation control technique ensures zero current switching and tight regulation of the resonant tank current. This inherent zero current switching property ensures low switching loss and a significantly low EMI footprint. Tight control of the resonant tank current ensures constant power transfer in case of static load condition and constant flux with flout the load for dynamic load conditions. Thus, the control feature is well suited for both static and dynamic in-motion wireless charging. H-bridge energy buffer structure is inserted in the switching node point, which eliminated the widely reported current sag problem. This novel circuit feature acts as an energy pulsation buffer, which harvests energy during input AC voltage peak period and delivers energy to the resonant tank during AC voltage zero crossing period. The converter is also bidirectional, thus enabling V2G power transfer as well. A wireless power transfer system of 800 W is designed and verified through simulation results.

The rest of the document is arranged as follows: section 2 introduces the new circuit and its operation principle. Section 3 is the analytical analysis of the proposed system. The current ripple during control periods, current sag during zero crossing and the buffer capacitor sizing is analyzed in detail. Section 4 is the simulation results which verifies the analytical analysis. Section 5 concludes the paper.

## 2. PROPOSED AC-AC CONVERTER

The proposed circuit is presented in Figure 2. It has two bidirectional AC Switches and two control signals in the main circuit. The resonant tank is designed as series tuned. Here,  $L$  is the coil self-inductance and  $C$  is the resonant capacitor and  $R_{eq}$  is the equivalent resistive load reflected from the secondary side.  $SW_1$  and  $SW_2$  are two circuit. IGBT/MOSFET semiconductor devices which together form a bidirectional AC switch.  $SW_1$  and  $SW_2$  emitter terminals are connected, thus one control signal  $S_1$  is sufficient to drive both devices. Similarly,  $SW_3$  and  $SW_4$  form the second switch while  $S_2$  is the control signal of this switch assembly. During zero crossing of the input voltage  $V_{in}$ , the resonant tank current  $i_L$  go through a sag due to low applied voltage to the resonant circuit. The buffer capacitor  $C_{buff}$  delivers energy during that period. The buffer circuit has H-bridge structure and its switch node is connected to the main circuit switch node. Due to the inherent antiparallel body diode full bridge structure of the H-bridge circuit, the buffer capacitor  $C_{buff}$  gets charged during  $S_1$  on period.  $C_{buff}$  discharges into the resonant tank through the four semiconductor switches  $SB_1, SB_2, SB_3$  and  $SB_4$ .

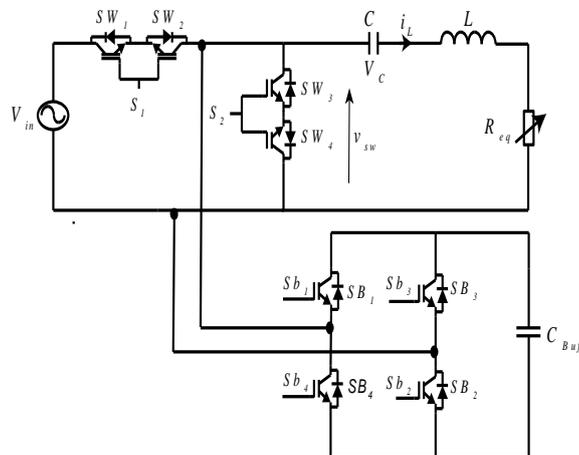


Figure 2. Circuit diagram of the proposed AC-AC converter

The main circuit operation is explained in Figure 3. Essentially there are two main modes of operation: quantum energy injection and circulating free oscillation. During energy injection track current increases and free oscillation decreases track current. The control objective is to keep a regulated constant track current by switching between the two modes. This operation is pictorially represented in Figure 4. Energy injection means positive power, as shown in Figure 4 (a). Thus, during positive input voltage and positive half cycle of the track current, switch  $S_1$  is turned on. Positive voltage and positive current results in positive power. Similar energy inaction by switching on  $S_1$  happens during negative current half cycle and negative voltage half cycle. On the other hand, during free oscillation there is no applied voltage to the resonant tank, but the load resistance is present. Thus, the load acts as a damping and decreases the resonant

tank current. Free oscillation modes are achieved by circulating the resonant tank current through the bidirectional switch  $SW_2$ .

This current regulation works well for sufficient input voltage. But, when the input voltage is low, then the track current fails to regulate. Even with energy injection, the track current falls to a low value. This is the case during the input voltage zero crossing, as shown in Figure 4 (b). The solution is a buffer circuit, which consists of an H-bridge interface and capacitor energy storage. Figure 5 is an illustration of this circuit. IGBT/MOSFET devices come with an antiparallel diode. That forms a diode bridge and acts as a rectifier. The diode conducts during switch  $SW_1$  turn on period and automatically charges the buffer capacitor. During the zero crossing of the input voltage, energy is supplied from the capacitor to the resonant tank. Energy injection happens by turning on  $SB_1, SB_2$  during positive current half cycle or  $SB_3, SB_4$  during negative current half cycle. Due to this energy supply to the resonant tank, the capacitor voltage decreases. Detailed description can be found in Table 1. The key waveforms explaining the operation is shown in Figure 6. The converter is designed for a typical electric vehicle wireless power transfer system. Example system is Evatran group level 2 battery charger. Specifications of the proposed system is given in Table 2.

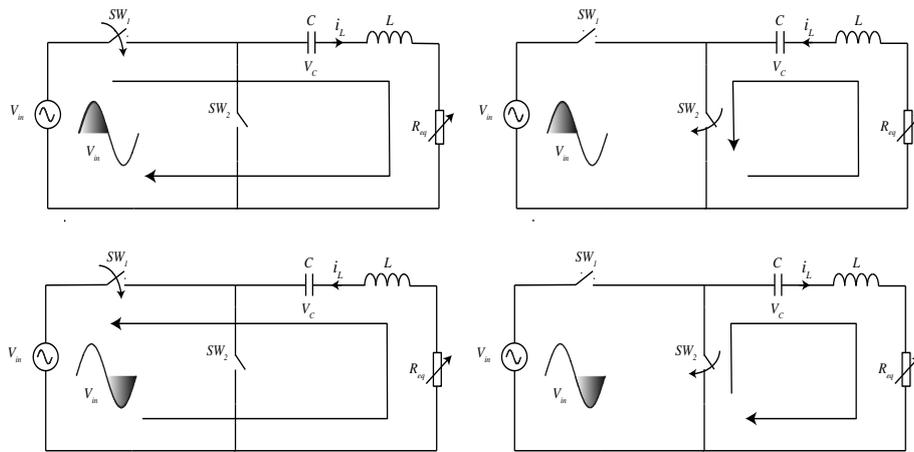


Figure 3. Operation of the main circuit

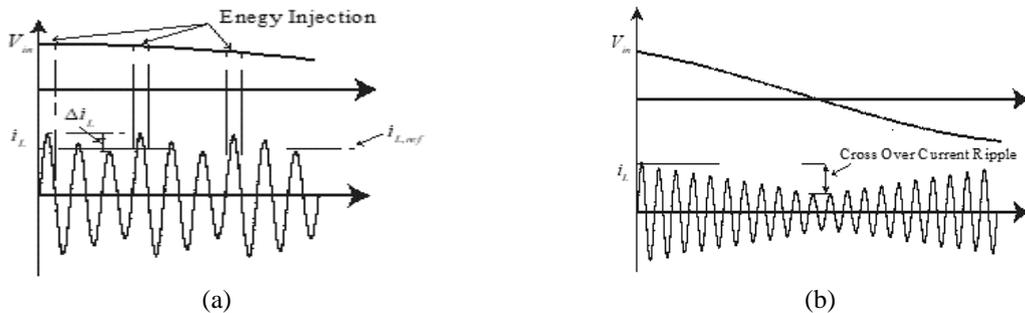


Figure 4. Effect of input voltage on track current: (a) current ripple due to control action and (b) current ripple due to voltage cross over

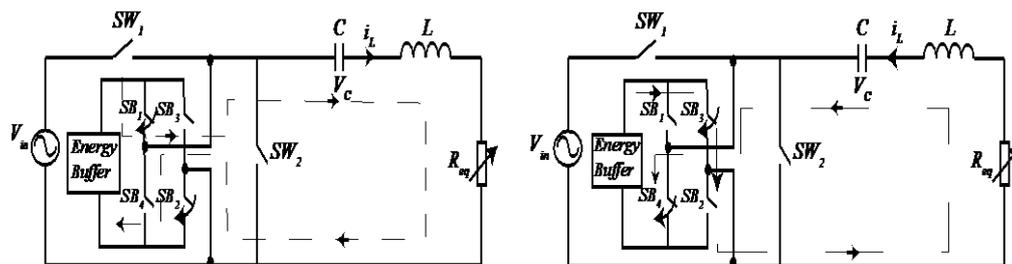


Figure 5. Operation of the buffer circuit

Table 1. Circuit operation and switching sequence table

Circuit Operation	$V_{in}$	$i_L$	Mode	S1	S2	Sb1	Sb2	Sb3	Sb4
Main Circuit	$V_{in} > 0, V_{in} > V_A$	$i_L > 0, i_L < i_{ref}$	Energy Injection	ON	OFF	OFF	OFF	OFF	OFF
Main Circuit	$V_{in} > 0, V_{in} > V_A$	$i_L > 0, i_L > i_{ref}$	Free Oscillation	OFF	ON	OFF	OFF	OFF	OFF
Main Circuit	$V_{in} > 0$	$i_L < 0$	Free Oscillation	OFF	ON	OFF	OFF	OFF	OFF
Main Circuit	$V_{in} < 0,  V_{in}  >  V_A $	$i_L < 0,  i_L  < i_{ref}$	Energy Injection	S1	OFF	OFF	OFF	OFF	OFF
Main Circuit	$V_{in} < 0,  V_{in}  >  V_A $	$i_L < 0,  i_L  > i_{ref}$	Free Oscillation	OFF	ON	OFF	OFF	OFF	OFF
Main Circuit	$V_{in} > 0$	$i_L > 0$	Free Oscillation	OFF	ON	OFF	OFF	OFF	OFF
Buffer Circuit	$V_{in} > 0, V_{in} < V_A$	$i_L > 0, i_L < i_{ref}$	Energy Injection	OFF	OFF	ON	ON	OFF	OFF
Buffer Circuit	$V_{in} < 0,  V_{in}  >  V_A $	$i_L < 0,  i_L  <  i_{ref} $	Energy Injection	OFF	OFF	OFF	OFF	ON	ON

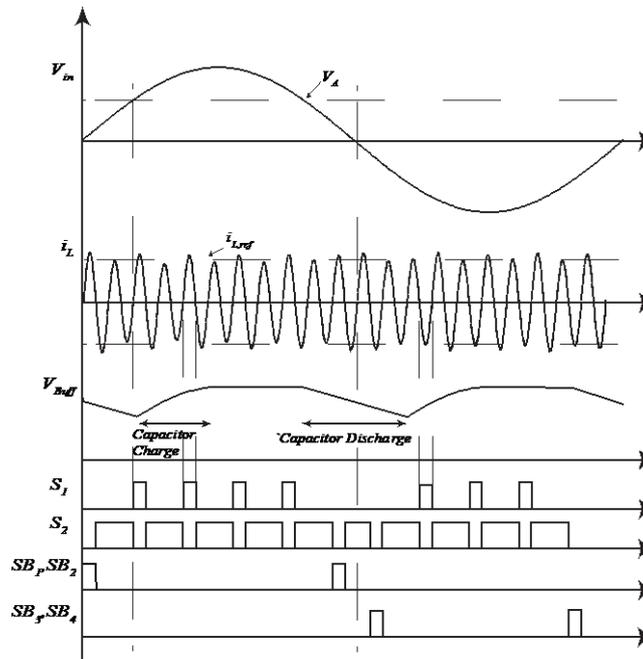


Figure 6. Key waveforms of the converter operation

Table 2. Parameters for wireless power transfer systems

Primary self inductance [ $\mu$ H]	Primary capacitance [nF]	Secondary self inductance [ $\mu$ H]	Secondary capacitance [nF]	Mutual inductance [ $\mu$ H]	Coupling coefficient
206.11	16.9	206.11	17.1	34.717	0.17
Operating frequency [kHz]	Input voltage (RMS) [V]	Output voltage (DC) [V]	Reference track current (RMS) [A]	Load power [W]	Load resistance [ $\Omega$ ]
85	220	280-420	15	800	100

### 3. ANALYTICAL STUDY

This section provides analytical formulation for some of the important design parameters. The main circuit is a series resonant converter. The control strategy is quantum energy injection and circulating free oscillation control. Quantum energy injection increases the track current while circulating free oscillation control reduces the track current. Employing the two modes, the current is regulated with a ripple. This ripple is analyzed in this section. When the input ac voltage reduces below a threshold value the current fails to regulate. The buffer circuit supplies power to the resonant tank during this period. The voltage at which the buffer switches on is called the activation voltage  $V_A$ . The analytical formulation for  $V_A$  is derived. Due to the energy supply to the resonant load, the buffer capacitor voltage reduces. The voltage ripple depends on the output power and the period of operation. An analytical formulation is presented to choose the two design parameters of buffer capacitor value and ripple voltage.

The input voltage  $V_{in}$  is a sine wave of much lower frequency than the track current.

$$V_{in} = \begin{cases} \hat{V}_{ac} \sin \beta \\ 0 \end{cases} \tag{1}$$

Here,  $\hat{V}_{ac}$  is the peak ac input voltage and  $\beta$  is the phase angle. The input voltage can be considered constant for the whole switching period. Circuit operation is expressed with the following equations.

$$\frac{di_L}{dt} = \frac{V_{in}}{L} - \frac{R_{eq}i_L}{L} - \frac{v_C}{L} \quad (2)$$

$$\frac{dv_C}{dt} = \frac{i_L}{C} \quad (3)$$

Here,  $L$  and  $C$  are resonant tank inductance and capacitance values. Parameters  $i_L$  and  $v_C$  are inductor current and capacitor voltage respectively. The general solution of the track current is (4).

$$i_L = \frac{\hat{V}_{ac} \sin \beta + v_C(0)}{\omega L} e^{-\frac{t}{\tau}} \sin \omega t \quad (4)$$

Here,  $v_C(0)$  is the initial value of capacitor voltage,  $\omega$  is natural resonant frequency,  $\tau = 2L/R_{eq}$  is time constant,  $\omega_0 = 1/\sqrt{LC}$  is resonant frequency.  $\omega = \sqrt{\omega_0^2 - \alpha^2}$ ,  $\alpha = R_{eq}/2L$ . As the converter operates in zero current switching mode, the initial inductor current is considered to be zero and the resonant capacitor voltage value will be maximum.

In order to calculate the current ripple during control period, we need to equate the energy injected in the resonant tank. We can simplify the problem to finding the maximum and minimum values of the peak current. The maximum current occurs at no load condition. If the previous current magnitude is equal or just below the reference value, and there is no damping from the load, the current will increase to a maximum value. On the other hand, the minimum value is obtained when there is maximum load present, input voltage is absent and the previous value of the current is equal to the reference value. The equations below quantify these situations. If we look closely to these equations, we see that the maximum current value increases with higher input voltage, reference current and  $L/C$  ratio, which is true for higher power systems. Thus, we need to look at the ratio of ripple current to the reference value. The minimum current is also dependent on the load and the time constant.

$$\frac{1}{2} L \hat{i}_{L,max}^2 = \frac{1}{2} L i_L^2 + \int_0^t v_{sw}(t) i_L(t) dt \quad (5)$$

$$i_{L,max} = \sqrt{I_{ref}^2 + \frac{\hat{V}_{ac}^2 + \hat{V}_{ac} \omega L I_{ref}}{\omega^2 LC}} \quad (6)$$

$$i_{L,min} = I_{ref} e^{-\frac{T}{\tau}} \quad (7)$$

There is a droop in the current magnitude as the voltage crosses zero value. We can term it as cross over current ripple. The underlying cause is the absence of sufficient input voltage to sustain the desired oscillation current. It is possible to quantify the point when the current starts to sag due to lack of voltage. This voltage can be termed as the activation voltage  $V_A$ .  $V_A$  is the point when buffer circuit starts to operate. The equation for  $V_A$  is (4).

$$V_A = \frac{R_{eq} I_{ref} \pi}{4} \quad (8)$$

The buffer capacitor supplies the energy during the period when the input voltage goes below the activation voltage. As the input voltage is an AC quantity, the buffer capacitor acts as the energy source until the magnitude of the input voltage again goes above the activation voltage. During this period, the buffer capacitor voltage reduces as it sources energy to the load. We can choose the buffer capacitor value and the minimum voltage of the buffer capacitor by equating the capacitor energy to the load energy. The total time of operation can be quantified as:

$$\Delta t = \sin^{-1} \frac{V_A}{\hat{V}_{ac}} - \sin^{-1} \frac{-V_A}{\hat{V}_{ac}} = 2 \sin^{-1} \frac{V_A}{\hat{V}_{ac}} \quad (9)$$

The buffer capacitor charges through the diode bridge to maximum ac voltage  $\hat{V}_{ac}$ . Now, the lowest value of buffer capacitor voltage  $V_{buff,min}$  is dependent on the load and the buffer capacitor value. The (10) can be used to choose  $V_{buff,min}$  and  $C_{buff}$ .

$$\left(\frac{1}{2}I_{ref}^2 R_{eq}\right) \left(2\sin^{-1}\frac{V_A}{\hat{v}_{ac}}\right) = \frac{1}{2}C_{buffer}(\hat{V}_{ac}^2 - V_{buff,min}^2) \quad (10)$$

#### 4. SIMULATION AND RESULTS

The wireless power transfer system with the proposed AC-AC converter is simulated in powersim software (PSIM). The magnetic link is simulated using a coupled inductor. An 800 W system is designed. The input of the system is 220 V root mean square (RMS), thus 311V peak. Output is rated as 400 V. The application can be stationary wireless charging or in motion wireless charging where the vehicle is moving over the transmitter. The current regulation is trying to regulate the track current at 15 A RMS, thus 21.2 A peak. Figure 7 shows there is a ripple in the regulated current of 2-3 A peak current, these 1-2 A of RMS current. This results from the inherent control action of the current regulation. The percentage of the ripple is less than 10% and thus is negligible for proper circuit operation. As discussed in the analytical section, the ripple increases with applied voltage, thus is higher during high input voltage and during buffer circuit operation.

Figures 7 and 8 shows track current waveform with and without the energy buffer. There is a prominent current sag during the input voltage zero crossing shown in Figure 7. Figure 8 shows a very well-regulated track current when the buffer is in operation. The buffer capacitor voltage is shown in Figure 9. When the input voltage exceeds the residual voltage in the buffer capacitor, the capacitor voltage increases. Capacitor voltage reaches the peak input voltage, which equals the input AC line voltage. The voltage is kept constant until the magnitude of input voltage goes below the activation voltage  $|V_A|$ . From that point to the point when the input voltage goes below the activation voltage, the buffer capacitor acts as the energy source. Thus, the capacitor voltage reduces to its minimum residual value. Then again when the input voltage goes above this residual voltage value, the buffer capacitor recharges.

Proper current regulation is necessary in both stationary and in-motion wireless charging. For stationary charging, we need a constant power output. For in-motion charging, we need to keep a constant flux in the magnetic link even when the load goes through substantial change. Figure 10 shows a well-regulated track current in the system during a step change in the load.

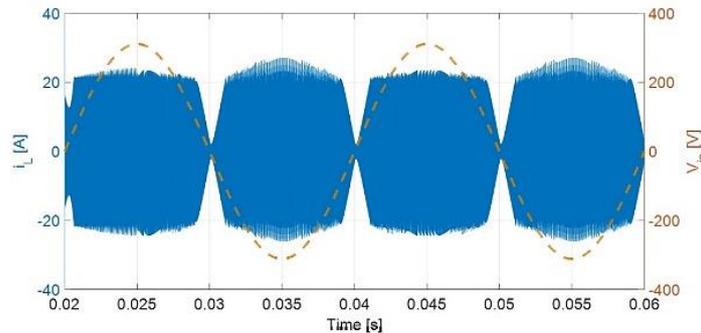


Figure 7. Track current  $i_L$  and Input voltage  $V_{in}$  when there is no buffer

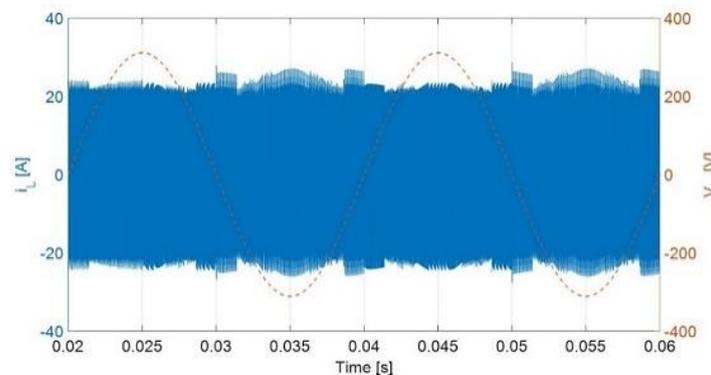


Figure 8. Track current  $i_L$  and Input voltage  $V_{in}$  when buffer is present

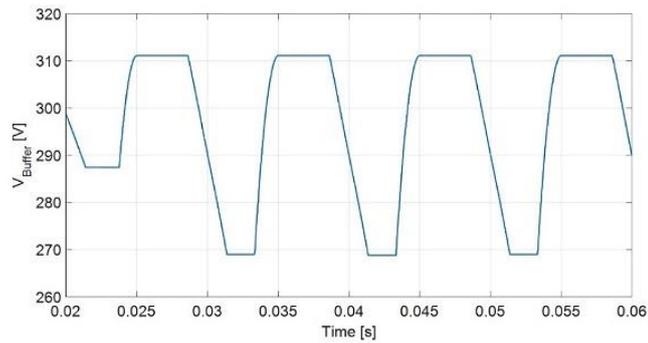


Figure 9. Buffer capacitor voltage  $V_{Buffer}$  during circuit operation

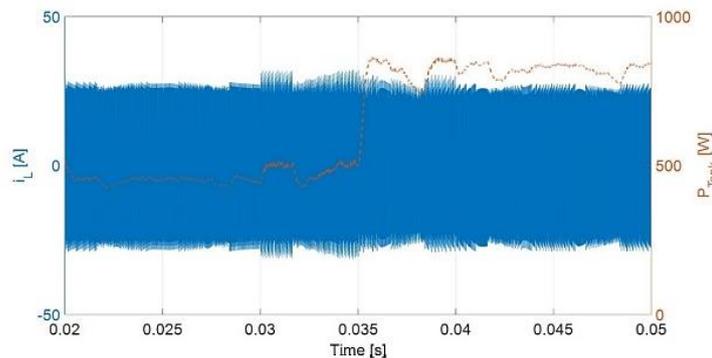


Figure 10. Track current and delivered power at a step load change condition

## 5. CONCLUSION

This paper introduces a minimum cost realization of a bidirectional AC-AC converter for wireless power transfer applications. A novel energy buffer structure is introduced which eliminates power sag and current sag problem during input voltage zero crossing. This novel approach enables single phase AC-AC matrix converter employment in wide range of battery charging applications. The control strategy maintains constant flux for both in motion and static charging conditions. These properties make this converter a suitable candidate for both static and dynamic wireless charging. An analytical design method is presented and an example design is carried out. Thorough simulation results verify the designed circuit operation.

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