

A Novel ZSB-PAM Power Regulation Method Applied in Wireless Charging System for Vehicular Power Batteries

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ABSTRACT

Wireless charging system for vehicular power batteries is becoming more and more popular. As one of important issues, charging power regulation is indispensable for online control, especially when the distance or angle between chassis and ground changes. This paper proposes a novel power regulation method named Z-Source-Based Pulse-Amplitude-Modulation (ZSB-PAM), which has not been mentioned in the literatures yet. The ZSB-PAM employs a unique impedance network (two pairs of inductors and capacitors connected in X shape) to couple the cascaded H Bridge to the power source. By controlling the shoot-through state of H bridge, the input voltage to H bridge can be boosted, thus the transmitter current can be adjusted, and hence, charging current and power for batteries. A LCL-LCL resonant topology is adopted as the main transfer energy carrier, for it can work with a unity power factor and have the current source characteristic which is suitable for battery charging. And finite element models (FEMs) of transmitter and receiver coils in the LCL-LCL topology are built in COMSOL. From those, corresponding parameters, like self-inductance, mutual inductance and parasitic resistances caused by skin and proximity effect, can be extracted. Additionally, apart from power regulation, employing ZSB-PAM can realize the optimal efficiency in either LCL-LCL topology or the whole charging system. At last, the conclusions are verified by simulations and experiments.

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INTRODUCTION

Wireless power transfer is not strange to human beings, since as early as 1889, Nikola Tesla had already realized that, however, it did not attract the attentions at that time. Until 2007, this magical technique finally shocked the world. The researchers of MIT proposed strongly coupled magnetic resonances (SCMR), by which they were able to transfer 60 watts wirelessly with ~40% efficiency over distances in excess of 2 meters [1]. However, its high operating frequencies (up to MHz) limit its applications to low power level, for there are hardly any power semiconductors can work in this range. Compared with SCMR, inductive power transfer (IPT) operates in lower frequencies (10 KHz~500 KHz), which has developed for more than ten years [2]. IPT mainly focuses on high power applications, which include power conversion [3], magnetic structure design [4], control algorithm and strategy [5], circuit topology [6] and foreign object detection [7]. As a typical application case, wireless charging system for vehicular power batteries is gaining the momentum in recent years, for it can remove the troublesome plug-in process, provide an inherent electrical isolation and adapt to harsh environments [7,8]. A typical representative is Online Electric Vehicle (OLEV) proposed by

Korea Advanced Institute of Science and Technology (KAIST) [9]. Many corporations, like Witricity, Bosch, Qualcomm and Evatran [10] have launched corresponding products, some of which have already been equipped in the vehicles of Citroen, Audi and so on. This paper mainly studies the wireless charging power regulation problem which is indispensable for online control, especially when the distance or angle between chassis and ground changes or required charging power for batteries increases endlessly. Traditional power regulation methods for wireless charging system normally include cascade DC/DC, dead time modulation and phase shifting control [11, 12]. However, cascade DC/DC may increase device numbers and decrease power density and efficiency; Dead time modulation may distort the output waves of H Bridge [11]; The maximal output voltage of H Bridge using phase shifting control is limited below and cannot exceed dc-rail voltage, and THD (total harmonic distortion) of output waves shows overall larger trend as the phase shifting angle increases.

Additionally, the imaginary power existed in the system will increase at large phase shifting angle if soft switch conditions are considered to be satisfied, and further cause circulating energy loss. This paper proposes a novel power regulation method named Z-Source-Based Pulse-Amplitude-Modulation (ZSB-PAM), which has not been mentioned in the literatures yet. It can defuse the charging power decreasing phenomenon caused by the mutual inductance and load variations, and further improve system efficiency. This paper is arranged as follows: First, the principles and control methods of ZSB-PAM are elaborated. Then the characteristics of LCL-LCL topology are given and finite element models (FEMs) of magnetic coils are built. At last, the efficiency is analyzed, and further improved by ZSB-PAM.

PRINCIPLES AND CONTROL METHODS OF ZSB-PAM

Harmonic Analysis

As we know, the LCL-LCL topology cascaded with H Bridge is a kind of high order resonant filters. Its amplitude-frequency characteristic is very steep, which indicates that only power signals at resonant frequency can be transmitted. The others may circulate in the resonant circuit or return back to the power source, and hence cause additional energy loss. These require that the square waves produced by H Bridge should be very close to quasi-sinusoidal resonant waveforms, which can be quantified as THD. FFT series of the square wave depicted in Fig.1 is given as

$$V = \sum_{n=1,2,3,\dots}^{\infty} \frac{2A}{n\pi} \left[\cos \frac{n\pi T_{dead}}{T} - \cos n\pi \left(1 - \frac{T_{dead}}{T}\right) \right] \sin n\omega_r t \quad (1)$$

Where A , n , T_{dead} and T represent the amplitude of the square wave, harmonic order, dead time and cycle time, respectively. And $\omega_r = 2\pi/T$ is system angular frequency.

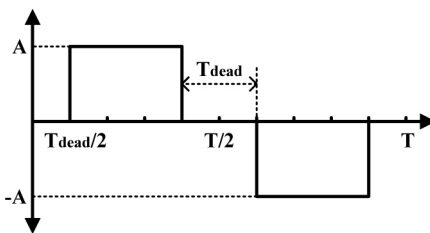


Fig.1. Typical square waves with different dead-times

By calculating respective harmonic amplitudes, THD can be obtained according to Eq. (2) when square waves include different dead-times.

$$THD = \frac{\sqrt{\sum_{n=2,3,4,\dots}^{\infty} V_n^2}}{V_1} \quad (2)$$

Fig.2 shows THDs of square waves (50 KHz) with different dead-times, from which, we can find that the lowest THD happens at 3us dead-time, rather than 0us dead-time, and the amplitude ratio between fundamental sine wave and square wave is about 1.135 in this case. Thus, with the purpose of having the lowest THD, dead-times should be fixed once system frequencies are determined. This result indicates that traditional phase shifting method is not very appropriate for online power regulation, for it will produce high THDs at long or short dead-times. However, this fixed dead-time is beneficial for ZSB-PAM, which just provides adjustable shoot-through time.

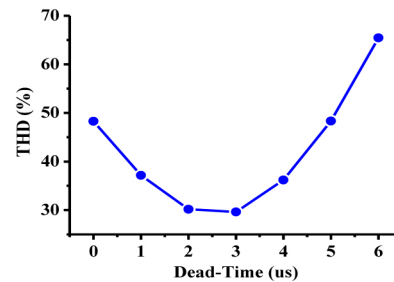


Fig.2. THDs of square waves with different dead-times

Basic Principle of ZSB-PAM

Z-Source was first proposed by Fangzheng Peng in 2003, which is initially used for stabilizing the widely changing voltage produced by fuel cell stacks [13]. Instead, in this paper, Z-Source is applied to produce a changeable output voltage, which can realize power regulation and further efficiency optimization. The overall system schematic is shown as

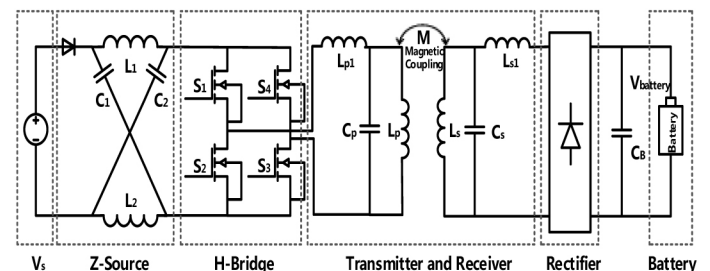


Fig.3. Schematic of wireless charging system based on ZSB-PAM

From which, we can find that the overall wireless charging system consists of power source, Z-Source, H bridge, transmitter, receiver, rectifier and power battery. By controlling the shoot-through state of H bridge, the input voltage to H bridge can be boosted through Z-Source, so the transmitter current can be adjusted, and hence, charging current and power for batteries. Obviously, Z-Source mainly consists of two pairs of inductors and capacitors (L_1 , C_1 and L_2 , C_2 connected in X shape) as well as a diode. Note that there is another Z-Source topology called Quasi-Z-Source, which has superior characteristics [14]. But, for the sake of analysis, the basic Z-Source topology is adopted. To demonstrate specific principles of that, Fig.3 is simplified to its equivalent circuit as shown in Fig.4.

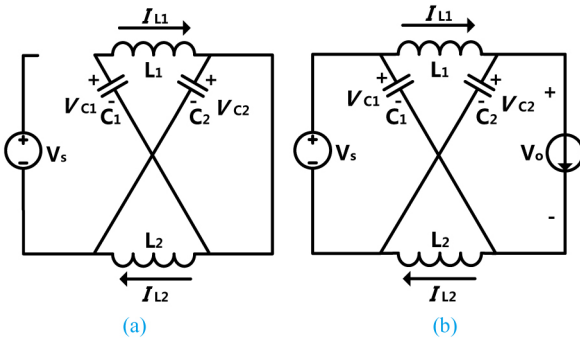


Fig. 4. Equivalent Circuit of Z-Source in Shoot-through State (a) and Non-shoot-through State (b)

Obviously, Z-Source is shorted by H Bridge in shoot-through state, as shown in Fig. 4 (a), whereas H Bridge becomes an equivalent current source as shown in Fig. 4 (b) when in non-shoot-through states. By controlling the ratio between shoot-through time and non-shoot-through time, the output voltage of Z-Source can be boosted. Detailed derivation process of boost factor is given as follows. For volt-seconds of the inductor should be identical in the steady state, we have

$$V_{C1} \cdot T_{\text{shoot-through}} = (V_{C2} - V_s) \cdot T_{\text{non-shoot-through}} \quad (3)$$

Where $T_{\text{shoot-through}}$ is the shoot-through time and $T_{\text{non-shoot-through}}$ is the non-shoot-through time, the sum of those is the cycle time T . From Fig. 4 (a) and Fig. 4 (b), one has

$$V_{C1} = V_{L1}, V_o = V_s + V_{L1} + V_{L2}, V_o = V_{C1} + V_{L1} \quad (4)$$

Z-Source becomes a symmetrical topology if L_1 and L_2 , C_1 and C_2 have the same inductance and capacitance, respectively, thus, we can get

$$V_{C1} = V_{C2} = V_C, V_{L1} = V_{L2} = V_L \quad (5)$$

Then substitute Eq.(4) and Eq.(5) into Eq.(3), which can be rewritten as

$$V_o = \frac{T}{T_{\text{non-shoot-through}} - T_{\text{shoot-through}}} \cdot V_s = BF \cdot V_s \quad (6)$$

Where BF is the boost factor produced by shoot-through state, and it is always greater than or equal to 1. In addition, the relationship among V_s , V_C and V_o is given as

$$V_C = \frac{T_{\text{non-shoot-through}}}{T_{\text{non-shoot-through}} - T_{\text{shoot-through}}} \cdot V_s = \frac{T_{\text{non-shoot-through}}}{T} \cdot V_o \quad (7)$$

Note that the additional shoot-through time does not affect the output waves, as that only exist in the intrinsic dead-time. On the other hand, the intrinsic dead-time limits the shoot-through time, and hence, boost factor.

Control Strategy of ZSB-PAM

Not like traditional Buck or Boost converter, the duty cycle $D_z = T_{\text{shoot-through}}/T$ of Z-Source can't arrive at 100%. By rewriting Eq. (6), we can have the voltage gain curve of Z-Source as shown in Fig. 5.

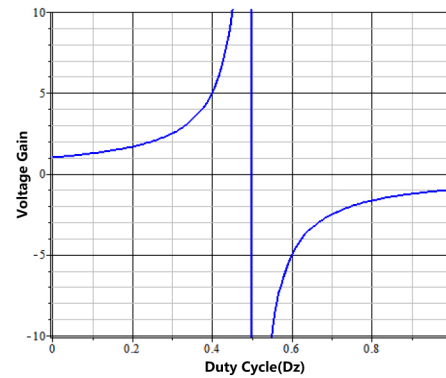


Fig. 5. Voltage Gain of Z-Source

It clearly shows that there are two operating regions. When D_z is greater than 0.5, Z-Source enters negative gain region, and produces a negative output voltage. But when D_z is less than 0.5, it produces a positive output voltage. In this paper, the former is obviously not practical, thus we should limit D_z below 0.5.

All the traditional control strategies [11] can be used to control Z-Source and their theoretical input-output relationships still hold. Taking the most widely used phase shifting control as an example, H Bridge works in the traditional model when the power source voltage is high enough, and Z-Source has no effect on output voltage. However, when the power source can't produce a desired voltage, H Bridge enters into the new operating mode shown in Fig. 6, which supplies the shoot-through state for Z-Source to boost the output voltage.

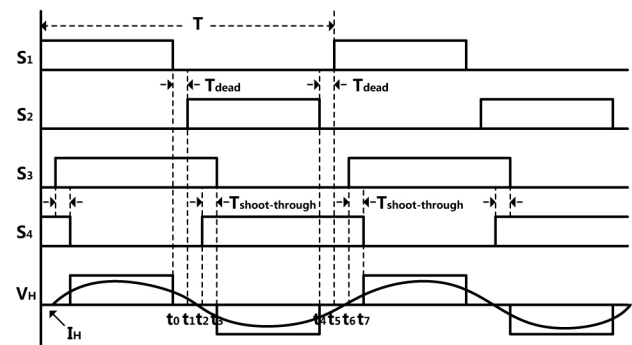


Fig. 6. Z-Source Based Voltage Boost Control