

A Bidirectional Contactless Power Transfer System Based on Quantum Modulation

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Abstract

Contactless power transfer is an emerging technology. It is widely used in industrial and consumer electronic products. In this paper, a bidirectional contactless power transfer system for wireless vehicle charger is presented based on quantum modulation method. By applying this novel amplitude modulation method, switching losses and electromagnetic noise are greatly reduced and the whole system efficiency increased as well. Firstly, the operational principle of the contactless power transfer system is reviewed. The frequency analysis of the contactless power transfer system based on series resonant converter is deduced in detail. Besides, the voltage gain and phase feature of resonant tank are shown. Then, the quantum method for bidirectional power flow is explained in detail. The controller framework based on a simple analogous circuit is analysed as well. In additional, a simulation of the bidirectional contactless power transfer system based on quantum modulation by computer is presented to demonstrate the effectiveness of this method. Then, the conclusion of contactless power transfer system of bidirectional power flow is given at the end.

Keywords: *contactless power transfer, vehicle charger, quantum modulation, voltage gain*

1. Introduction

Compared with traditional power transfer method with plugs and sockets, electronic products with contactless power transfer (CPT) technology have considerable advantages. This technology enables electronic products to work freely and safely in hostile environments such as under water, under mine and in dusty situations. Therefore, the CPT technology is employed in numerous applications ranging from low power to high power electronic products which can be found in biomedical implants, vehicle chargers, universal platform chargers for consumer electronics and so on [1-6]. In particular, the CPT systems are preferable for vehicle chargers because of its convenient and safe operation in rainy day. Works focused on the CPT systems for vehicle battery chargers are presented in [7] to [14]. In [7], design considerations for the wireless electric vehicle battery charger are presented, in which a variable frequency controller is used. In addition, the optimal design methods for a maximum efficiency of a CPT system to the vehicle battery charger are shown in [8] to [10]. Furthermore, multi-phase pickup for a large lateral tolerance contactless power transfer system is discussed in [11]. However, the electric vehicles and vehicle to grid systems need a bidirectional power flow system to feed back the battery power to grid for saving energy of electric vehicles. Thus, CPT systems with the function of bidirectional power flow are attractive for these applications [12-18]. U. K. proposed a bidirectional inductive power

interface for vehicles in V2G systems [12-14]. Moreover, a dynamic multivariable state-space model for bidirectional inductive power transfer systems is presented [15]; D. J. focused on the synchronization technique for bidirectional IPT systems [16]. On the other hand, other works pay attention to controller design of bidirectional CPT systems. A varying frequency controller for bidirectional inductive power transfer systems is explained in [17]. The optimal PID controller for bidirectional inductive power transfer system using multi-objective genetic algorithm is shown in [18].

With high efficiency for the whole load range of resonant converters, the quantum modulation is proposed in [19]. The novel modulation method introduced a discrete energy control to CPT systems. With quantum modulation, the switches turn on and off at the zero-crossing point of resonant tank current, which ensuring soft switching at all of the load range. Thus, the efficiency increases greatly than varying frequency controller or phase-shift controller [19-25]. A quantum control for multiple users CPT system is proposed in [19]. The current fluctuation analysis of a quantum CPT system is presented in [21], which is helpful for the design of CPT system based on quantum modulation. Furthermore, the sliding mode control for quantum CPT system is discussed in [21] to [26].

Unfortunately, above arts about bidirectional CPT system are mainly based on varying frequency and shift-phase modulation with low efficiency when the load is away from rated value. On the other hand, to ensure two-way power flow, a complex synchronous technology of the pulse should be exert to two inverters based on primary side and secondary side. In this paper, a bi-directional CPT system with the LC-T-LC resonant converter based on quantum modulation is analyzed. Based on this modulation, the efficiency of CPT system for the whole load range can be improved greatly compared with traditional modulation methods.

The paper is organized as follows: in section 2 the operating principle and the modelling of the proposed CPT system is discussed first; after which the quantum modulation is explained in detail in section 3. In section 4 a simulation study is carried out to verify the analysis. Final conclusions are shown in section 5.

2. Operation Principle of Contactless Power Converter

A bidirectional CPT system of a vehicle battery charger is presented in this paper and the block diagram is shown in Figure 1. It consists of two identical full-bridge inverters and a LC-T-LC resonant converter. Bidirectional power flow can easily be controlled from primary side to secondary side by adjusting the logical principle of switches of the two inverters.

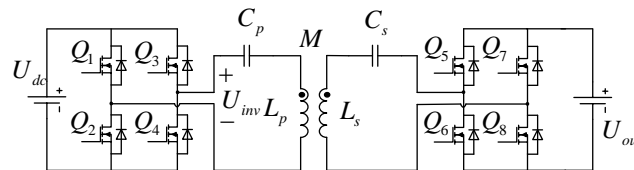


Figure 1. Topology of Bidirectional Contactless Power Transfer System

Figure 2 shows the T-type transformer model of the LC-T-LC resonant converter. The capacitor C_p and C_s are placed on the primary side and the secondary side, respectively, to compensate the large leak inductance.

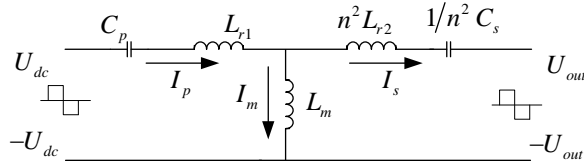


Figure 2. T-style Model of Contactless Power Transfer System

Observed from Figure 2, the impedance of the transformer is represented as (1) and (2):

$$Z_1 = \frac{1}{sC_p} + sL_{r1} + sL_m / (sL_{r2} + \frac{1}{sC_s} + R_L) \quad (1)$$

$$Z_1 = \frac{1}{sC_p} + sL_{r1} + \frac{s^3 L_{r2} L_m C_s + s^2 L_m C_s R_L + sL_m}{s^2 L_{r2} C_s + s^2 L_m C_s + sR_L C_s + 1} \quad (2)$$

And, the primary side coil current is expressed as

$$I_p = \frac{U_{inv}}{Z_1} \quad (3)$$

The circuit equations are listed from (4) to (6) by using Kirchhoff's current/voltage laws.

$$I_p \left(\frac{1}{sC_p} + sL_{r1} \right) + sI_m L_m = U_{in} \quad (4)$$

$$I_p \left(\frac{1}{sC_p} + sL_{r1} \right) + I_s \left(\frac{1}{sC_s} + sL_{r2} + R_{ac} \right) = U_{inv} \quad (5)$$

$$I_m + I_s = I_p \quad (6)$$

Define the voltage gain as

$$\text{Gain} = \frac{U_{out}}{U_{inv}} \quad (7)$$

Then,

$$\text{Gain} = \frac{sL_m R_{ac}}{\left(\frac{1}{sC_p} + sL_{r1} + \frac{s^3 L_{r2} L_m C_s + s^2 L_m C_s R_{ac} + sL_m}{s^2 L_{r2} C_s + s^2 L_m C_s + sR_L C_s + 1} \right) \left(\frac{1}{sC_s} + sL_{r2} + sL_m + R_{ac} \right)} \quad (8)$$

In which R_{ac} is the ac equivalent resistance,

$$R_{ac} = \frac{8}{\pi^2} R_L$$

Let $s=j\omega$, then the output voltage gain to ω is expressed,

$$\text{Gain} = f(\omega) \quad (9)$$

To analysis the gain feature of CPT system, differential equation of Gain to ω is shown

$$\frac{df(\omega)}{d\omega} = 0 \quad (10)$$

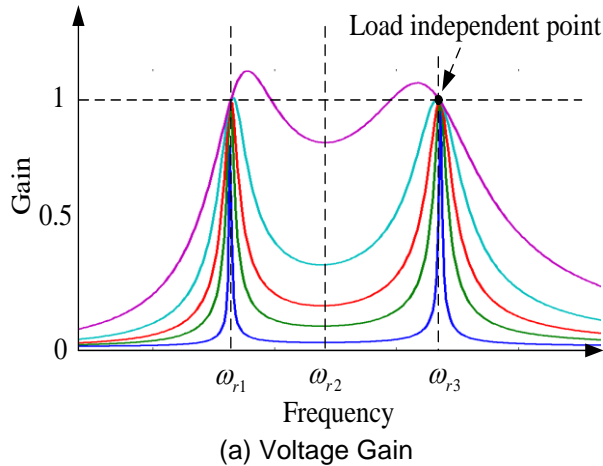
Substituting (8), (9) into (10), the solver of equation (10) can be achieved, and the critical frequency is gotten,

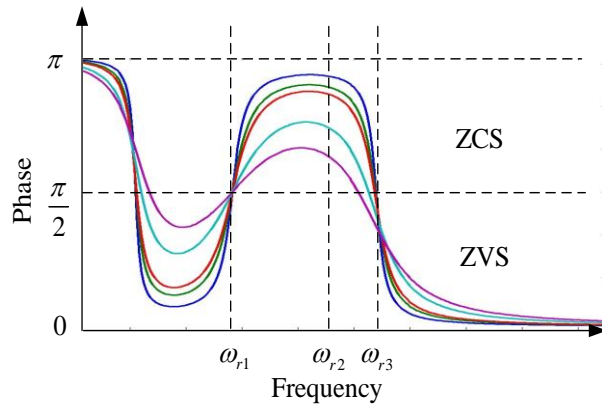
$$\omega_{r1} = \frac{1}{\sqrt{(L_{r1} + 2L_m)C_p}} \quad (11)$$

$$\omega_{r2} = \frac{1}{\sqrt{(L_{r1} + L_m)C_p}} \quad (12)$$

$$\omega_{r3} = \frac{1}{\sqrt{L_{r1}C_p}} \quad (13)$$

Figure 3 shows the analytical results in frequency domain. The Figure 3 (a) is the voltage gain about frequency, while (b) is the phase plot. To observe figure (a), there is a load independent point at frequency point ω_{r3} . When the CPT system works at this frequency, the output voltage gain would not change at diverse loads. Look at the figure (b) which is the phase plot of the primary coil current in CPT system, when the phase is above 90° , the zero current switching is achieved; otherwise the zero voltage switching is achieved. When, the system operate at the resonant frequency, the ZCS and ZVS are achieved simultaneously, which maintain a high efficiency of CPT systems. To ensure the stability of CPT systems, a slight inductive load is preferred for the full-bridge, so here a little higher than the resonant frequency ω_{r3} is suggested.





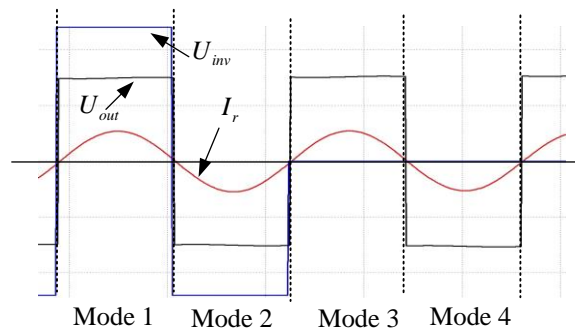
(b) Phase Plot

Figure 3. Frequency Features of LC-T-LC Resonant Converter

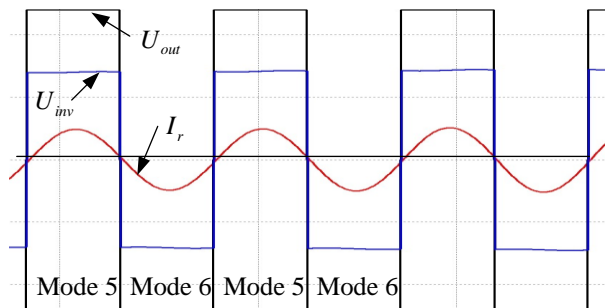
3. Quantum Modulation

3.1. Operational Principle

Quantum modulation is employed in this paper to control the bidirectional power flow of the CPT systems. The key scheme of quantum modulation is that the switching events happen at the resonant frequency which ensuring ZVS and ZCS in the whole operating range. Figure 4 shows typical waveforms of quantum modulation in CPT systems.



(a) Powering Pattern



(b) Generation Pattern

Figure 4. Mode Analysis of Quantum Modulation

Figure 4 (a) shows the powering pattern of quantum modulation in which the power is transferred from primary side to secondary. The powering pattern consists of four modes, positive powering mode, negative powering, positive freely oscillation mode, negative freely oscillation mode. In mode 1 and mode 2, the power is transferred from voltage source to battery, while in mode 3 and mode 4, the power oscillates freely from resonant tank to load battery. In mode 3 and 4, the input voltage source is isolated from resonant tank, and the resonant tank feed energy to load battery.

Figure 4 (b) presents the generation pattern of quantum modulation which includes two modes, positive powering mode and negative powering mode. In this pattern, the output voltage is larger than input voltage, so the power is transferred from source to load.

Note to Figure 4, the input voltage and output voltage of resonant converter is square wave because their voltages are clamped by input voltage source and output battery respectively. On the other hand, the resonant current of primary side is a normal sinusoidal form. This is because the switching frequency is exactly like the native resonant frequency which ensures high efficiency with soft switching.

3.2. Switching Logics

The switching logics are listed in Table 1 and Table 2 of the quantum modulation about the six modes. Table 1 is the switch status of primary inverter while Table 2 expresses the secondary switching status.

Table 1. Switching Principle of Primary Side Inverter

Mode	Q_1	Q_2	Q_3	Q_4	D_1	D_2	D_3	D_4
1	Off	On	On	Off	Off	Off	Off	Off
2	On	Off	Off	On	Off	Off	Off	Off
3	On	Off	Off	Off	Off	Off	On	Off
4	Off	Off	On	Off	On	Off	Off	Off
5	Off	Off	Off	Off	Off	On	On	Off
6	Off	Off	Off	Off	On	Off	Off	On

Table 2. Switching Principle of Secondary Side Inverter

Mode	Q_5	Q_6	Q_7	Q_8	D_5	D_6	D_7	D_8
1	Off	Off	Off	Off	On	Off	Off	On
2	Off	Off	Off	Off	Off	On	On	Off
3	Off	Off	Off	Off	Off	On	On	Off
4	Off	Off	Off	Off	On	Off	Off	On
5	On	Off	Off	On	Off	Off	Off	Off
6	Off	On	On	Off	Off	Off	Off	Off

Figure 5 shows the detail of power flow under quantum modulation in resonant converter and the mode analysis is given as following.

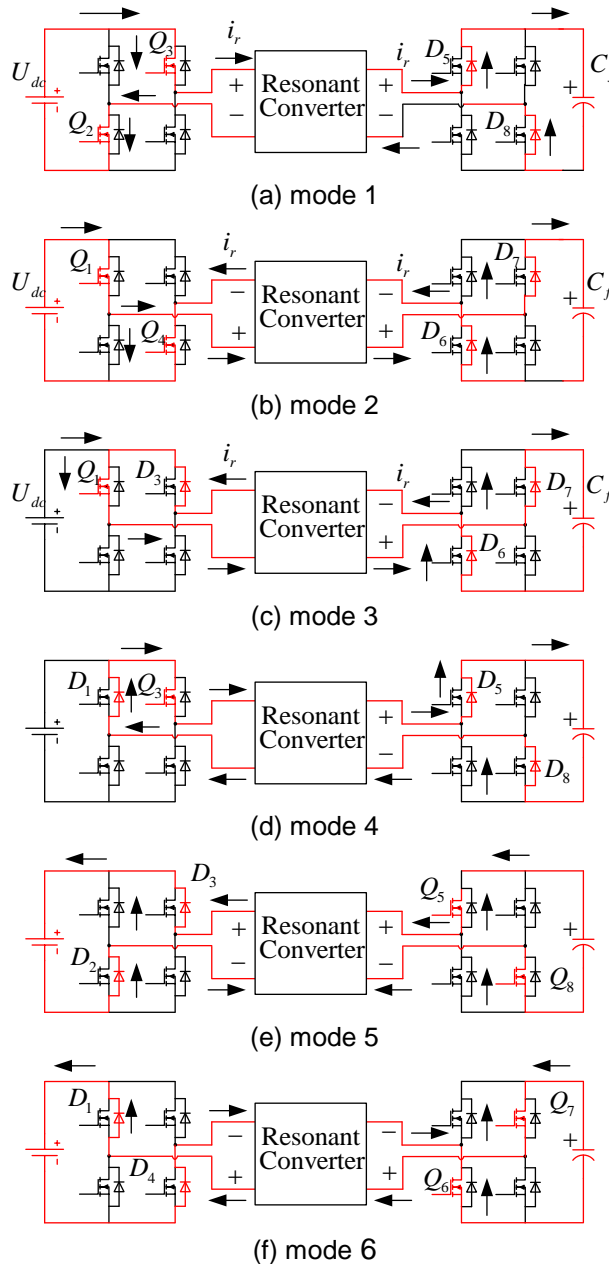


Figure 5. Mode Analysis of Quantum Modulation

3.2.1. Powering Mode (mode 1 and mode 2)

In powering mode, the switches Q_1 , Q_4 and Q_2 , Q_3 turn on and turn off complementarily to delivery energy from source to load. In mode 1, the switch Q_3 and Q_2 turn on, the source voltage is feed on resonant converter. Because the source voltage is larger than load voltage, the freewheeling diodes D_5 and D_6 conduct in nature. In mode 2, the resonant current reverses. Then, the switches Q_3 and Q_2 turn on. Similarly, the freewheeling diodes on secondary inverter conduct in nature.

3.2.2. Freely Oscillation Mode (mode 3 and mode 4)

In power oscillation mode, the source voltage isolates from resonant converter. In mode 3, the switch Q_1 turns on, and other switches in primary inverter turn off. The power flows from resonant tank to load, and the switch Q_1 and freewheeling diodes D_3 provide energy path for resonant tank. In mode 4, the resonant current reverses. Then, the switch Q_3 turns on. And the freewheeling diode D_1 naturally conducts.

3.2.3. Generation Mode (mode 5 and mode 6)

In generation stage, all switches in primary inverter turn off. Q_5, Q_8 and Q_6, Q_7 turn on alternatively to deal power from load to source. In Figure 6 (e), power flows from load to resonant tank when Q_5 and Q_8 turn on and off alternatively. At the same time, D_2 and D_3 turn on natively. Thus, power feedbacks to source voltage. When the resonant current reverses in (f), the switch Q_6 and Q_7 provide path from output voltage to source voltage. Similarly, the freewheeling diodes D_1 and D_4 turn naturally at zero across point.

3.3. Controller Framework

The controller framework applied quantum modulation of bidirectional CPT systems is shown in Figure 6. At first, the output voltage is compared to reference voltage. Then, the error is compensated by a PI controller. The output value of PI controller is compared with zero through comparator U_1 to produce the mode signal $u(t)$. Afterwards, the mode signal $u(t)$ is synchronized by a D trigger U_2 . At last, the quantum controller signal $u(kT)$ is added to logic gates U_3 to U_6 to produce gate pulse signal. Through the driver, the gate pulse signals are amplifier to drive switches from Q_1 to Q_8 of primary side inverters and secondary inverters.

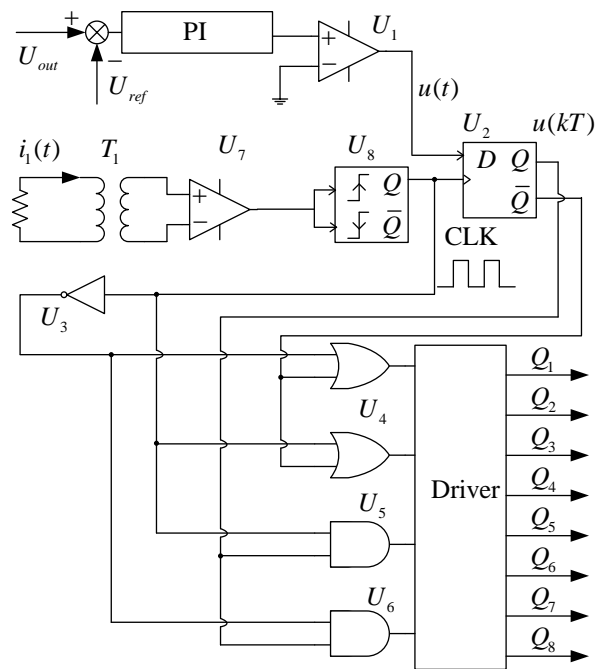


Figure 6. Controller Framework

4. Simulation Analysis

To demonstrate the theoretical analysis, a simulation of the bidirectional CPT system in Figure 1 is constructed and tested. The nominal values of the power components and control parameters are listed in Table 3.

Table 3. Circuit Parameters of the Bidirectional CPT System

Symbol	Value and part number
Q_1-Q_8	MOSFETs
D_1-D_8	Diodes
U_{dc}	24V
C_{r1}	4.7nF
C_{r2}	4.7nF
L_1	175uF
L_m	55uF
C_f	10uF
R_L	5 Ω
U_{ref}	15V
f_r	212kHz

The waveforms of proposed bidirectional CPT system for the vehicle charger are shown from Figure 7 to Figure 8. Figure 7 shows the transient responses of the inverter voltage and the resonant current based on quantum modulation. Observed from Figure 7, the inverter voltage become zero when in the freely oscillation mode while in powering mode it is a pulse waveform.

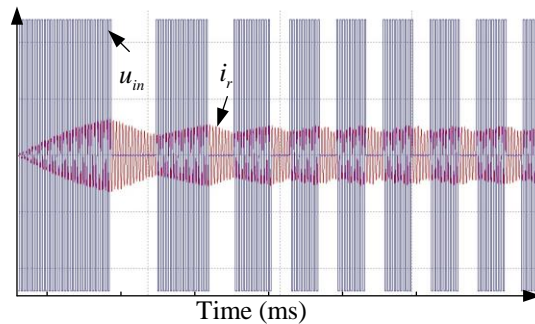


Figure 7. Waveforms of CPT System based on Quantum Modulation

Figure 8 shows switching event of CPT system. From the simulation results, it can be known that the resonant current performance a perfect sine waveform. Simultaneously, all the switches in this circuit operate in zero current switching and zero voltage condition. It is obvious that the inverter based on quantum modulation display high efficiency. Furthermore, Figure 9 shows the step response with the reference voltage 15V. According the plot, the novel controller based on quantum modulation can obtain a stable output voltage in a short settle time.

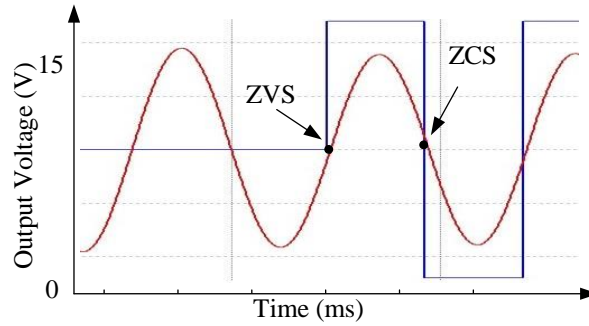


Figure 8. Soft Switching

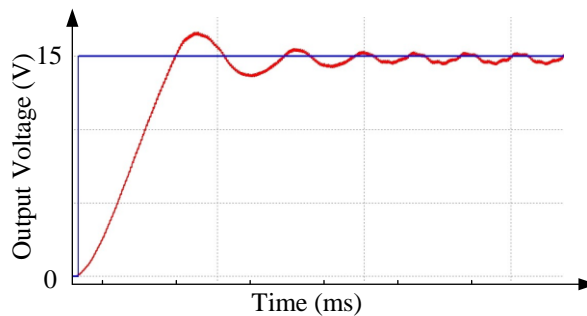


Figure 9. Step up Response

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5. Conclusions

In this paper, the problem of designing a bidirectional CPT system based on LC-T-LC resonant tank has been addressed. The quantum modulation is introduced in this system. First, the mathematical model of LC-T-LC resonant converter in frequency domain is established. The output voltage gain and phase characteristic are deduced as well. The optimal frequency and soft switching region are suggested by the model. Then, a promising control method named quantum modulation is proposed. This method ensures high efficiency of CPT system because it operates with soft switching in the whole load range. Furthermore, the design method of the controller based on a simple analogue circuit is shown in close form. Finally, the simulation results validate the theory proposed in this paper.

Acknowledgements

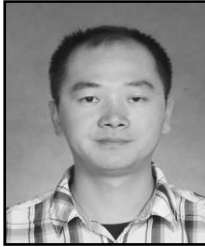
This work is supported by Project 51277120 by National Science Foundation of China and ITER Special Project (2011GB113005). This work is also supported by State Energy Smart Grid R&D Centre (China, Shanghai).

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