

A Self-tuning Variable Frequency Control for Multi-level Contactless Electric Vehicle Charger

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Abstract—This paper proposes a self-tuning controller for a multi-level inductive Electric Vehicle (EV) battery charger application. By controlling the energy injection frequency of the Inductive Power Transfer (IPT) system, multiple charging levels (4 in number) are achieved. Maximum performance is leveraged by the proposed IPT system using its capability of self-tuning the switching operations to the natural resonant frequency of the IPT system, thereby benefiting from soft-switching operations (zero-current switching). Either a digital or analog control circuit can be used to implement the proposed controller. The results are shown by simulating the proposed controller with different charging levels using MATLAB/Simulink. These results show that the proposed controller effectively enables IPT-based contactless EV charging at multiple charging levels, with soft-switching operations. This self-tuning capability is specifically useful in IPT systems that have variable resonance frequency.

Index Terms—inductive power transfer, self-tuning control, soft-switching, variable frequency control.

I. INTRODUCTION

More convenience and safety to the use of EVs is brought about the new technology of contactless Electric Vehicle (EV) charging based on Inductive Power Transfer (IPT). It can be used to transfer electric power without any electrical contact between the transmitter and receiver. Greater safety, reliability and robustness by virtue of its immunity from dust or weather conditions can be reaped, besides the added advantage of eliminating sparks and the risk of electrical shocks. In essence, it is a safe, robust and clean way of charging EVs, and has rapidly gathered a surge of interest in both commercial and industrial applications [1]–[4]. Static charging and dynamic (in-motion) charging constitute the two major categories of contactless EV charging. While the goal of static charging is to charge the EV using a contactless charger when the EV is parked in a charging station, a dynamic EV charging system is aimed at charging the EVs while they are in motion. The former solution is targeted at safe, efficient and convenient overnight recharging of EVs. A typical contactless EV charging system based on IPT is shown in Fig. 1.

The literature boasts of a wide range of converter topologies and control strategies for IPT systems and resonant converters [5]–[12]. These methods encompass power-frequency control [13], [14], phase-shift and frequency control [15], [16], load detection [17], power flow control [18], and Sliding Mode Control (SMC) [19]–[22]. The control methods may have a

self-tuning capability [23], [24]. Small variations due to fluctuations in the load on the receiver end can be expected of the resonance frequency for dynamic IPT applications. Energy-injection free-oscillation method is one of the very effective methods that are predominantly applied as a control technique, and has been deployed in many studies. This study also utilizes the same technique to design the proposed controller [5], [6], [10].

A control method based on energy-injection free-oscillation technique for multi-level EV battery charger applications based on IPT systems is proposed, which is capable of working with three-phase full-bridge AC/DC/HFAC converter. Four user-defined levels each with a charging power rate, namely, Levels 1, 2, 3 and 4, can be used through the controller for the contactless charging of the EVs. The proposed controller benefits from Zero-Current Switching (ZCS), besides facilitating the self-tuning of the switching operations to the resonance frequency of the IPT system, thereby guaranteeing its maximum performance. MATLAB/Simulink is utilized to simulate the proposed controller at various charging levels, the results of which are then presented. The controller may be implemented either based on a digital or an analog control circuit.

II. PROPOSED CONTROL METHOD

The resonant current, voltage or power in an IPT system can be definitively controlled using many methods, one of which is the energy-injection and free-oscillation technique.

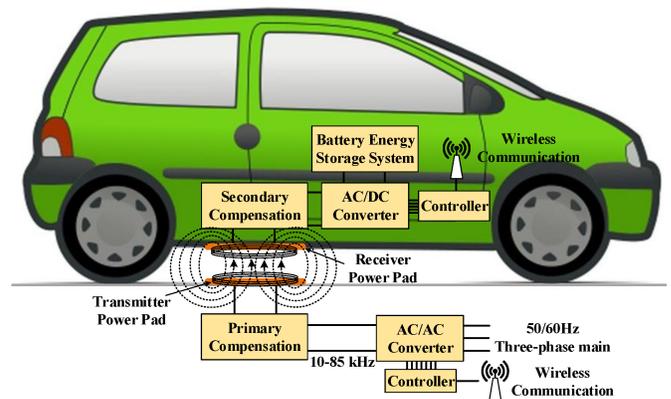


Fig. 1. A typical contactless electric vehicle charging system based on inductive power transfer.

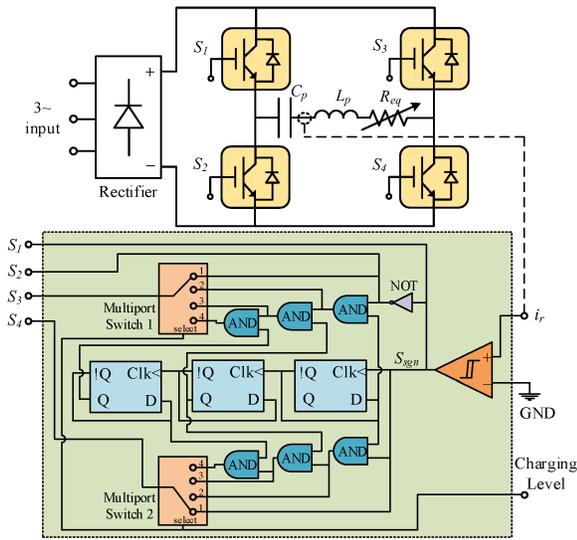


Fig. 2. The proposed controller with an analog control circuit.

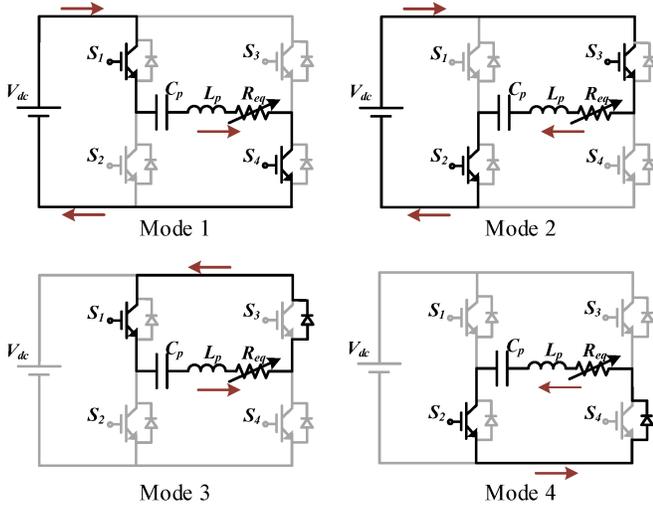


Fig. 3. Different modes of operation in the proposed converter.

By constantly switching the operation mode of the converter between two free-oscillation and energy-injection modes, the rate of energy injected into the primary LC tank can be regulated, thereby controlling the resonant current [5], [6], [10]. The four modes tabulated in Table I describe the operation of the controller.

Designed based on an analog circuit and composed of D-type flip-flops, logic gates, a voltage comparator and multiport switches, a full-bridge AC/DC/HFAC converter with the proposed controller is illustrated by Fig. 2. A reduction in the frequency of the energy injection half cycles and an increase in the number of free-oscillation cycles is documented as a consequence of using the flip-flops in conjunction with logic gates to alter the energy injection rate to the LC tank based on user-defined levels of 1, 2 and 3 charging power rates. Thus, using this method, regulation of the transferred

power to the LC tank can be made. As depicted by Fig. 4 which shows the typical waveforms of the resonant current and output voltage of the inverter facilitated by the proposed controller, each mode begins and ends at zero-crossing points. This triggers a soft-switching operation of the inverter, as a result of which higher efficiency is observed in the converter in comparison with the conventional converters. Furthermore, the conventional digital controllers (DSP/FPGA) fail to meet the higher operating frequencies that the proposed controller supports due to its analog design that leads to a simplified implementation.

III. THEORETICAL ANALYSIS

A theoretical analysis of the IPT system is necessitated to compute the theoretical values of different parameters like power output, resonant current ripple, and many more, at a number of charging levels that the proposed controller can achieve. The differential equation of an LC tank with primary self-inductance of L , primary capacitor C , and a reflected resistance of R_{eq} can be expressed as:

$$\frac{d^2 i}{dt^2} + \frac{R_{eq}}{L} \frac{di}{dt} + \frac{1}{LC} i = 0 \quad (1)$$

where i is the primary resonant current, v_c is the primary capacitor resonant voltage, and V_t is the inverter output voltage. Since using the proposed method the switching operations only occur at zero-current crossing points, the initial conditions for (1) can be expressed as follows:

$$i(0) = 0, \quad L \frac{di}{dt}(0) = V_t - v_c(0) \quad (2)$$

Using the initial conditions given in (2), equation (1) can be solved for a half-cycle analytically. The resonant current and primary resonant voltage can be obtained as follows:

$$i(t) = \frac{V_t - v_c(0)}{\omega L} e^{-t/\tau} \sin(\omega t) \quad (3)$$

$$v_c(t) = v_c(0) + \frac{[V_t - v_c(0)]\tau}{\omega LC(1 + \tau^2 \omega^2)} \left(\tau \omega - e^{-t/\tau} [\sin(\omega t) + \tau \omega \cos(\omega t)] \right) \quad (4)$$

where $\omega = \sqrt{\omega_0^2 - \alpha^2}$ is the natural resonance frequency, $\alpha = R_{eq}/2L$ is the damping coefficient, $\omega_0 = 1/\sqrt{LC}$ is the resonance frequency, and $\tau = 2L/R$ is the damping time constant. Equations (3) and (4) can be used to calculate output

TABLE I
SWITCHING STATES IN DIFFERENT MODES OF OPERATION IN CURRENT REGULATION CONTROL MODE.

Mode	Type	Current direction ($i > 0$)	Energy injection enabled	S_1	S_2	S_3	S_4
mode 1	Energy injection	1	1	1	0	0	1
mode 2	Energy injection	0	1	0	1	1	0
mode 3	Free oscillation	1	0	1	0	0	0
mode 4	Free oscillation	0	0	0	1	0	0

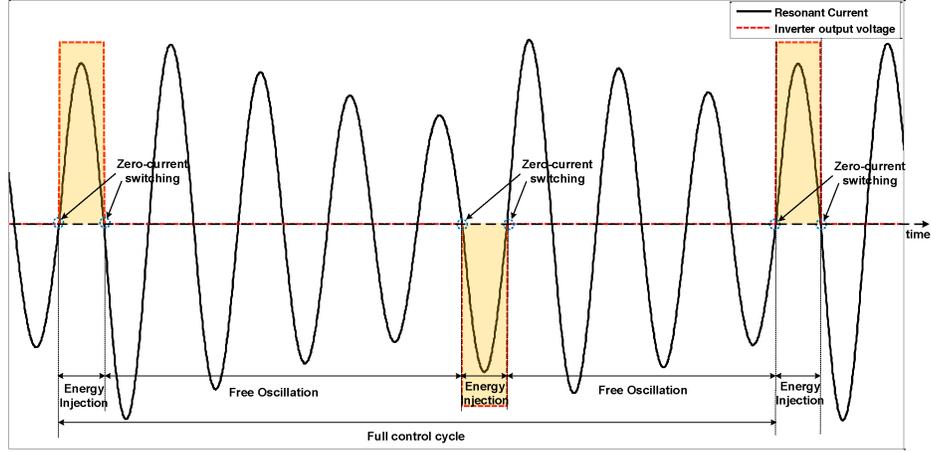


Fig. 4. Typical waveforms of resonant current and inverter output voltage applying the proposed control method based on energy-injection free-oscillation technique.

TABLE II
SPECIFICATIONS OF THE SIMULATED INDUCTIVE CHARGING SYSTEM SYSTEM.

Parameter	Value
Primary and secondary self-inductances	150 μ H
Primary and secondary compensation capacitors	0.1 μ F
Resonance frequency	35 kHz
Grid line voltage	208 V

TABLE III
SIMULATION RESULTS

Charging Level	RMS Resonant Current (A)	THD of Current (%)	Output Power (kW)
Level 1	237.10	0.7	52.74
Level 2	120.60	1.7	13.71
Level 3	63.63	2.9	3.52
Level 4	33.31	6.7	0.89

power, resonant current ripple, Total Harmonic Distortion (THD), etc.

In order to calculate the output power, the average injected power in each half-cycle can be calculated as follows:

$$P_{inj} = \frac{\int_0^{\frac{\pi}{\omega}} V_t i(t) dt}{\pi/\omega} \quad (5)$$

By substituting (3) in (5) the injected power to the IPT system can be obtained as follows:

$$P_{inj} = \frac{\omega \tau^2 V_t [V_t - v_c(0)] (1 + e^{-\frac{\pi}{\tau\omega}})}{\pi L (1 + \tau^2 \omega^2)} \quad (6)$$

The output power then can be calculated by averaging the injected power given by (6) in a full control cycle.

IV. SIMULATION RESULTS

MATLAB/Simulink simulation environment is used to model and simulate the inductive charging system utilizing the proposed control method (Fig. 2) in order to demonstrate the verification of the effectiveness of the proposed multi-level variable frequency control method for contactless EV charging systems. A three-phase power supply, a full-bridge rectifier, transmitter (primary) and receiver (secondary) coils, resonant capacitors, a full-bridge inverter controlled by the proposed controller capable of multi-level inductive charging, and a battery charging circuit for the EV at the secondary

constitute the simulation model, the specifications of which are tabulated in Table II.

The Table III documents the results of the simulations conducted across the four charging levels. Moreover, Fig. 5 depicts the waveforms of current and voltage. It can be deduced from these results that at a resonance frequency of 41.1 kHz, the resonant current can be used by the proposed controller to self-tune the switching operations. By changing the rate of energy injection, various charging levels can be obtained. The current harmonic distortion (THD) computations reveal that resonant current has low harmonic levels. Soft-switching operations will reduce the switching losses of the converter by a great extent, an action which is made possible by the controller, as shown in Fig. 5.

V. CONCLUSION

This paper proposed and presented an efficient way to enable inductive electric vehicle charging at various power levels through a self-tuning controller that is designed based on the energy-injection control technique for resonant circuits. The frequency of the energy injection to the system was altered to achieve the different charging levels. The need for further switching frequency is eliminated by the proposed controller's capability to self-tune the converter's switching operations to the IPT system's natural resonance frequency. Furthermore, the converter's efficiency is greatly increased and high operating frequencies are enabled through the activation of its soft-switching operations (zero-current switching). High operating

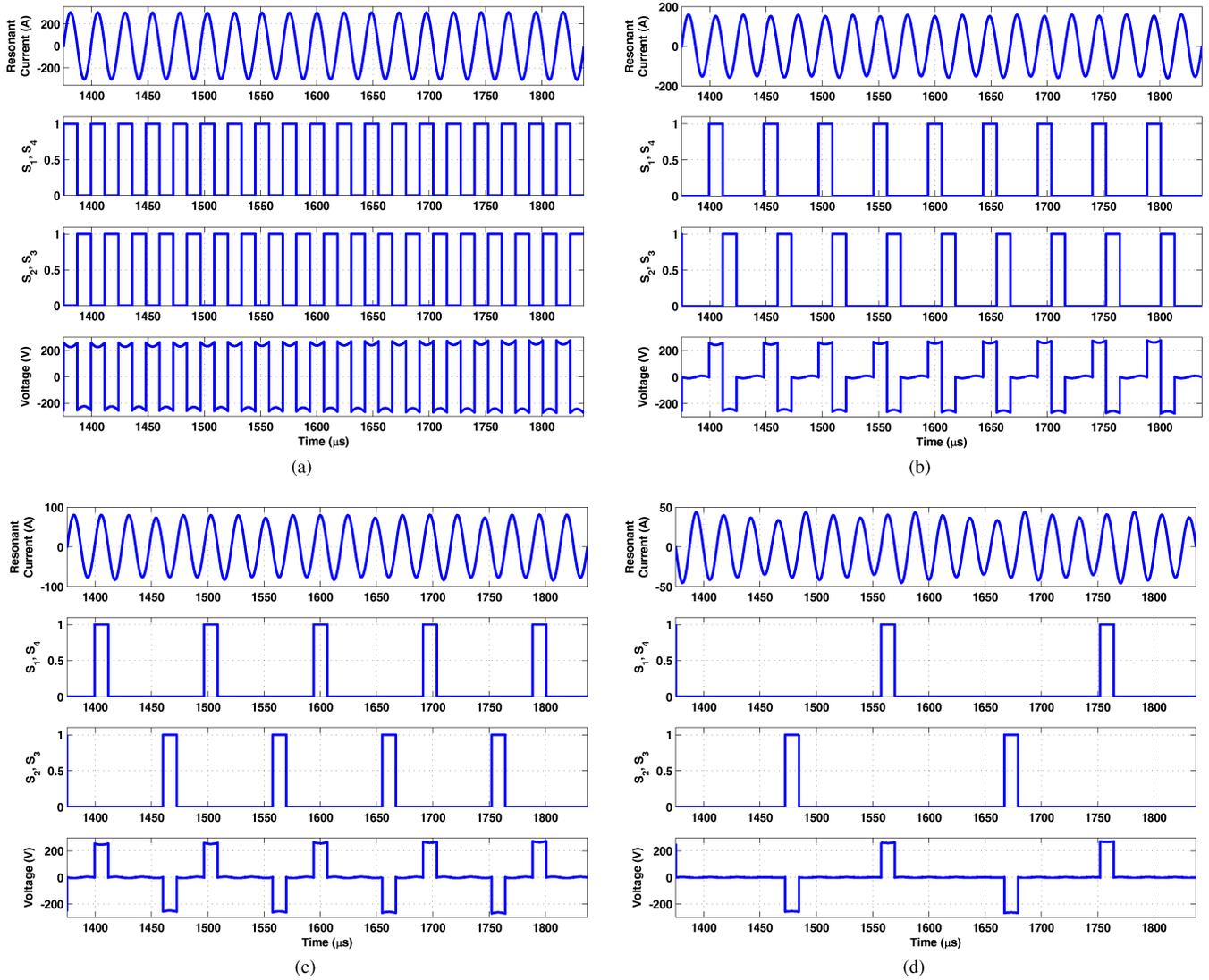


Fig. 5. Current, voltage and switching signals waveforms in different charging levels: (a) Level 1 charging with 52.7 kW output power, (b) Level 2 charging with 13.7 kW output power, (c) Level 3 charging with 3.5 kW output power, (d) Level 4 charging with 0.8 kW output power.

frequencies with enhanced efficiency may be expected through the proposed simplified design of the controller, eliminating the need for DSP and FPGA solutions.

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