

Conceptual study on grid-to-vehicle (G2V) wireless power transfer using single-phase matrix converter

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ABSTRACT

This paper presents the conceptual study on grid-to-electric vehicle (G2V) wireless power transfer (WPT) using Single Phase Matrix Converter (SPMC). In this work, the SPMC is used as a direct AC to AC converter to convert the input supply voltage at 50 Hz frequency to the output of 20 kHz to meet the WPT switching frequency operation of the transmitter and receiver coils. The high frequency AC voltage of the receiver coil is then rectified to a DC form by using SPMC. Through the proposed system, the battery of an electric car can be charged wirelessly, thus removing the annoying wires of the conventional electric vehicle charging system. The reduction in size of the charging system, power losses and optimum efficiency are among the advantages of the proposed system. MATLAB/Simulink (MLS) has been used to simulate the proposed model. Selected simulation result are presented to verify the proposed work.

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1. INTRODUCTION

The WPT technology is a modern power transfer topology first introduced by Nikola Teslas more than 100 years ago [1-7] which refers to the transmitting of electrical power through air. The most popular approach to WPT employs an electromagnetic field (EMF) of some frequency as a means by which the electrical power was transmitted [1]. The WPT technology involves the process of electrical energy transmission from a power source to an electrical load across an air gap without using any wires or connectors [8, 9]. The key elements of a WPT system are the transmitter and receiver coils.

An electric vehicle (EV) could be a vehicle fuelled by an electric engine instead of an internal combustion motor and the engine employs battery control [10, 11]. Modern improvements in battery innovation, framework integration, optimal design, investigation and improvement by major vehicle producers have driven to the generation of electric vehicles on the roads of the city [12].

The WPT innovation, which can dispose of all the troublesome charging, is desirable for EV owners in comparison with conventional charging [13]. By exchanging vitality wirelessly to the EV, charging gets to be the most straightforward task. The drivers as it were got to stop their car and take off for a stationary WPT framework. For a dynamic WPT framework, which suggests that the EV can be driven; the EV can run without a stop until the end of time [14]. In expansion, the battery capacity of remote charging EV can be diminished to 20 percent or less than in conductive charging EV [15-25].

Figure 1 shows the typical concept of WPT for an EV system which consists of several stages to wirelessly transfer power from the supply to the load. It uses AC power as a source and change it to a DC form with power factor correction (PFC). The main parts of the WPT system could be summarized as follows:

- The loosely coupled transmitting and receiving coils.
- The compensation network.
- The power electronics converters and control electronics.

The main difference between the proposed wireless charger and the conventional wireless charger system is that the two power electronics converters (AC to DC and DC to AC) is replaced by a SPMC circuit topology as shown in Figure 2. In this work, the SPMC is utilized to operate as a direct AC to AC converter to increase the operation frequency from 50 Hz to 20 kHz, thus removing the conventional two stage AC to DC and DC to AC converters. This enhanced circuit topology could lead to the reduction of the number of devices, and hence, reducing the total losses from the devices and improving the power density of the proposed wireless charging system.

2. THE PROPOSED GRID TO VEHICLE WPT

The proposed grid-to-vehicle (G2V) wireless power transfer (WPT) battery charger system schematic circuit is shown in Figure 3. In the transmitter side, the SPMC1 is used to create a high-frequency output AC voltage. By employing the LC compensation network, a constant high frequency current can be maintained in the transmitter coil. Similar to the transmitter side, the parallel compensation is also adopted in the receiver side. With constant primary coil current and parallel secondary side compensation, the output acts like a current source. At a certain coupling, the current in the receiver coil is almost constant. By changing the duty ratio of SPMC2, the output power could be controlled.

The switching algorithm for the proposed G2V WPT battery charger system was developed based on the switching algorithm of AC to AC converter with safe-commutation technique. The SPMC1 is controlled to operate as a direct AC to AC converter with the switching frequency of 20 kHz, whilst, the SPMC2 is controlled to operate as an AC to DC converter.

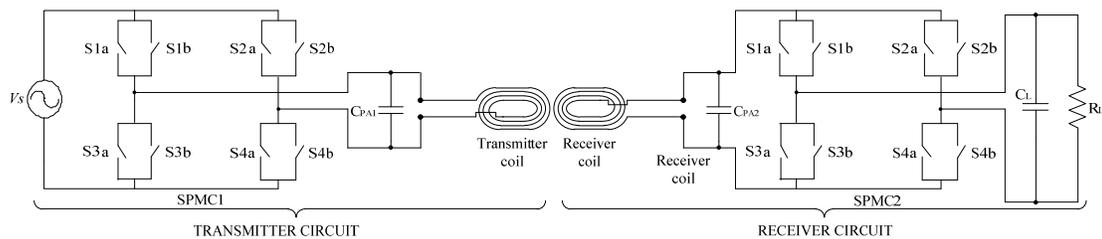


Figure 3. The proposed grid to vehicle (G2V) wireless power transfer (WPT)

2.1. AC to AC converter operation

The proposed switching strategies as tabulated in Table 1 are divided into four different modes called Modes 1, 2, 3 and 4 for different direction of output AC voltage. Four different switching states are developed to define complete possible operation during positive and negative cycle. The following set of rules is then defined;

- Mode 1: At this time, both switches S1a and S2b are turned 'ON' as shown in Figure 4(a). Then, S4a is turned 'ON' (after delay time) with the PWM switching pattern (providing overlap period). During this stage, current is flowing in the inductance (energized) through S4a and de-energized (commutation operation) through the S1a and S2b due to S4a 'OFF'.
- Mode 2: During this time, S4a is completely turned 'OFF' and the inductive load is de-energized due to overlap period of S3a and S4b as shown in Figure 4(b). Thus, S1b is turned 'ON' with the PWM switching pattern.
- Mode 3: Similar to Mode 1, during positive cycle operation, both switches S3a and S4b are turned 'ON' as shown in Figure 4(c). Then, S2a is turned 'ON' (after delay time) with the PWM switching pattern (providing overlap period).
- Mode 4: At this time, S2a is completely turned 'OFF' and the inductive load is de-energized due to overlap period of S1a and S2b as shown in Figure 4(d). Thus, S3b is turned 'ON' with the PWM switching pattern. A completed period is ended as shown in Figure 4(d).

Table 1. Switching algorithm for AC to AC converter at SPMC1

Input cycle	Output cycle	States	PWM Switches	Commutation Switches
Positive	Positive	1	S4a	S1a and S2b
	Negative	2	S2a	S3a and S4b
Negative	Positive	3	S3b	S1a and S2b
	Negative	4	S1b	S3a and S4b

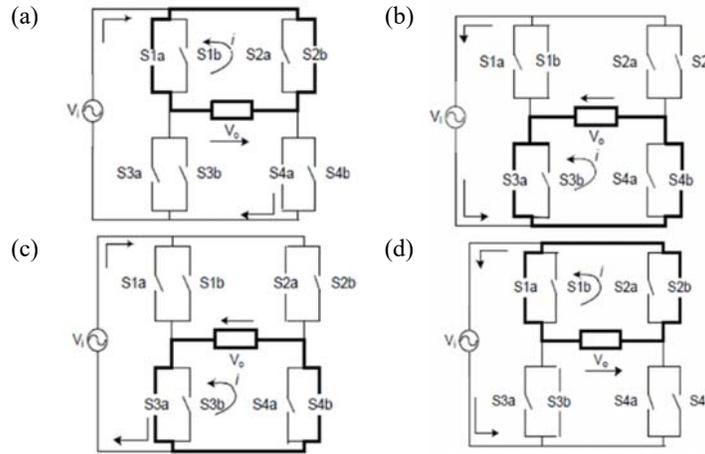


Figure 4. States of switching operations with safe-commutation techniques (a) Mode 1 (positive cycle), (b) Mode 2 (negative cycle), (c) Mode 3 (positive cycle), (d) Mode 4 (negative cycle)

2.2. AC to DC converter operation

By referring to Figure 5(a) for positive cycle operation, switch S1a is controlled by PWM signal, whilst switches S4a and S3b are always turned ‘ON’ prior to any switching functions. A similar arrangement is developed for the negative cycle implementation, where switch S3b is controlled by PWM signal, whilst switches S1a and S2b are always in the ‘ON’ state prior to any switching function as illustrated in Figure 5(b).

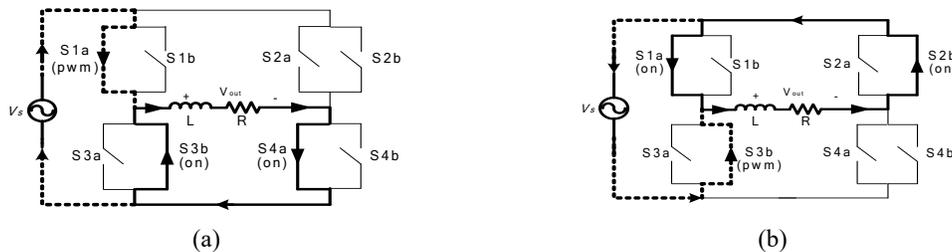


Figure 5. Controlled AC to DC (a) Positive cycle operation, (b) Negative cycle operation

3. COMPUTER SIMULATION MODEL

Figure 6(a) shows the top level main model of the proposed grid-to-vehicle (G2V) wireless power transfer (WPT) battery charger system. Table 3 shows the parameters used in the modelling of the proposed grid-to-vehicle (G2V) wireless power transfer (WPT) battery charger system. A subsystem is used in order to optimize the large model by breaking into a hierarchical set of smaller model for ease in implementation. Figures 6(b) to 6(f) are among the main subsystems represented by controlled unit model of AC to AC operation, AC to DC operation and PWM generator model.

The modelling of SPMC arrangement in MLS is shown in Figure 6(b), whilst Figure 6(c) shows the modelling of common emitter anti-parallel IGBT, with diode pair. The controller unit implements the operation of required switching state as presented in the previous section. It was divided into two operations either to control the AC to AC operation or AC to DC operation as shown in Figure 6(d).

Table 2. Parameters of the G2V WPT battery charger system

Parameters	Values
Input voltage, V_s	100 V, 50 Hz (Single phase)
Modulation Index	0.5
Loads	Resistor = 50 Ω , L = 5 mH
Switching frequency, f_s	20 kHz
Output frequency	20 kHz (SPMC1) and 50 Hz (SPMC2)

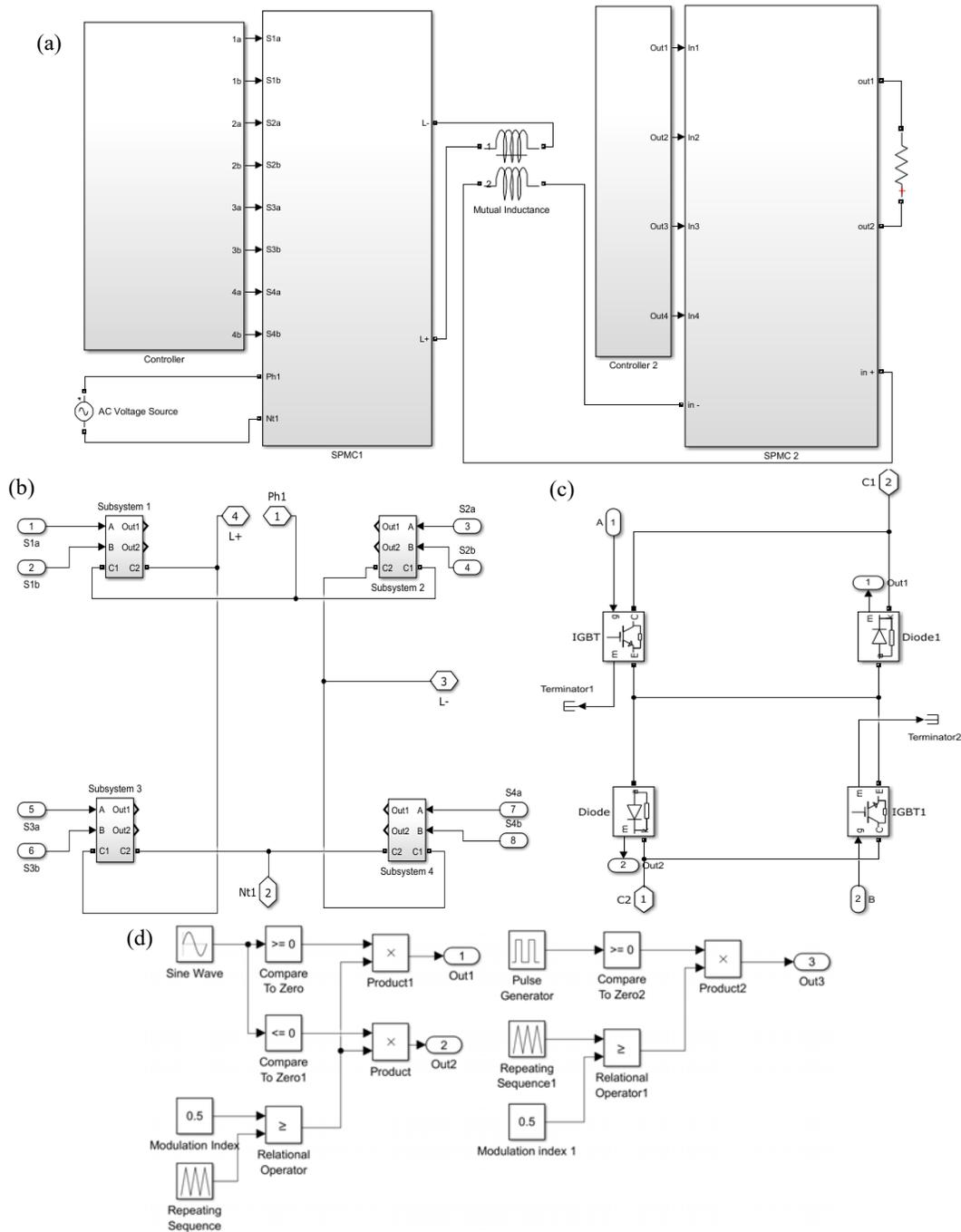


Figure 6. (a) Top level main model, (b) SPMC circuit model, (c) Bidirectional switch, and (d) PWM generator

4. RESULTS AND DISCUSSION

This section presents the selected simulation results on the operation of the proposed grid-to-vehicle (G2V) wireless power transfer (WPT) battery charger system. The function of the proposed operation includes; a) controlled AC to AC operation with safe commutation strategies, and b) wireless power transfer function, and c) AC to DC operation. Simulation studies were performed using MATLAB/Simulink to evaluate the operation of the proposed converter.

Figures 7 (a) and 7(b) show the simulation results of the supply voltage and current waveforms whilst Figures 8 (a) and 8 (b) show the results of output AC to AC converter that is fed to the transmitter coil of the WPT function.

A modulation index of 0.5 was used to illustrate sample results for a case of inductive load at a switching frequency of 20 kHz. A sinusoidal input voltage of 100V (pk-pk) at 50 Hz and a resistive-inductive load of 50 ohm and 5 mH were initially used in this stage.

Figures 9 (a) and 9 (b) illustrate the results obtained from SPMC2 which is controlled to operate as an AC to DC converter with pure resistive load. It clearly shows that the output voltage and current waveforms are in DC forms. The introduction of capacitive load produces results as shown in Figure 10. It was observed that undesirable ripples as shown in Figure 9 (a), were successfully minimised.

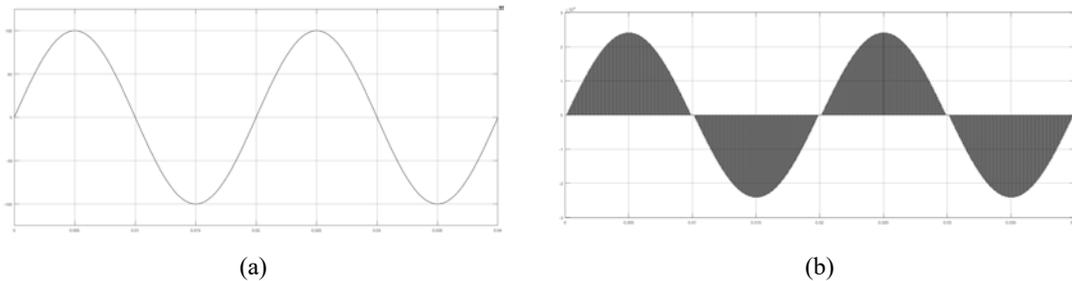


Figure 7. Waveform of (a) input voltage (V_{in}); (b) input current (I_{in})

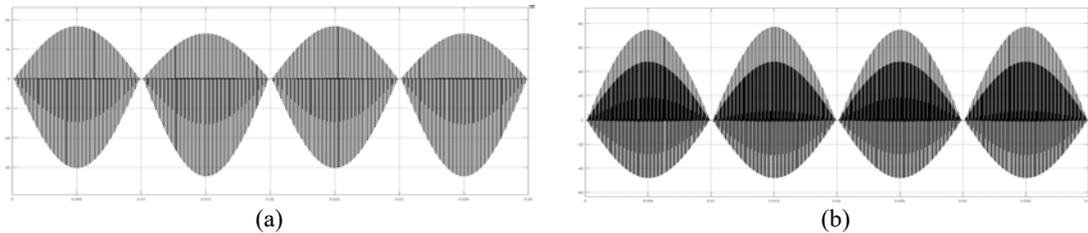


Figure 8. (a) Transmitter current waveform (I_p), (b) transmitter voltage waveform.

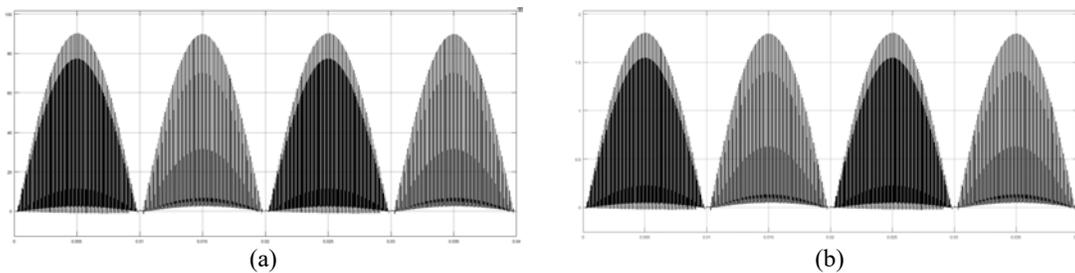


Figure 9. (a) Transmitter current waveform (I_p), (b) transmitter voltage waveform.

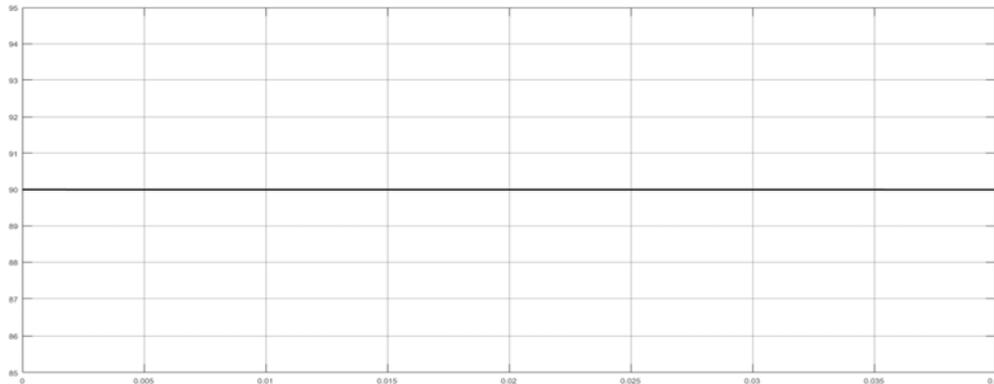


Figure 10. Output voltage (V_o) waveform with RC load

5. CONCLUSION

In this paper, the design and operations of the conceptual study on grid-to-vehicle (G2V) wireless power transfer using single phase matrix converter has been presented. Two types of operation were investigated; a) controlled AC to AC with safe commutation strategies, and b) AC to DC with capacitive load. In particular, the variation of modulation index by using pulse width modulation (PWM) technique to synthesize relevant output AC and DC waveforms has been considered. System simulations were performed using MATLAB/Simulink to ascertain basic power circuit behaviour and possible inaccuracies. It has been shown that the use of SPMC can be used to perform direct AC to AC converter, removing the complexity of the conventional AC-DC-AC converter, and thus, reducing the total losses of devices and improving the power density of the proposed wireless charging system.

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