Pulse Density Modulation Controlled WPT Charger for LEVs

Gungor Bal
Department of Electrical and Electronics Engineering, Faculty of Technology,
Gazi University
Ankara, Turkey
gunbal@gazi.edu.tr

Kenan Unal
Department of Motor Vehicles and Transportation Technology, TUSAŞ Kazan Vocational School,
Gazi University
Ankara, Turkey
kenanunal@gazi.edu.tr

Selim Oncu
Department of Electrical and Electronics Engineering, Engineering Faculty,
Karabuk University,
Karabuk, Turkey
soncu@karabuk.edu.tr

Nihat Ozturk
Department of Electrical and Electronics Engineering, Faculty of Technology,
Gazi University
Ankara, Turkey
ozturk@gazi.edu.tr

***Abstract*— Light Electric Vehicles (LEV) are increasingly used today to increase mobility in crowded cities. The charging process of LEVs, whose usage has increased, has been one of the issues that should be paid attention to. For this purpose, LEVs owned or rented by users need to be charged quickly and reliably. By using Wireless Power Transfer (WPT), this needed quick and reliable charging can be achieved for LEVs. In this paper, Pulse Density Modulation (PDM) is used for charging in Constant Voltage (CV) mode during wireless charging of LEVs with WPT. The simulation study required for CV charging was carried out with MATLAB/Simulink. A WPT system has been proposed that produces a constant output voltage in response to changing battery internal resistance in CV charging mode.**

Keywords—Wireless Power Transmission, Pulse Density Modulation, Constant Voltage Charge

I. INTRODUCTION

The use of Light Electric Vehicles (LEVs) has been one of the steps to increase mobility in cities. Considering the vehicle traffic and the damage caused by the vehicles to the environment, especially in crowded cities, LEVs have started to be preferred especially when there is a need for short distance relocations. For this purpose, short-term LEV rental companies have started to emerge in the world. The increase in the use of LEVs also increases the need for charging of these vehicles. There are two types of charging systems for charging, wired and wireless charging. Wireless Power Transfer (WPT) does not require a person to make a physical connection for charging [1], [2]. In this way, possible accidents can be prevented from occurring [3].

There are multiple power control techniques used for wireless power transfer operation [4]–[7]. One of these techniques is Pulse Density Modulation (PDM) [8]. The PDM technique is a technique that is used to control the output power of a resonant inverter at a fixed switching frequency by deleting some switching signals in a certain order, bringing the resonant current to a damped oscillation state [9].
In literature, the use of PDM technique in WPT applications is mostly done by using controlled rectifiers in the secondary circuit [10], [11]. In order to realize the PDM technique used on the secondary side, FPGA should be used in the controlled rectifier in the secondary circuit. Considering these systems as a product, not just a prototype, more than one Vehicle Assembly (VA) must be connected in a Ground Assembly (GA) and one FPGA must be used in each VA. The use of an FPGA in each VA is not an efficient method in terms of cost-effective production.

In this study, 32 irregular PDM techniques were used in GA for wireless charging of LEVs. Thanks to the proposed method, only FPGA can be used in GA and a more cost-effective charging system can be realized. Simulation studies in MATLAB/Simulink were performed in CV charging mode. The variation of the internal resistance of the battery was changed at 20 ohm intervals. With the PI controller, the required PDM sequence was determined and it was observed that the output voltage could be kept constant.

II. SERIES-SERIES COMPENSATED WIRELESS CHARGE

The block diagram of the WPT system controlled with irregular 32 PDM from the GA side for the CV mode charging process proposed in this study is presented in the Fig. 1.

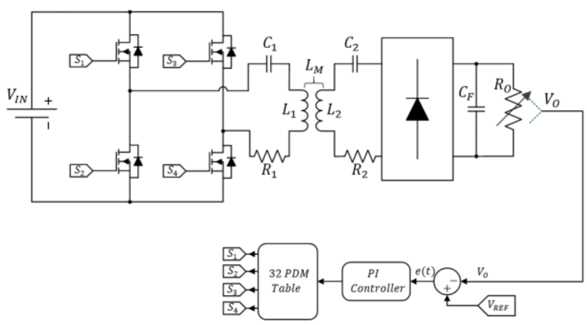

Fig. 1. Proposed SS Compensated CV Mode Charging System

Here, C_1 and C_2 represent GA capacitor and VA capacitor, respectively, L_1 and L_2 represent GA transmitter inductance and VA receiver inductance, R_1 and R_2 are transmitter and receiver winding resistances, C_F is rectifier filter capacitor, and R_O is battery internal resistance. The T-type equivalent circuit model of the proposed system is presented in the Fig. 2.

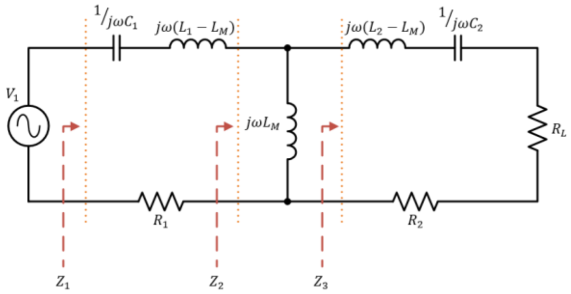

Fig. 2. T-type Equvailent Circuit of the SS Compensated WPT System

Here, $R_L = 8R_O/\pi^2$ represents the internal resistance of the battery with the rectifier. The input impedance of the SS compensated WPT system is presented in Eq. 1 [12].

$$\boldsymbol{Z_3} = j\omega(L_2 - L_M) + {}^{1}/_{j\omega C_2} + R_L + R_2$$

$$\boldsymbol{Z_2} = j\omega L_M \,//\, \boldsymbol{Z_3} \quad (1)$$

$$\boldsymbol{Z_1} = {}^{1}/_{j\omega C_1} + j\omega(L_1 - L_M) + R_1 + \boldsymbol{Z_2}$$

Zero Phase Angle (ZPA) is defined as the zero phase difference between the inverter voltage and current used in the charging process with WPT. In order for ZPA to be realized, the inverter must operate at the frequency where the imaginary part of the input equivalent impedance ($\boldsymbol{Z_1}$) is zero [13]. The values of the circuit elements used in this study are presented in Table 1.

TABLE I. CIRCUIT VALUES

Parameters	Values
C_1 and C_2	14,66 nF
L_1 and L_2	246 µH
L_M	30 µH
R_1 and R_2	0,01 Ω
R_O	200-340 Ω
C_F	200 µF
f_s	83.824 kHz

Here, f_s is the switching frequency. When the input impedance was calculated according to the values in Table 1, the switching frequency was chosen as 83,824 kHz.

III. Irregular Pulse Density Modulation

The Irregular 32 PDM switching table is shown in the Fig. 3. With the PDM technique, the WPT inverter is continuously switched under ZPA conditions, allowing the output voltage to be controlled. In this way, both the VA rating will be low and the WPT output voltage will be controlled. Since the ZPA frequency does not change, especially at heavy output load values, a fixed frequency switching signal is sufficient during this process.

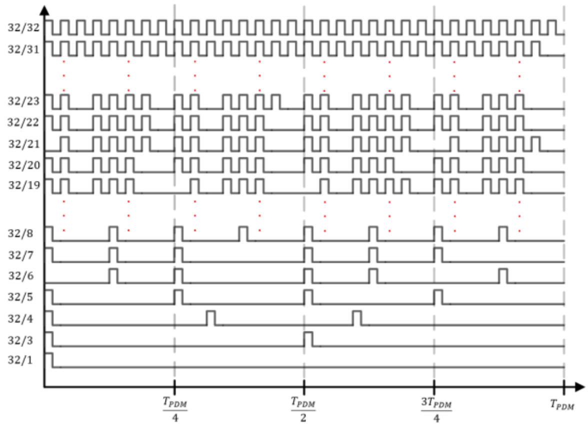

Fig. 3 Irregular 32 PDM Sequences

During the charging process of a battery, there are Constant Current (CC) and Constant Voltage (CV) modes. By charging the batteries according to the charging profile indicated in the figure, the battery life will be longer, the performance of the battery will not decrease and it will be safe [14].

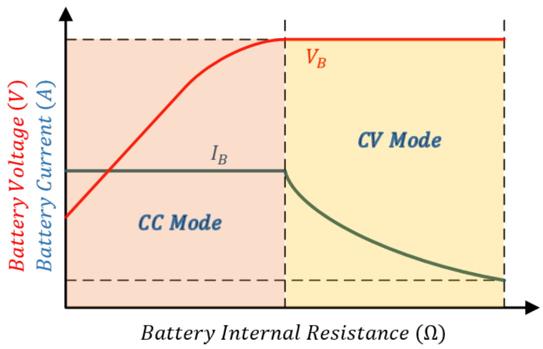

Fig. 4. Lithium-Ion Battery Charge Profile

According to Fig.4. , it is seen that the internal resistance of the battery increases continuously during the charging of the battery [14], [15]. Therefore, the internal resistance of the battery in CC mode is lower than in CV mode [15].

IV. Simulation Study

The MATLAB/Simulink model of the proposed PDM controlled WPT system is presented in Fig. 5. In order to model the change of battery internal resistance, a simulation study was carried out by including the load resistors in the system at certain intervals. Battery internal resistance values have been increased from 200 Ω for CV mode to 340 Ω by increasing 20 Ω each. The purpose of CV mode charging is that the output voltage remains constant at 36V, although the internal resistance of the battery increases. The purpose of this system is to keep the output voltage at a constant 36V,

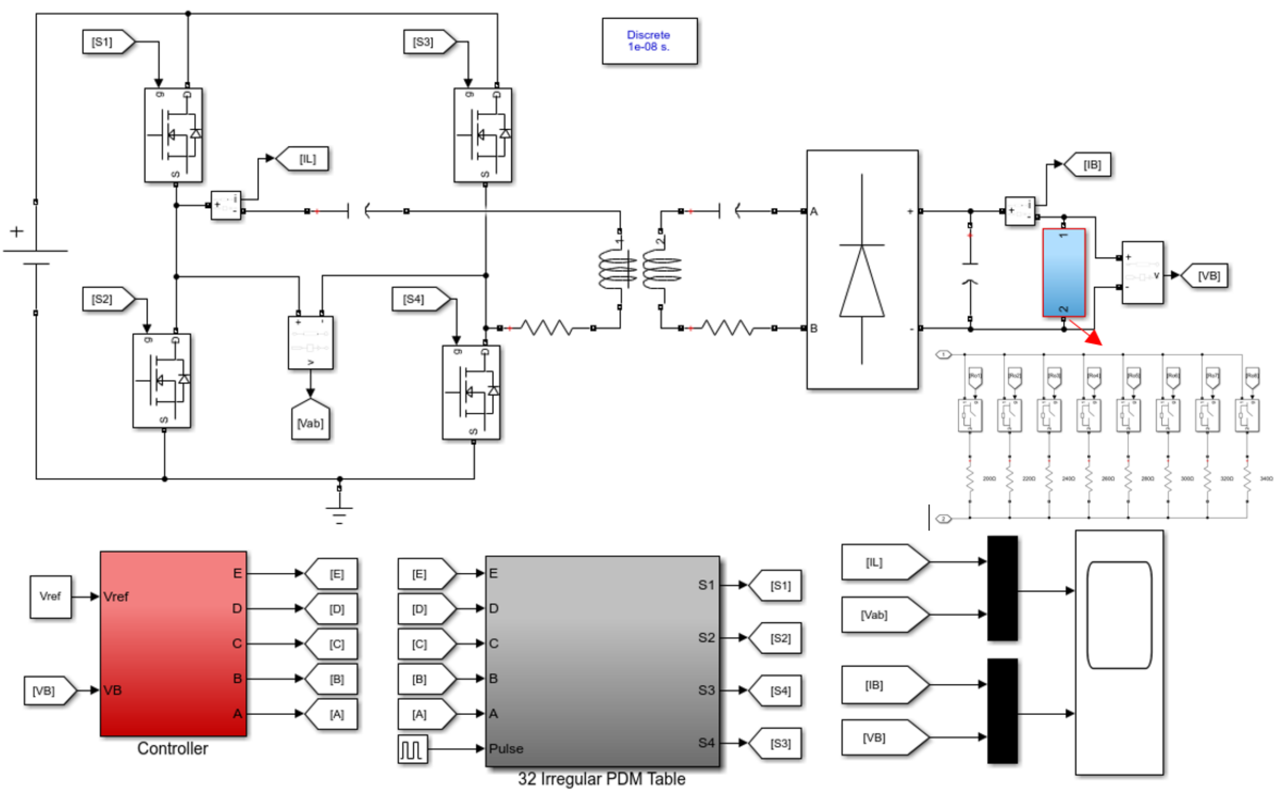

Fig. 5. MATLAB/Simulink Model of the PDM Controlled WPT CV Charger

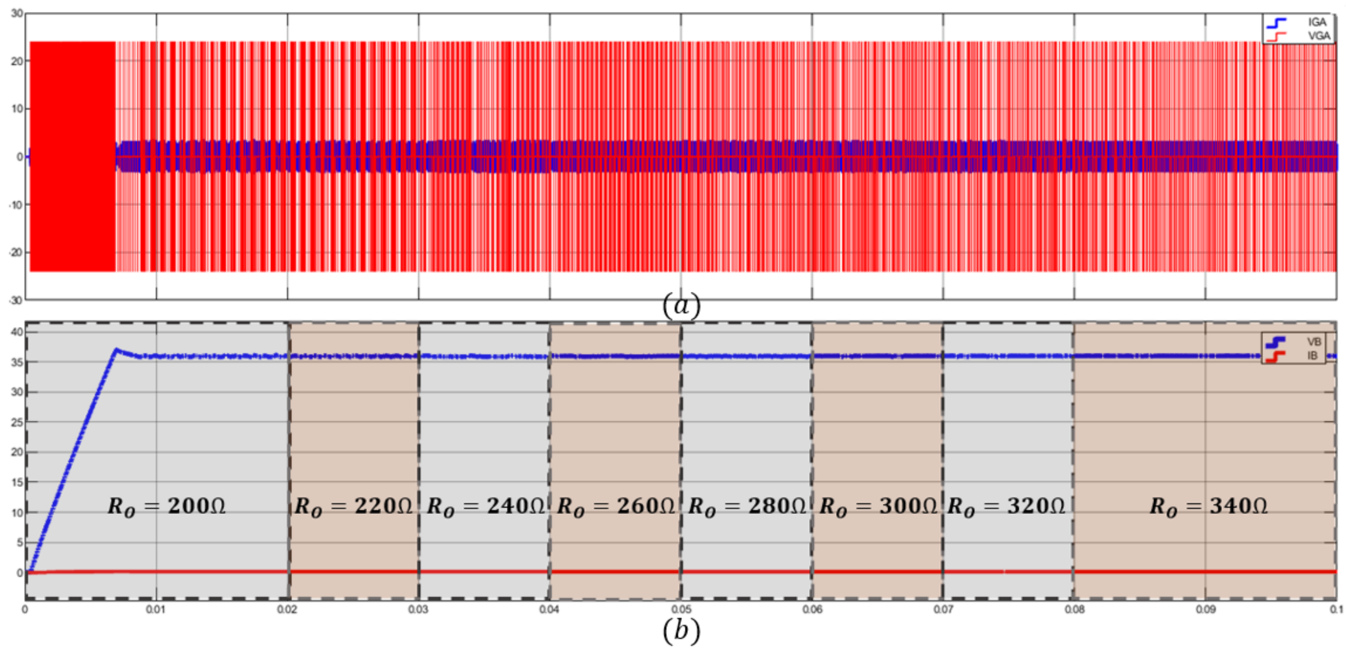

Fig. 6. a-) Ground Assembly side Inverter Voltage and Resonant Current ,b-) Output Voltage and Output Current

although the internal resistance of the battery increases in a system whose input voltage is fed from a 24V DC grid and in CV mode charging. The current and voltage signals on the GA side of the PDM controlled WPT charging system are shown in the Fig. 6-a. As can be seen in the figure, a zoomed-in version of some of the deleted pulses is presented in the Fig. 7-c. The output voltage and output current values of the CV mode simulation study of the PDM controlled WPT charging system are given in Fig. 6-b. In the simulation study, the error signal is obtained by reading the output voltage and taking the difference from the reference voltage. Error signal The required PDM sequence is determined in the PI controller to reduce the error to zero. The PDM sequence determined in the PI controller is transmitted to the 32 irregular PDM table and switching signals are generated. According to the simulation results, the zoomed version of the output current signal is presented in Fig. 7-a and the zoomed version of the output voltage is presented in Fig. 7-b.

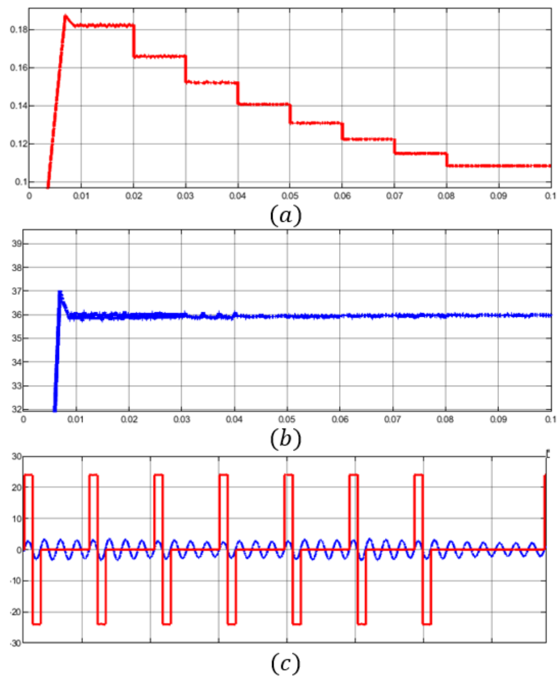

Fig. 7 Zoomed signals of WPT system, a-) Output Current, b-) Output Voltage, c-) GA side Inverter Voltage and Resonant current

V. Conclusion

In this study, PDM controlled CV mode charging system simulation by GA side for LEVs was carried out in MATLAB/Simulink. Thanks to the proposed system, only one PDM switching signal generator is used in the WPT inverter on the GA side. The experimental work of the PDM control is carried out with FPGAs, if the output voltage of the active rectifier needs to be kept constant with the PDM control on the VA side, one FPGA should be used in each receiver. For LEVs, using FPGAs on all VA sides is cost-inefficient. Therefore, using one FPGA at each GA side charging station is a lower cost system. In the experimental study of the proposed system, only one communication module will be required to transfer voltage information from the VA side to the GA side. However, the cost of the communication module is lower than the FPGA. As a result of the simulation studies, the output voltage of a WPT system fed from a 24V DC microgrid could be kept at a constant voltage of 36V under variable output resistance conditions with the irregular 32PDM technique.

Acknowledgements

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