The Implementation of Pulse-Density Modulated Wireless Power System Using a Sliding Mode Controller

DOI
https://doi.org/10.18690/um.feri.4.2025.27

ISBN
978-961-286-986-1

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The efficiency of the wireless power transfer (WPT) using a half-bridge inverter on the transmitter side can be increased by switching from frequency modulation (FM) to pulse density modulation (PDM). The method of generating PDM, described and implemented in this paper is based on a sliding mode controller (SMC), which also serves as a transmitter coil current controller. The current controller is in a cascade with the output voltage controller, which can be implemented either on the transmitter or on the receiver side.

Keywords:
inductive power transfer,
half-bridge inverter,
pulse density modulation,
sliding mode control,
FPGA

University of Maribor Press

I Introduction

Wireless charging is currently very popular, especially with low-powered consumer-grade mobile devices [1]. Efficiency of the transfer is usually not a concern, because of the low transferred power and slow charging speeds.

The most popular method of wireless power transfer is the inductive power transfer (IPT). The main advantages are safety, robustness, and ease of use. On the other hand, the IPT systems can transfer power only across short to medium distances with limited efficiency. The efficiency heavily depends on the coupling coefficient between the transmitter and the receiver coil. The coupling coefficient is affected by distance and misalignment between the coils. Therefore, it is important to correctly position the transmitter and the receiver coil.

Low-power systems usually replace full-bridge high-frequency inverters with half-bridge inverters. This reduces the complexity and price of the transmitter. The downside is, that the voltage and current control of the IPT system is limited to frequency modulation, which results in additional circuit losses. The solution can be pulse density modulation (PDM). The PDM is usually implemented using delta-sigma modulation, which usually results in limited modulation resolution [2].

This paper presents the different implementations of the PDM, using a sliding mode current controller, which results in better resolution and precise control of the transmitter current.

II Implementation of PDM

The IPT system is usually controlled using the fundamental or average transmitter voltage. The average transmitter voltage, generated by the half-bridge inverter using PDM can be calculated using:

$$\bar{u}_T = \left(\frac{2U_{DC}}{\pi} d \right) \sin\left(\omega_s t\right) = \bar{U}_T \sin\left(\omega_s t\right) \tag{1}$$

where d is the pulse density of the modulation, with a value between 0 and 1, with 0.1 step resolution in case the sigma-delta modulation is used [2].

However, pulse density modulation can also be implemented using sliding mode control (SMC), which is relatively easy to implement on systems with transistor switches. In IPT systems, SMC is usually implemented on the receiver side, for controlling the DC-DC converter for battery charging [3]. SMC presents non-linear control with variable structure. The change in the structure of the system is based on the location of the error signal regarding the sliding surface [4].

The bounded sliding mode surface is presented in Fig. 1. The boundary layer ε was introduced in order to reduce the chattering of the controller. The two-dimensional sliding surface $S = 0$ is dependent on the parameters x_1 and x_2. The sliding mode surface is defined by:

$$S = k_\alpha x_1 + k_\beta x_2 \tag{1}$$

where S is the sliding trajectory, which is dependent on the x_1 and x_2. Parameter k_α is the constant of the first parameter and k_β is the constant of the second parameter. Both constants should be positive.

To implement PDM on a half-bridge converter, SMC is used to control the transmitter current, instead of the output voltage of the DC-DC converter. The main objective of the SMC is to minimize the error between the reference transmitter current and the average, measured transmitter current. The error can be expressed as:

$$x_1 = I_{T,ref} - I_T \tag{2}$$

where x_1 is the first parameter of the sliding trajectory, $I_{T,ref}$ is the reference transmitter current and I_T is the measured average current.

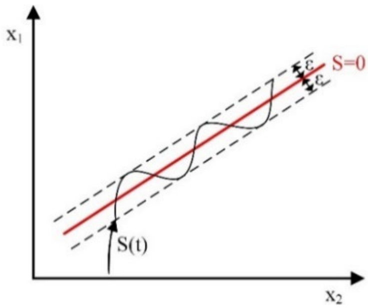

Figure 1: Sliding surface with boundary layer

The second sliding trajectory parameter is derived from the first parameter using:

$$x_2 = \int_t x_1(t)\,dt \tag{3}$$

The control output depends on the value of the sliding mode trajectory. The output of the half-bridge inverter switches from on-state to off-state with the following control law:

$$U_T = \begin{cases} \dfrac{2U_{DC}}{\pi} & S \geq \varepsilon \\ 0 & S < -\varepsilon \end{cases} \tag{4}$$

If the sliding surface is more than ε, the error is positive. The reference current is larger than the measured current. Therefore, the inverter must generate a voltage in order to increase the transmitter current. On the other hand, if the trajectory is below −ε, the error is negative. The transmitter current is greater than the reference current and the inverter should be off.

III Experimental results

The proposed implementation of the PDM was tested on a small-scale IPT system. The basic elements of the system are presented in Fig. 2. The system was powered by the constant voltage from the laboratory power supply. For the transmitter and receiver coil, two Qi-compatible coils were used. The sliding mode transmitter controller and PI voltage controller were implemented on the transmitter side using a Field Programmable Gate Array (FPGA). The wireless transfer distance was set to 6 mm. During experiments, the maximum DC-to-DC efficiency was up to 85%, at maximum output voltage and perfect coil alignment.

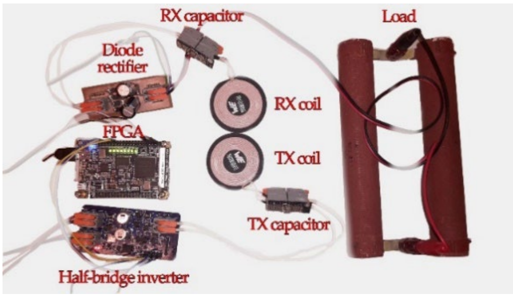

Figure 2: System with nonlinear elements

The main problem of the PDM is that the transmitter current has no constant amplitude. Therefore, it is important to control the average transmitter current and not the peak transmitter current. This can be achieved by using an averaging circuit after the current sensor.

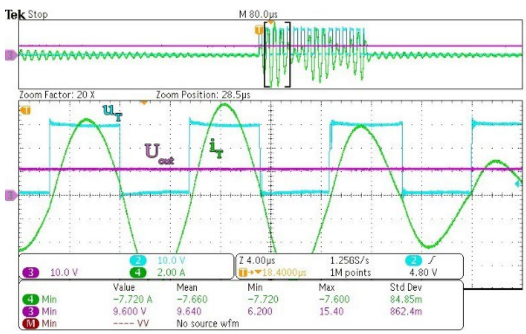

Figure 3: Detailed input signals of IPT system with perfectly aligned coils

The input signals of the operating IPT system are presented in Fig. 3, for the case, when the coils are perfectly aligned and Fig. 4., when the coils are misaligned by 10 mm in the *y* direction. In both cases, the controlled output voltage is 10 V. The blue signal represents the transmitter voltage, the green signal represents the transmitter current, and the purple signal represents the output voltage. In Fig. 4 the coupling coefficient is lower due to the coil misalignment. The current controller therefore increases the PDM, to reduce the error between reference and measured voltage.

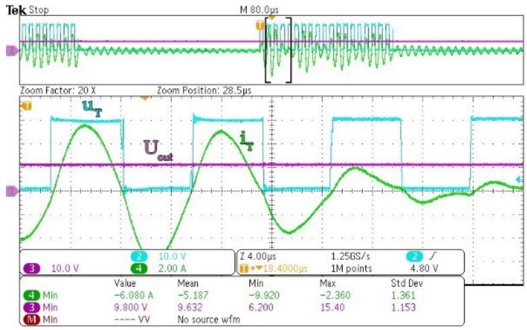

Figure 4: Detailed input signals of IPT system with misaligned coils

IV Conclusion

The efficiency of the IPT system using half-bridge inverter, can be increased by replacing frequency modulation for PDM. The PDM is usually implemented using delta-sigma modulation which result in limited modulation resolution. On the other hand, if PDM is implemented using sliding mode controller, the resolution of the modulation is increased. Additionally, the transmitter current is controlled with desired reference and can help limit the current at low coupling coefficients.

References

[1] X. Lu, D. Niyato, P. Wang, D. I. Kim, and Z. Han, "Wireless charger networking for mobile devices: Fundamentals, standards, and applications," *IEEE Wireless Communications*, vol. 22, no. 2, pp. 126–135, 2015

[2] H. Li, J. Fang, S. Chen, K. Wang, and Y. Tang, "Pulse density modulation for maximum efficiency point tracking of wireless power transfer systems," *IEEE Transactions on Power Electronics*, vol. 33, no. 6, pp. 5492–5501, 2017.

[3] V. Utkin, "Sliding mode control of dc/dc converters," *Journal of the Franklin Institute*, vol. 350, no. 8, pp. 2146–2165, 2013.

[4] Y. Shtessel, C. Edwards, L. Fridman, A. Levant et al., Sliding mode control and observation. *Springer*, 2014, vol. 10.