

# Research on Control Strategy of Full-Bridge LLC

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**Abstract:** Aiming at the application of full-bridge LLC resonant converter in electric vehicle on-board charger, a PSM+PFM hybrid modulation method is used to optimize the working situation of the LLC resonant converter. At the same time, by combining the advantages of phase shift modulation (PSM) and pulse frequency modulation (PFM), linear active disturbance rejection control (LADRC) is designed to realize efficient closed-loop compensation of the converter, and improve the stability and dynamic response performance of the system under different load conditions. The experimental results show that the control strategy can effectively improve the efficiency and performance of the LLC resonant converter and meet the demand of EV charging.

**Keywords:** LLC Resonant Converter; PSM+PFM Hybrid Modulation; Linear Active Disturbance Rejection Control; Electric Vehicle Charger.

## 1. Introduction

With the development of new energy vehicles, the demand for power conversion equipment that can achieve efficient performance and high power density has increased. LLC resonant converters are meeting this requirement [1].

The traditional modulation strategy is pulse frequency modulation (PFM), which controls the output voltage by adjusting the switching frequency. However, it is very difficult to optimize the design of LLC converters suitable for wide voltage gains using traditional single PFM modulation methods[2]. In order to broaden the voltage gain range and maintain the low cost and high efficiency of the LLC resonant converter, a hybrid modulation method of PSM and PFM is used in this paper to optimize the steady-state performance of the LLC resonant converter in wide voltage gain range applications.

In addition, the traditional control strategy is PI control, although its control mode is simple in structure, easy to realize and understand, and low in cost, but its response speed is slow and anti-disturbance ability is weak, which is not conducive to the stability of the system. At present, in addition to PI controllers, there are other controllers to improve system stability, such as optimal trajectory control[5] and sliding mode control[6]. Although these controllers are more stable than traditional PI controllers, they still have significant limitations.

The active disturbance rejection control method[7] (ADRC) is a controller based on modern control theory proposed by researcher Jingqing Han. It has strong anti-interference ability and robustness. Linear active disturbance rejection control (LADRC) was proposed by Zhiqiang Gao, which greatly simplified the parameter tuning of ADRC and provided a good reference for subsequent scholars[8]. Based on the above research, this paper designs a control strategy based on linear active disturbance rejection control PSM+PFM hybrid modulation for LLC resonant converter.

## 2. LLC Resonant Converter Modulation Scheme

### 2.1. The Principle of PSM + PFM Hybrid Modulation

The traditional full-bridge LLC resonant converter adopts frequency conversion control. If a wider output voltage is required, a single frequency conversion adjustment will cause the converter frequency variation range to be too large, which is not conducive to the resonant cavity parameter design and reduces the converter efficiency. In order to enhance the ability of low voltage output of the converter, researchers put forward a control method combining phase shift and frequency conversion[4], which can make up for the shortcomings of single modulation. When the converter is started, the system works in frequency conversion mode, and the output voltage is controlled by increasing the switching frequency. When the switching frequency reaches the quasi-resonant frequency, the switching frequency remains unchanged, and the system switches to the phase shift mode, and the output voltage is controlled by the size of the phase shift Angle  $\theta$ , as shown in Figure 1.

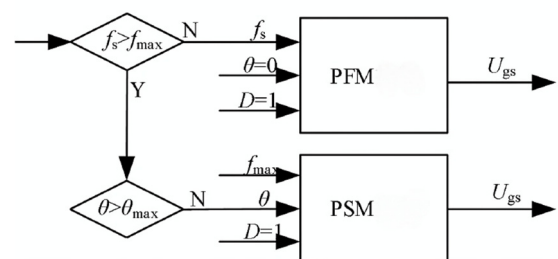


Figure 1. Hybrid modulation strategy diagram

## 3. Small Signal Modeling

Small-signal modeling of LLC resonant converter is the basis for analyzing closed-loop control and parameter design of the converter. We can get the transfer function of the system from small-signal modeling.

### 3.1. PFM Mode Small Signal Modeling

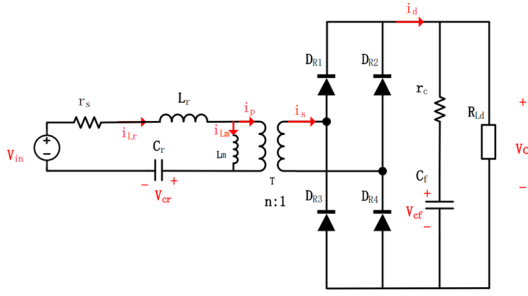


Figure 2. Full-bridge LLC resonant converter small-signal model equivalent circuit

At present, there are two commonly used small signal modeling methods: **Extended Describing Function Method** and sweep frequency method. Here, we use the **Extended Describing Function Method** to model the small

signal of the LLC resonant converter under PFM modulation. The equivalent circuit diagram of the LLC resonant converter is shown in Figure 2.

In order to obtain the small signal model of the full-bridge LLC resonant converter, perturbation and linearization should be performed at the steady-state operating point[3]. After small signal perturbation is performed on the large signal model of the LLC resonant converter, the small signal perturbation equation can be obtained by variable perturbation simplification. Considering only small signal disturbance  $\hat{f}_{sn}$ , ignore  $\hat{V}_{in}$  and  $\hat{d}$ , the small signal state space model of the full-bridge LLC resonant converter is obtained:

$$\begin{cases} \frac{d\hat{x}}{dt} = A\hat{x} + B\hat{u} \\ \hat{y} = C\hat{x} + D\hat{u} \\ \hat{x} = (\hat{i}_{r_s}, \hat{i}_{r_c}, \hat{v}_{crs}, \hat{v}_{crs}, \hat{i}_{m_s}, \hat{i}_{m_c}, \hat{v}_{co})^T \\ \hat{u} = (\hat{f}_{sn}), \hat{y} = (\hat{v}_o) \end{cases} \quad (1)$$

$$A = \begin{bmatrix} \frac{-r_s + H_{is}}{L_r} & \frac{L_r \Omega_s - H_{ic}}{L_r} & -\frac{1}{L_r} & 0 & \frac{H_{is}}{L_r} & \frac{H_{ic}}{L_r} & -\frac{H_{vo}}{L_r} \\ -\frac{L_r \Omega_s + G_{is}}{L_r} & -\frac{r_s + G_{ic}}{L_r} & 0 & -\frac{1}{L_r} & \frac{G_{is}}{L_r} & \frac{G_{ic}}{L_r} & -\frac{H_{vo}}{L_r} \\ \frac{1}{C_r} & 0 & 0 & \Omega_s & 0 & 0 & 0 \\ 0 & \frac{1}{C_r} & -\Omega_s & 0 & 0 & 0 & 0 \\ \frac{H_{is}}{L_m} & \frac{H_{ic}}{L_m} & 0 & 0 & -\frac{H_{is}}{L_m} & \frac{L_m \Omega_s - H_{ic}}{L_m} & \frac{H_{vo}}{L_m} \\ \frac{G_{is}}{L_m} & \frac{G_{ic}}{L_m} & 0 & 0 & -\frac{G_{is} + L_m \Omega_s}{L_m} & -\frac{G_{ic}}{L_m} & \frac{G_{vo}}{L_m} \\ \frac{K_{is} r'_c}{C_o r_c} & \frac{K_{ic} r'_c}{C_o r_c} & 0 & 0 & -\frac{K_{is} r'_c}{C_o r_c} & -\frac{K_{ic} r'_c}{C_o r_c} & -\frac{r'_c}{C_o r_c R_L} \end{bmatrix} \quad (2)$$

$$B = (\omega_r I_{rc}, -\omega_r I_{rs}, \omega_r V_{crs}, -\omega_r V_{crs}, \omega_r I_{mc}, -\omega_r I_{ms}, 0)^T$$

$$C = (K_{is} r'_c, K_{ic} r'_c, 0, 0, -K_{is} r'_c, -K_{ic} r'_c, \frac{r'_c}{r_c})$$

$$D = 0$$

According to the above state space equation, the transfer function expression of switching frequency  $f_s$  to output voltage  $V_o$  can be obtained as follows:

$$G(s) = \frac{\hat{v}_o}{\hat{f}_{sn}} = C \cdot (SI - A)^{-1} \cdot B + D \quad (3)$$

The LLC resonant converter system parameters are substituted into the above state space equation, and the Bode diagram of  $G(s)$  is drawn using MATLAB, as shown in Figure 3.

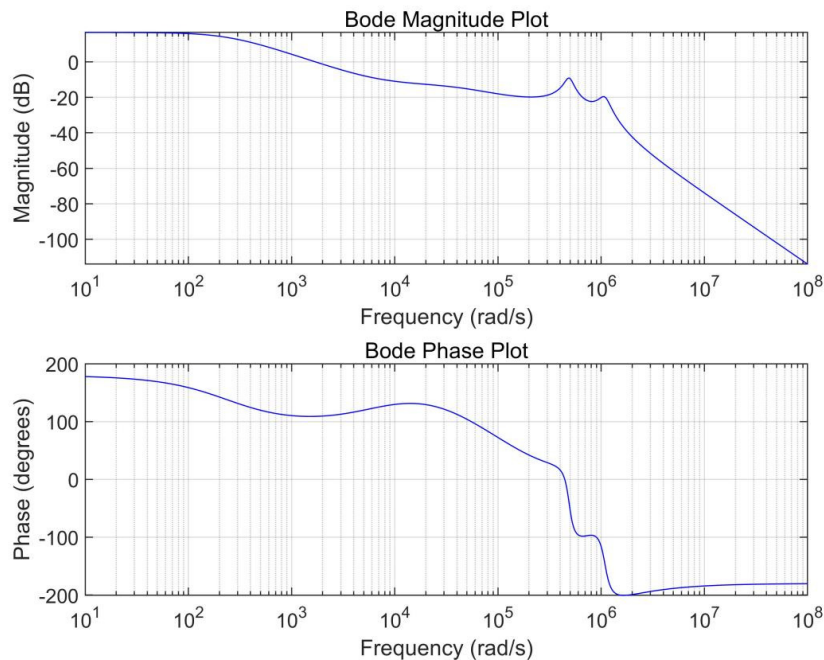


Figure 3. Bode diagram of PFM mode open-loop transfer function

### 3.2. Small Signal Modeling in PSM Mode

The full-bridge LLC resonant converter in phase-shift modulation mode directly uses the sweeping frequency

method to obtain the transfer function from input to output, substitute the parameters of the LLC system, and draw the Bode diagram of the transfer function in PSM mode, as shown in Figure 4.

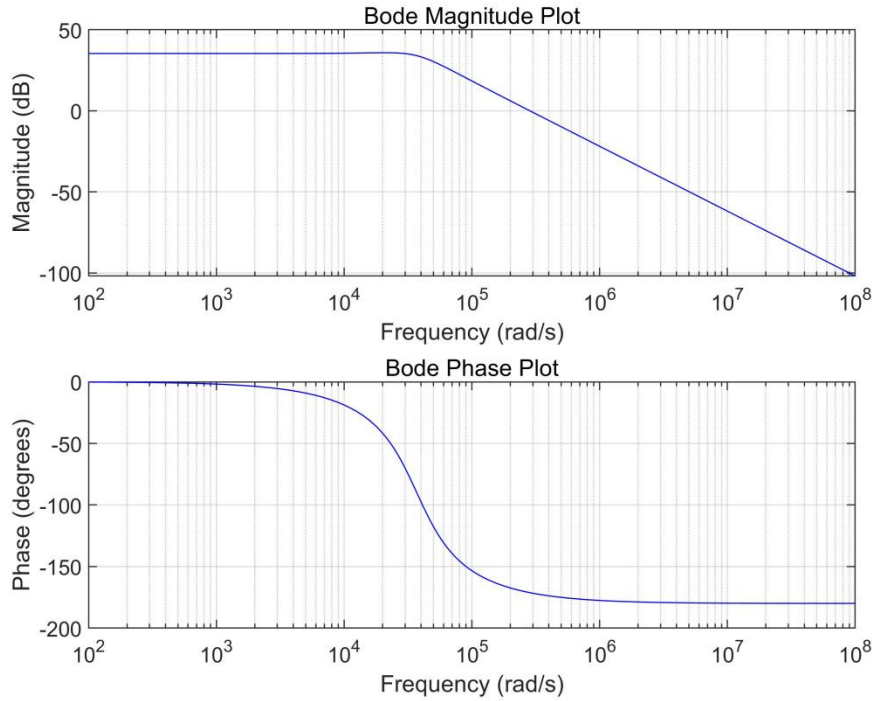


Figure 4. Bode diagram of PSM mode open loop transfer function

## 4. Controller Design

LADRC controller structure: The designed LADRC controller includes tracking differentiator, extended state observer and linear state error feedback control law. The tracking differentiator is used to extract the differential information of the input signal, the extended state observer is used to estimate the total disturbance of the system, and the linear state error feedback control law is used to generate the control signal. The parameters of LADRC controller are adjusted according to the dynamic characteristics and load requirements of LLC resonant converter. Ensure the system has good stability and dynamic response performance under different load conditions. The control block diagram of LADRC control is shown in Figure 3.1.

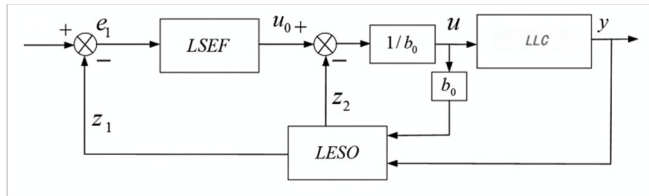


Figure 5. ADRC control block diagram

The first is the system under PFM modulation, where  $e_1$  is the error between the output voltage and the reference voltage,  $u$  is the switching frequency,  $b_0$  is the disturbance compensation coefficient,  $y$  is the output voltage, and  $z_1$  and  $z_2$  are the state variables of the extended state observer respectively. Among them:

$$\dot{y} = bu + f_1 = b_0u + bu - b_0u + f_1 = b_0u + (b - b_0)u + f_1 = b_0u + f \quad (4)$$

Select the state variable  $x_1 = y, x_2 = \dot{y}$ , let  $h = f$ , then

the equation of state is:

$$\begin{cases} \dot{x}_1 = x_2 + b_0u \\ \dot{x}_2 = h \\ y = x_1 \end{cases} \quad (5)$$

The expression equation of LESO can be obtained from the above equation as follows:

$$\begin{cases} \dot{z}_1 = z_2 - \beta_1(z_1 - y) + b_0u \\ \dot{z}_2 = -\beta_2(z_1 - y) \end{cases} \quad (6)$$

Where,  $\beta_1$  and  $\beta_2$  are observer gain parameters. As a rule of thumb, observer bandwidth  $\omega_0$  is set to  $1e5$ , it's given by  $\omega_0 = 5\omega_c, \omega_c = 0.2e5$ , the transfer function of the system tells us that  $b_0 = 5e6$ . At this point, all parameters can be adjusted.

In phase shift mode, parameter  $u$  represents phase shift Angle  $\theta$ , parameter  $y$  represents system output voltage, observer bandwidth is set to  $\omega_0 = 1e5$ , controller bandwidth  $\omega_c = 0.2e5$ , and  $b_0 = 1e11$  can be obtained by debugging  $b_0$ .

LADRC parameters only need to configure two parameters  $\omega_0$  and  $\omega_c$  to achieve the desired control effect of the controller [8]. In the subsequent simulation experiment, the response performance and stability of the system can be optimized by debugging various parameters.

## 5. Experimental Verification

### 5.1. Experimental Platform Construction

MATLAB and Simulink were used to simulate the hybrid modulated full-bridge LLC resonant converter.

### 5.2. Experimental Results and Analysis

As shown in Figure 6, when the system is started, working in PFM mode, the output voltage soon stabilizes at 360V. At 0.02s, the system switches to PSM mode, and the output

voltage also quickly stabilizes at 360V.

As shown in Figure 7, it is the inductance current in PFM mode, and the curve is very perfect. At 0.02s, it switches to

PSM mode, and as shown in Figure 8, it is the inductance current in PSM mode.

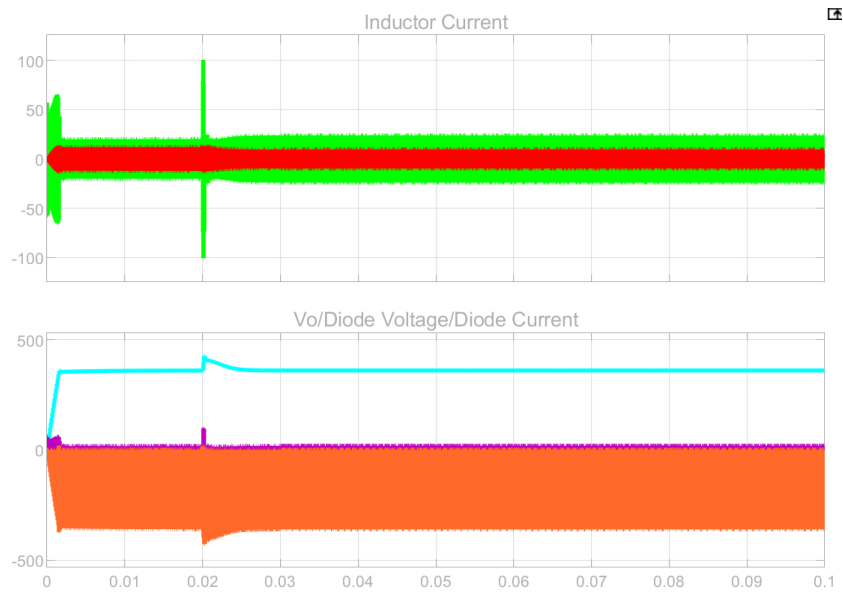


Figure 6. Output voltage and current waveform

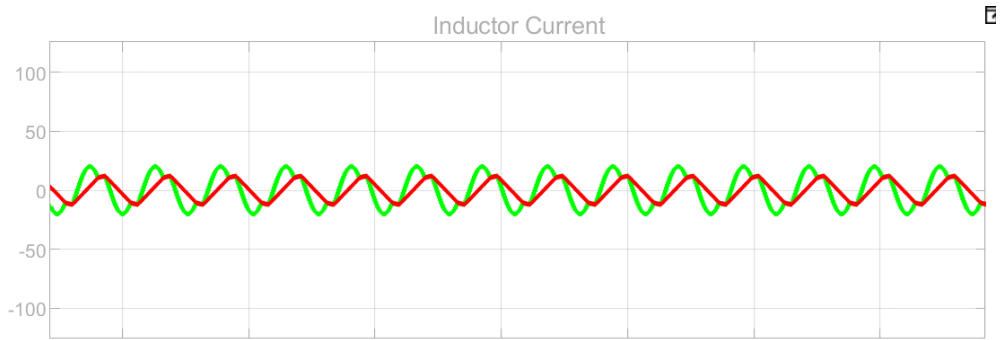


Figure 7. PFM mode resonance current diagram

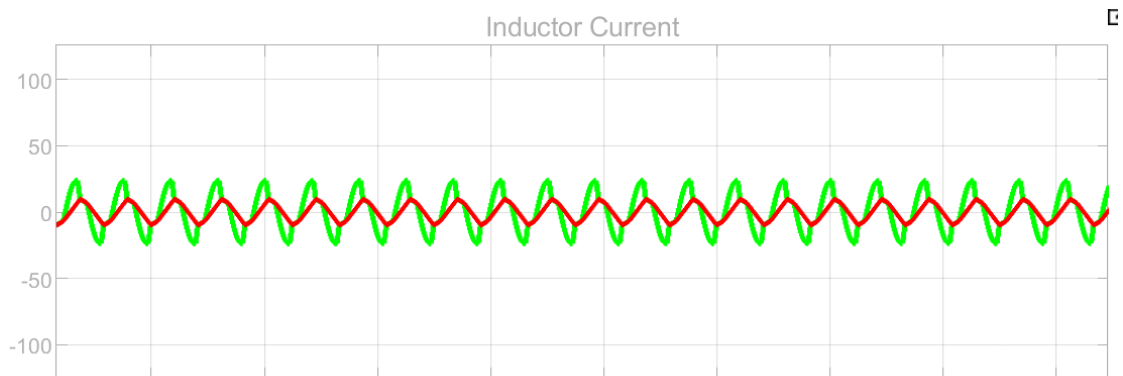


Figure 8. Resonance current diagram of PSM mode

The full-bridge LLC resonant converter using PSM and PFM hybrid modulation combined with LADRC control strategy has significantly higher efficiency than the traditional PFM single modulation mode under light load, as shown in FIG. 9.

## 6. Summary

This paper presents a control strategy of LLC resonant converter based on PSM+PFM hybrid modulation and LADRC closed-loop compensation. By combining the advantages of PSM control and PFM control, a first-order

LADRC controller is designed to realize efficient closed-loop compensation of the converter. The experimental results show that the control strategy can effectively improve the working efficiency and control performance of the LLC resonant converter, and meet the demand of EV charging. In the future research, the parameters of LADRC controller will be further optimized to improve the robustness and response performance of the system.

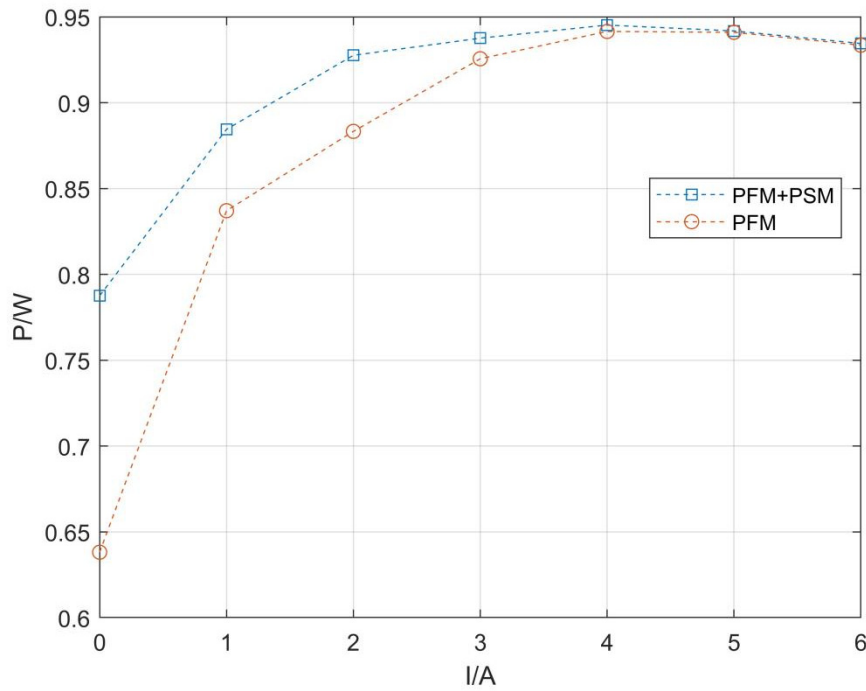


Figure 9. PFM modulation and PSM+PFM modulation light load efficiency curve

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