An Optimized Control for LLC Resonant Converter with Wide Load Range

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Abstract: This paper presents an optimized control which makes LLC resonant converters operate with a wider load range and provides good closed-loop performance. The proposed control employs two paralleled digital compensations to guarantee the good closed-loop performance in a wide load range during the steady state, an optimized trajectory control will take over to change the gate-driving signals immediately at the load transients. Finally, the proposed control has been implemented and tested on a 150W 200kHz 400V/24V LLC resonant converter and the result validates the proposed method.

1. Introduction
LLC resonant converter has been widely used in consumer or industrial fields and it is an excellent candidate for front-end DC/DC applications because of its high efficiency and hold-up capability [1].

However, compared with PWM converter, it is well known that it is difficult to analysis and control the LLC resonant converters because that the complex operation modes existing in the resonant tank. Also, the average modeling method isn’t a good method to predict the dynamic performance of the LLC because of the relationship between the natural frequency and the switching frequency. Thus, many methods and strategies have been proposed to build the model of the LLC and control the LLC. The extended describing function (EDF) [2-6] provides an accurate small signal model of the resonant converters and the state-trajectory [7-9] can intuitively describe the resonant tank dynamic behavior.

The traditional control of LLC resonant converter is voltage mode control with only one-way linear compensation, this means the load range of LLC is limited because of the limited bandwidth and the performance of load transients isn’t ideal because of the fast dynamic characteristics of the resonant tank. Many methods have been proposed to solve this problem, like current mode control [10], average current mode control [11], bang-bang charge control [12], charge current control [13] and fuzzy control [14]. Current mode control and average current mode control are too complex to sense the resonant current, also, these two methods are analog methods, so some non-linear control algorithms can’t be applied. Bang-Bang charge control is also an analog methods, this method proposes a good closed performance and a simple current detection circuit compare to current mode control, but this method can’t ensure the same duty circle for two switching tubes in primary side. Charge current control is an improved method for bang-bang charge control, but this method is lack of the experiment results. Fuzzy control is an advanced PID control, this method is very simple but the performance of the closed loop isn’t ideal.

This paper proposes an optimized control for LLC resonant converters which compares two paralleled digital control in steady state with the optimized trajectory control in load transients. The
compared two paralleled digital PID control are designed to cover the wider load range. By forcing the state variables to track the desired trajectory, the optimized trajectory control can ensure the time required to reach the new steady state is minimal and overshoot is avoid at load transients compared with traditional PID control.

First, the operation principle of the proposed optimized control will be illustrated. Second, The design of the control in steady state and the optimized trajectory control in load transients will be introduced. Finally, the co-simulation of the proposed control with saber and matlab will be given and experiment results are demonstrated on a 150W 200kHz 400V/24V LLC converter.

2. Operation Principle Of the Proposed Optimized Control

2.1. The Proposed System Structure Drawing

Figure 1 shows the system structure drawing of the proposed control including the control parts, the control parts include two paralleled digital control to insure a good closed-loop performance in a wide load range.

![System Structure Drawing](image)

**Figure 1.** The system structure drawing of proposed control

2.2. The Operation Principle Of The Proposed Control

The flow chart of the proposed control is showed in Figure 2. At first, the system starts work and the output voltage and the load current can be sampled by the digital control, then the control system will judge the sampled load current, if the load current located in the area where the PID1 module can regulate, the PID1 will work, otherwise, the PID2 module will work. At the load transients, the current optimized algorithm which based on the trajectory control will take over to give a $\Delta T$ that compare with the period that gave by PID modules. At the steady states, the system only be controlled by PID modules, however, the combination with the PID modules control and the current optimized algorithm will work at the load transients.
3. The design of the Proposed Control

3.1. The Design of The PID Modules

Figure 3(a) shows the circuit of the resonant converter, Figure 3(b) shows the equivalent circuit of the LLC resonant converter. In the equivalent circuit, \( i_r, i_m, V_{cr}, V_{co} \) are static volume, \( V_{AB} \) is the system input and \( V_o \) is the system output.

Based on the equivalent circuit, the equations of the \( V_{AB} \) can be get

\[
v_{AB} = L_r \frac{d i_r}{dt} + i_r r_s + v_{cr} + n \cdot sgn(i_p) v_o
\]

Based on the extended describing function, the nonlinear volume can be replaced with equations as

\[
v_{ab} = f_1(d, V_o) \sin \omega t + n \cdot sgn(i_p) v_o + f_2(i_p, i_{Ri}, V_o) \sin \omega t + f_3(i_p, i_{Ri}, V_o) \cos \omega t
\]

\[
i_R = f_4(i_p, i_{pc})
\]

Utilize the state equations based on the EDF, the transfer function of LLC converter can be get, in this paper, the examples as:

\[
v_{in} = 400V, v_o = 24V, L_o = 470.87uH, C = 8.07nH, C_o = 220uF, f_s = 200kHz, r_e = 15m\Omega, r_e = 15m\Omega, R_L = 4\Omega
\]

The transfer function can be expressed as:

\[
\text{Figure 2. The flow chart of the proposed control}
\]
\[
F = \frac{-693722.1866(x - 1.379e011)(x - 8.629e005)(x + 3.03e005)(x^2 + 8.629e005x + 2.452e012)}{(x + 5.283e006)(x^2 + 1226x + 2.335e009)(x^2 + 1.459e005x + 1.163e012)(x^2 + 3.56e005x + 4.033e012)}
\]

Based on the transfer function, the bode chart can be drawn and the compensation can be design to control the steady state.

3.2. The current optimized algorithm based on trajectory control

The current optimized algorithm at the load transient is based on trajectory control and the trajectory control is proposed based on the graphical state-plane analysis.

Figure 4(a) shows the trajectories of the different loads (from light load to heavy load), every circle represents a steady state at a constant load, the heavier the load is, the larger the circle radius will be, when the load steps, the optimized trajectory control will be applied by changing the pulse widths of the driving signals to reduce the frequency to force the state variables to hit the new steady state. By sensing the current of the output and suppose the resonant current at the load step is constant, the relationship between the output current and the difference between the cycles (t1-t2) can be estimated.

Figure 4(b) shows the resonant voltage and resonant current in resonant tank and exciting current in time-domain, supposing the current is constant when exciting current reach the resonant current, the resonant voltage at t1 can be estimated is (4), and resonant voltage at t2 can be estimated is (5), V_{cr} is the resonant voltage and V_{in} is the input voltage.

At last the relationship between the load current and difference between the cycles can be estimated is (6), though the geometric relationships in the state trajectory figure of the resonant tank, the geometric relationship is shown in figure 5.

\[
I_{t_1} - I_{t_2} = \frac{nV_o T}{L_m} \quad (3)
\]

\[
v_{cr} (t_1) = \frac{\pi I_{t_1} Z_0}{2n} + 0.5V_{in} \quad (4)
\]

\[
v_{cr} (t_2) = \frac{\pi (I_{t_1} + I_{t_2}) Z_0}{4n} + 0.5V_{in} \quad (5)
\]

\[
t_2 - t_1 = \frac{L_m (I_{t_2} - I_{t_1})}{nV_{in}} \quad (6)
\]

**Figure 4.(a)** The trajectories of the different loads  **Figure 4.(b)** The strategy of the sampling
The radius $r$ of the steady state at $t_1$ is given by $V_{cr}(t_1)$, $V_{cr}(t_2)$, $I_{cr}(t_1)$, and $V_{cr}(t_2)$.

**Figure 5.** The geometric relationships in the state trajectory figure of the resonant tank, $r = \frac{\sqrt{2}I_{RMS}Z_0}{V_{in}}$

and $I_{RMS}$ is the effective value of the resonant current and using the pythagorean theorem, the equation can be estimated is (5)

### 4. The Simulation and Experimental Results

The co-simulation of the proposed control with saber and matlab is implemented and the simulation is verified on a 400V/24V LLC converter. The comparison of the simulation results of the load step-down(8A-2A) between the traditional voltage control mode and combination control are shown in Figure 6(a) and Figure 6(b). The results of the simulation proved that the load extended from 1.67A-13A to 0.5A-13A. The experimental results of the load step-down(8A-2A) on a 400V/12V is shown in Figure 7.

**Figure 6.(a) Traditional voltage mode**

**Figure 6.(b) The proposed control**

**Figure 7.** Experimental result(8A-2A)

### 5. Discussion And Conclusion
In this paper, the optimized digital control of LLC converter is investigated to extend the load range and improve the performance of the load transients. The co-simulation and the experiment verify the results of the co-simulation. The most advantage of this digital control is that more advanced algorithm can be applied and the more accurate control can be carried out. But there are some problems in this control, when the resonant frequency increases, this control requires high performance controller and it is difficult to catch the point of the load step and to get more accurate \( t_2 - t_1 \), the more accurate calculation should be studied.

References
[1] B. Yang, Topology investigation for front end DC-DC power conversion for distributed power system, PhD dissertation in Virginia Tech, 2003.
[2] R.J. King and T.A. Stuart, Small-signal model of the series resonant converter, IEEE Trans. on Aerosp. Electron. Syst., vol. AES-21, Issue 3, pp. 144-149, 1985.
[3] B. Yang and F.C. Lee, Small-signal analysis for LLC resonant converter, in CPES Seminar, 2003, S7.3, pp. 101-109, 2003.
[4] E.X. Yang, F.C. Lee, and M.M. Jovanovic, Small-signal modeling of LLC resonant converter, in Proc. IEEE-PESC’92, pp. 167-178, 1992.
[5] Shuilin Tian, Fred C. Lee and Qiang Li, Equivalent circuit modeling of LLC resonant converter, Power Electronics, IEEE Transactions on, Vol. 31, NO.5, pp. 1251-1259, 2016.
[6] B. Cheng, F. Musavi and W. Dunford, Novel small signal modeling and control of an LLC resonant converter, in Proc. IEEE APEC, 2014, pp. 2828-2834.
[7] C.H. Lee, and K. Siri, Analysis and design of series resonant converter by state plane diagram, IEEE Trans. on Aerosp. and Electron. Syst. Vol. AES-22, Issue 6, pp. 757-763, Nov. 1986.
[8] M. Kim, and J. Kim, Modeling and optimal trajectory control of the series resonant converter pulse-width modulated or current-controlled for low switching loss, in Proc. IEEE-APEC’93, pp. 752-758, 1993.
[9] W. Feng, Y.C. Lee and P. Mattavell, Simplified optimal trajectory control (SOTC) for LLC resonant converters, Power Electronics, IEEE Transactions on, Vol. 28, NO. 5, pp. 2415-2416, May 2013.
[10] J. Jang, M. Joung, S. Choi, Y. Choi, and B. Choi, Current mode control for LLC series resonant dc-to-dc converters, in Proc. Int. Power ELEcTron. Conf. and Expo. (APEC’11), 2011, pp. 21-17.
[11] J. Jang, P.S. Kumar, D. Kim, and B. Choi, Average current-mode control for LLC series resonant dc-to-dc converters, in Proc. Int. Power Electron. And Motion Control Conf. (IPEC’12), 2014, pp. 923-930.
[12] Z. Hu, L. Wang, Y.-F. Liu, and P. C. Sen, Bang-Bang charge control for LLC resonant converters, in Proc. Power Electronics, Congr. and Expo. (ECCE’13), Denver, CO, 2014.
[13] Hangseok Choi, Charge current control for LLC resonant converter, IEEE 2015.
[14] Concettina Buccella, Carlo Cecati, Hamed Latafat and Kaveh Razi, Digital control of a half-bridge LLC resonant converter, in EPE-PEMC 2012 ECCE Europe, Novi Sad, Serbia.