Circuit Technology of LLC Current Resonant Power Supply

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ABSTRACT

For relatively large capacity power supplies, such as ones for large screen TVs and server devices, LLC current resonant power supplies are commonly used to meet the requirements for high efficiency, reduced size and lower noise. An LLC current resonant power supply uses leakage inductance of a transformer for resonance and the voltage gain varies along with the switching frequency, which makes the design of a transformer more difficult than other control methods. Fuji Electric is working on the development and mass production of control ICs of LLC current resonant power supplies and provides technical support for customers in the area of power supply development. This paper describes the principle of operation of an LLC current resonant power supply and the design method and characteristics of transformers.

1. Introduction

As power supplies for electrical and electronic equipment, switching power supplies, which have realized compact sizes, low prices and high efficiency have come to be commonly used in recent years, thanks to the evolution of ICs and other electronic components. With relatively large-capacity power supplies, in particular, demand is growing for higher efficiency, lower noise and reduced size along with the growth in screen size of flat-screen TVs and the capacity increase of server equipment led by evolution of telecommunications.

In this field of switching power supplies, Fuji Electric has commercialized a control IC for LLC current resonant power supplies, which can configure compact and thin power supplies ranging from the 100 W class to relatively large capacity 500 W class, and offer high efficiency and low noise. This control IC features the integration of a function for preventing shoot-through current caused by short-circuiting of the upper arm metal oxidesemiconductor field-effect transistor (MOSFET) and lower arm MOSFET, which has become an issue with the LLC current resonant converter, and operation in the low standby power mode under light load such as during equipment standby. This makes it possible to configure a power supply that provides higher safety and does not require a power supply exclusivley for standby, which was conventionally necessary for lowering the standby power.1

At the same time, in order to facilitate smooth power supply development when customers adopt Fuji Electric’s control ICs for power supplies, we provide demo boards, application materials and proposal of constants for IC peripheral circuits. In addition, we provide support with regard to design of transformers, which are especially difficult to design and crucial to power supply operation.

This paper describes the operating principle of an LLC current resonant power supply, transformer design method and example and typical characteristics of a prototype power supply using the transformer.

2. LLC Current Resonant Converter

Figure 1 shows the circuit diagram of an LLC current resonant converter.

This circuit is composed of a half-bridge circuit that connects 2 MOSFETs (Q1 and Q2) in series, a capacitor for resonance (C1), a transformer (T), output rectifier diodes (D1 and D2) and an output electrolyte capacitor (C2). Np is the number of turns of the primary winding of the transformer and NS is the number of turns of the secondary winding.

A transformer used in an LLC current resonant converter has a small coupling coefficient to provide large leakage inductance, which is used as the inductor for resonance. An equivalent circuit diagram indicating the leakage inductance is shown in Fig. 2. Lr1 and

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the operation controls the resonance current. Figure 4 shows the current pathways of the respective states.
(a) State A: Q1 is on and a current in the positive direction $I_{Q1}$ flows through Q1.
(b) State B: Q1 is turned off with $I_{Q1}$ in the positive direction, which, in the period immediately after the turn-off, causes current in the negative direction to flow to Q2 through the body diode of Q2 and the resonance current $I_{r}$ changes continuously. While the current flows through the diode, Q2 is then turned on.
(c) State C: When $I_{r}$ turns from the positive to the negative direction, a current in the positive direction $I_{Q2}$ flows through Q2.
(d) State D: Q2 is turned off with $I_{Q2}$ in the positive direction, which, in the period immediately after the turn-off, causes current in the negative direction to flow to Q1 through the body diode of Q1 and the resonance current $I_{r}$ changes continuously. While the current flows through the diode, Q1 is then turned on.
In State B, zero voltage switching takes place, in which the body diode of Q2 turns on first and, with the voltage of Q2 almost 0, Q2 is turned on. In State D, the same applies to Q1.

4. Operation Modes of LLC Current Resonant Converter

The LLC current resonant converter uses a circuit system that controls the output voltage by frequency modulation and, to determine the I/O characteristics, an equivalent circuit as shown in Fig. 5 is generally used.

The output voltage is shown by the voltage $V_{po}$, converted to the primary side. The AC equivalent resistance $R_{ac}$ is represented by formula (1).

$$R_{ac} = \frac{8}{\pi} n^2 \frac{V_o}{I_o} = \frac{8n^2}{\pi^2} R_o \quad \text{.......................... (1)}$$

$R_{ac}$: AC equivalent resistance (Ω)
$n$: Transformer turns ratio
$V_o$: Output voltage (V)
$I_o$: Output current (A)
$R_o$: Load resistance (Ω)

where $n$ is represented by formula (2).
In this equivalent circuit, the input-to-output voltage gain is as shown by formula (3).

\[
\frac{V_{po}}{V_s} = \frac{1 + \frac{L_m}{L} \left(1 - \frac{\omega^2}{\omega_0^2}\right) + jQ \left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)}{1/n}
\]

where \(\omega\), \(\omega_0\) and \(Q\) are shown by formulae (4) to (6).

\[
\omega = 2\pi f_s
\]

\[
\omega_0 = \frac{1}{\sqrt{L_rC_r}}
\]

\[
Q = \frac{\sqrt{L_m}}{V_C R_{ac}}
\]

\(V_{po}\): Output voltage converted to primary side (V)

\(V_s\): Equivalent input voltage (V)

\(L_r\): Leakage inductance (H)

\(C_r\): Capacitance of resonant capacitor (F)

\(Q\): Quality factor

\(L_m\): Magnetizing inductance (H)

\(R_{ac}\): AC equivalent resistance (Ω)

The LLC current resonant converter shown in Fig. 1 is a half-bridge converter, the input voltage in the equivalent circuit is therefore equal to half the input voltage.

\[
V_s = \frac{V_{in}}{2}
\]

\(V_{in}\): Input voltage (V)

\(V_s\): Equivalent input voltage (V)

Formulae (1) to (3) have been used to find the input-to-output voltage gain for switching frequency \(f_s\) (see Fig. 6). With the LLC current resonant converter, the operation mode changes at the maximum value of the input-to-output voltage gain. Of the regions corresponding to the different modes, the region in which the frequency is lower than the maximum voltage gain frequency is referred to as the capacitive operation region. Operation in this region causes a shoot-through between the upper and lower arm. If this occurs, the MOSFET may be broken. Therefore, in order to avoid this condition, the converter is generally used in the frequency region in which the frequency is higher than the maximum voltage gain frequency. In addition, the region in which \(f_s\) is higher than the resonance frequency \((f_o = \omega_0/2\pi)\) is generally not used for reasons including that the output voltage change is too small for the change of \(f_s\) to provide high controllability. For that reason, it is used in the region for the voltage boost mode, in which the input-to-output gain is larger than 1.

5. Transformer Design of LLC Current Resonant Converter

This chapter describes the procedure for designing a transformer that actually uses the LLC current resonant control IC, followed by the result of design of the transformer with specific specifications and verification with an actual power supply.

5.1 Design procedure

As described in Chapter 4, the LLC current resonant converter operates in the voltage boost mode and the input-to-output voltage gain should be determined so that it operates in the voltage boost mode even at the maximum input voltage. First, determine the number of turns of the transformer secondary winding, followed by the number of turns of the primary winding. Resonance frequency \(f_o\) is the maximum switching frequency, and it should be determined in advance in a range that does not exceed the maximum frequency of the IC.

(1) Determine the number of turns of the transformer secondary winding \(N_s\) by using formula (8).

\[
N_s = \frac{(V_o + V_F) T_{on}}{2A_s B_m}
\]

\(V_o\): Output voltage (V)

\(V_F\): Forward voltage drop of rectifier diode (V)
5.2 Design example

The following shows an example of transformer design. Figure 7 is the transformer peripheral circuit actually designed.

- Input voltage $V_{in}$: 390 V (350 to 400 V)
- Output voltage $V_o$: 12 V
- Output current $I_o$: 12 A ($R_o=1 \Omega$)
- Transformer used: EE4717
  - $A_e=90 \text{ mm}^2$
  - $l_e=70 \text{ mm}$
  - $B_m=0.20 \text{ T}$

Resonance frequency: Around 125 kHz

- Minimum switching frequency: 85 kHz ($T_{ON}=5.88 \mu s$)
- Forward voltage drop of rectifier diode $V_F$: 0.6 V

(1) Transformer secondary winding $N_s$ (from formula (8))

$$N_s = \left( \frac{V_o + V_F}{V_{in}} \right) \frac{T_{ON}}{2A_e B_m} = \left( 12 + 0.6 \right) \times 5.88 \times 2 \times 90 \times 0.20 \approx 2.1$$

Accordingly, set $N_s$ to the minimum of 3 turns.

(2) Transformer turns ratio $n$ (from formula (9))

$$n = \frac{N_p}{N_s} \geq \frac{V_o}{(V_{in} + V_F)} = \frac{200}{12 + 0.6} \approx 15.9$$

(3) Number of turns of transformer primary winding $N_p$ (from formula (10))

$$N_p = n N_s = 15.9 \times 3 = 47.7$$

Accordingly, set $N_p$ to the minimum of 48 turns.

(4) Calculation of transformer leakage inductance $L_r$

With the EE4717 transformer, the leakage inductance per turn is 38 nH and the leakage inductance with the number of turns of the primary winding $N_p=48$ is 87.6 μH [$=48^2 \times 38 \text{ (nH)}$].

$$l_{tg} = \frac{\mu_0 A_e N_s^2}{L_m} = \frac{l_{tg}}{\mu_c} \frac{A_e}{\mu_0}$$

$T_{ON}$: Maximum on time of switching element (s) (Equal to 1/2 of minimum switching period)

$A_e$: Effective cross-sectional area of transformer core (m²)

$B_m$: Magnetic flux density of core (T) ($B_m$ shall be a value that does not cause core saturation)

$N_p$: Number of turns of transformer primary winding

$L_m$: Magnetizing inductance (H)

$l_e$: Effective magnetic path length of core (m)

$\mu_c$: Amplitude permeability of core (=3,000 H/m)
5.3 Characteristics of prototyped transformer

Operation waveforms with a power supply using the prototyped transformer are shown in Fig. 8. The switching frequency at the rating is 110 kHz, which is almost equal to the value targeted in the design.

In addition, the conversion efficiency of the power supply using the prototyped transformer has proved to be high at 93 to 94% (see Fig. 9).

6. Postscript

This paper has described an example of transformer design and the typical characteristics of a power supply that uses the prototype transformer. The aim is to allow customers to smoothly adopt and use Fuji Electric’s LLC current resonant control ICs.

In the future, we intend to continue to develop in a timely manner products that meet the demands of the market and strive to support customers with even smoother power supply development.

References

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