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 oxide semiconductor 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 exclusively 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 regards 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 (Q_1 and Q_2) in series, a capacitor for resonance (C_r), a transformer (T), output rectifier diodes (D_1 and D_2) and an output electrolyte capacitor (C_o). N_p is the number of turns of the primary winding of the transformer and N_S 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. L_{r1} and

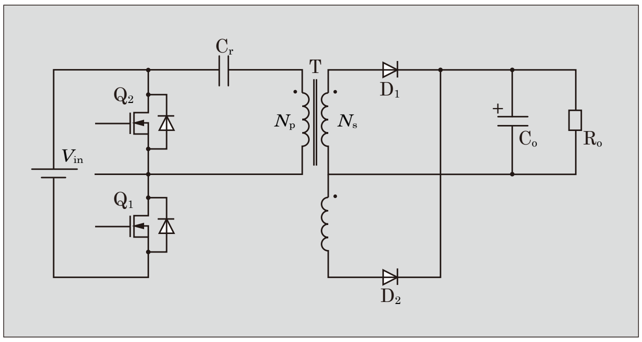

Fig.1 LLC current resonant converter circuit

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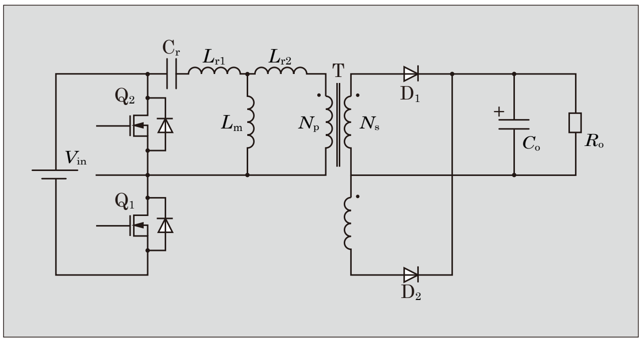

Fig.2 Equivalent circuit diagram indicating leakage inductance

L_{r2} represent the leakage inductance and Lm the magnetizing inductance.

3. Basic Operation of LLC Current Resonant Converter

Figure 3 shows operation waveforms of the LLC current resonant converter. The basic operation can be divided into 4 states from A to D and repetition of

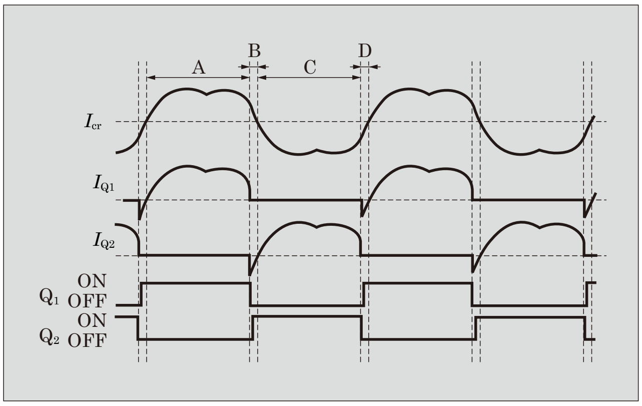

Fig.3 Operation waveforms of LLC current resonant converter

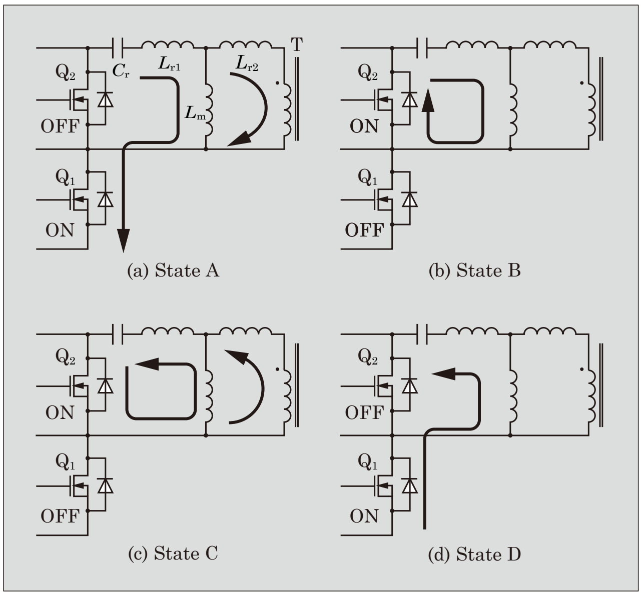

Fig.4 Current pathways

the operation controls the resonance current. Figure 4 shows the current pathways of the respective states.

(a) State A: Q_1 is on and a current in the positive direction I_{Q1} flows through Q_1.

(b) State B: Q_1 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 Q_2 through the body diode of Q_2 and the resonance current I_{cr} changes continuously. While the current flows through the diode, Q_2 is then turned on.

(c) State C: When I_{cr} turns from the positive to the negative direction, a current in the positive direction I_{Q2} flows through Q_2.

(d) State D: Q_2 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 Q_1 through the body diode of Q_1 and the resonance current I_{cr} changes continuously. While the current flows through the diode, Q_1 is then turned on.

In State B, zero voltage switching takes place, in which the body diode of Q_2 turns on first and, with the voltage of Q_2 almost 0, Q_2 is turned on. In State D, the same applies to Q_1.

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).

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

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).

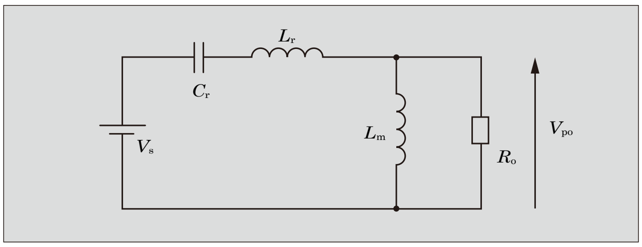

Fig.5 Equivalent circuit of LLC current resonant converter

$$n = \frac{N_p}{N_s} \quad (2)$$

N_p: Number of turns of transformer primary winding

N_s: Number of turns of transformer secondary winding

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

$$\frac{V_{po}}{V_s} = \frac{1}{1+\frac{L_r}{L_m}\left(1-\frac{\omega_0^2}{\omega^2}\right)+jQ\left(\frac{\omega}{\omega_0}-\frac{\omega_0}{\omega}\right)} \quad (3)$$

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

V_s: Equivalent input voltage (V)

L_r: Leakage inductance (H)

L_m: Magnetizing inductance (H)

ω, ω_0: Angular frequency (rad/s)

where ω, ω_0 and Q are shown by formulae(4) to (6).

$$\omega = 2\pi f_s \quad (4)$$

ω: Angular frequency (rad/s)

f_s : Switching frequency (Hz)

$$\omega_0 = \frac{1}{\sqrt{L_r C_r}} \quad (5)$$

ω_0 : Angular frequency (rad/s)

L_r : Leakage inductance (H)

C_r : Capacitance of resonant capacitor (F)

$$Q = \sqrt{\frac{L_r}{C_r}}\frac{1}{R_{ac}} \quad (6)$$

L_r : Leakage inductance (H)

C_r : Capacitance of resonant capacitor (F)

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.

$$V_s = \frac{V_{in}}{2} \quad (7)$$

V_s : Equivalent input voltage (V)

V_{in} : 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=$w_o/2\pi$) 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.

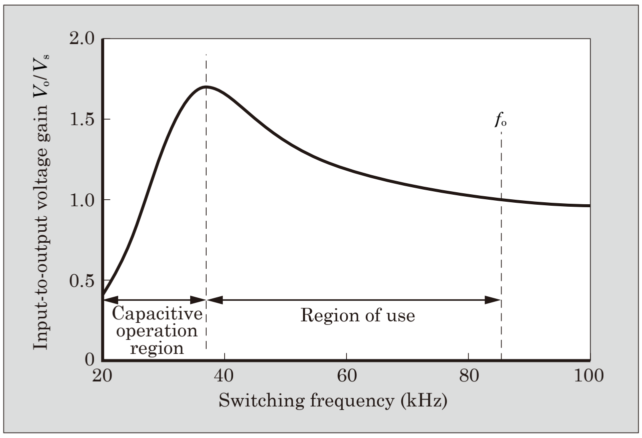

Fig.6 Input-to-output voltage gain against switching frequency

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).

$$N_s = \frac{(V_o + V_F)T_{ON}}{2A_e B_m} \quad (8)$$

N_s : Number of turns of secondary winding

V_o : Output voltage (V)

V_F : Forward voltage drop of rectifier diode (V)

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 (m^2)
B_m : Magnetic flux density of core (T) (B_m shall be a value that does not cause core saturation)

(2) To ensure operation in the voltage boost mode even at the maximum input voltage, determine the transformer primary-to-secondary turns ratio n by using formula (9). Note that V_s is the value at the maximum input voltage.

$$n=\frac{N_p}{N_s}\geq\frac{V_s}{(V_o+V_F)} \quad \cdots\cdots (9)$$

n : Turns ratio
N_p : Number of turns of transformer primary winding
N_s : Number of turns of transformer secondary winding
V_s : Equivalent input voltage (V)
V_o : Output voltage (V)
V_F : Forward voltage drop of rectifier diode (V)

(3) Determine the number of turns of the transformer primary winding by using formula (10).

$$N_p=nN_s \quad \cdots\cdots (10)$$

N_p : Number of turns of transformer primary winding
n : Turns ratio
N_s : Number of turns of transformer secondary winding

(4) Find the leakage inductance L_r.

In this converter, the leakage inductance of the transformer is used as the inductor for resonance. The number of turns of the primary winding N_p determines L_r measured from the transformer primary winding.

(5) Determine the capacitance of the resonance capacitor C_r.

From the resonance frequency f_o and L_r, calculate C_r by using formula (5).

(6) Determine the magnetizing inductance L_m.

Find the input-to-output voltage gain in which the rated value is obtained at the output voltage when the input voltage is the lowest, and determine L_m. The switching frequency here is at the minimum and determined in view of the voltage gain and core gap. The core gap of the transformer l_g is calculated by using formula (11).

$$l_g=\frac{\mu_0 A_e N_p^{\,2}}{L_m}-\frac{l_e}{\mu_c} \quad \cdots\cdots (11)$$

l_g : Transformer core gap (m)
μ_0 : Space permeability (= $4\pi\times10^{-7}$ H/m)
A_e : Effective cross-sectional area of transformer core (m^2)
N_p : Number of turns of transformer primary winding
L_m : Magnetizing inductance (H)
l_e : Effective magnetic path length of core (m)
μ_c : Amplitude permeability of core (=3,000 H/m)

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 Ω)
○ Transformer used EE4717
A_e=90 mm^2
l_e=70 mm
B_m=0.20 T
○ Resonance frequency Around 125 kHz
○ Minimum switching frequency 85 kHz (T_{ON}= 5.88 μs)
○ Forward voltage drop of rectifier diode V_F 0.6 V

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

$$N_s=\frac{(V_o+V_F)T_{ON}}{2A_eB_m}=\frac{(12+0.6)\times5.88}{2\times90\times0.20}\fallingdotseq 2.1$$

Accordingly, set N_s to the minimum of 3 turns.

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

$$n=\frac{N_p}{N_s}\geq\frac{V_s}{(V_o+V_F)}=\frac{200}{(12+0.6)}\fallingdotseq 15.9$$

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

$$N_p=nN_s=15.9\times3=47.7$$

Accordingly, set N_p to the minimum of 48 turns.
From (1) to (3), the transformer turns ratio n=16.

(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 87.6μH [=48^2 × 38 (nH)].

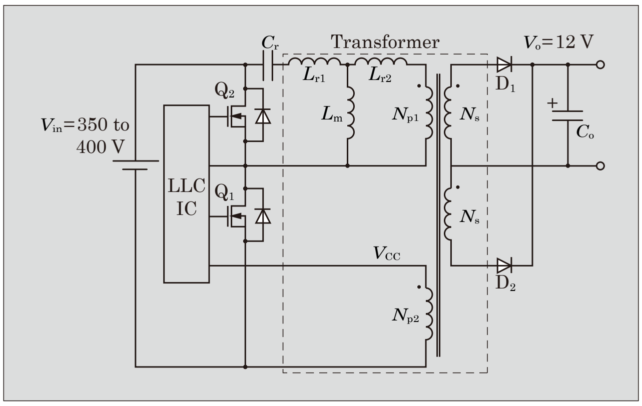

Fig.7 Diagram of peripheral circuit of designed transformer

(5) Determination of resonance capacitor C_r

Substituting f_o=125 kHz and L_r=87.6 µH in formula (5) provides C_r of 0.019 µF, so the capacitor of 0.022 µF is selected.

(6) Determination of magnetizing inductance L_m

Find L_m in which the rated value is obtained at the output voltage when the input voltage is at the lowest. The minimum value of the input voltage is 350 V and the input-to-output voltage gain here should be determined from the number of turns of the transformer.

$$\frac{V_{po}}{V_s} = \frac{V_o + V_F}{\frac{N_s}{N_p}\frac{V_{in}}{2}} = \frac{12+0.6}{\frac{3}{48}\times\frac{350}{2}} \fallingdotseq 1.2$$

Accordingly, using formula (3), find L_m that provides an input-to-output voltage gain of 1.2 or larger when the switching frequency is at the lowest (here, f_s=85 kHz).

As a result, L_m should be 490 µH or lower. Then, L_m=450 µH is selected and the transformer core gap l_g is determined by using formula (11), which results in approximately 0.6 mm.

$$l_g = \frac{\mu_0 A_e N_p^2}{L_m} - \frac{l_e}{\mu_c}$$
$$= \frac{4\pi\times10^{-7}\times90\times10^{-6}\times48^2}{450\times10^{-6}} - \frac{70\times10^{-3}}{3{,}000} \fallingdotseq 0.6\times10^{-3}$$

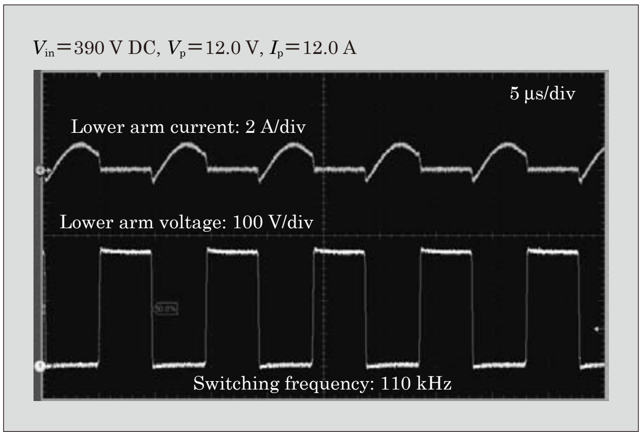

Fig.8 Operation waveforms

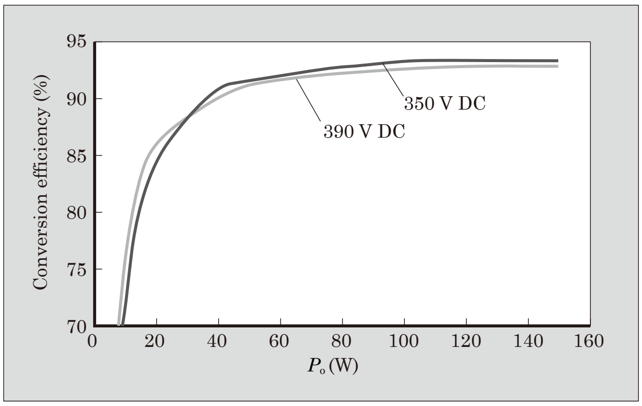

Fig.9 Conversion efficiency characteristics of prototyped transformer

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

(1) Yamadaya, M. et al. 2nd Generation LLC Current Resonant Control IC, "FA6 A00N Series". FUJI ELECTRIC REVIEW. 2013, vol.59, no.4, p.245-250.