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Design Consideration of Low-Profile LLC Resonant Converter for Reducing Temperature of the Transformer

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Abstract: This paper presents the design consideration of a low-profile LLC resonant converter using two flat transformers. The trend toward high power density, high efficiency, and low profile in power supplies has exposed a number of limitations in the use of magnetic component structures. The LLC resonant converter can be operated at a high switching frequency with high efficiency because the switching loss is reduced by soft-switching. However, flat transformer loss causes problems at a high switching frequency. As a result, temperature of flat transformers becomes high. Therefore, it is necessary to reduce the transformer temperature by analyzing the loss. In this proposed converter, flat transformer is integrated into advanced power conversion application systems. Low-profile power module of profile of about 14mm is achieved. Temperature inside of transformer repressed to 66.5 ℃ and an overall efficiency of about 96.5% was obtained.

Keywords: LLC resonant converter, soft switching, Thermal design, flat transformer

1. Introduction

The trend of high power density DC-DC converters leads us to develop converters capable of operating at high switching frequencies with high efficiency. The Conventional PWM technique processes power by controlling the duty cycle and interrupting the power flow. All the switching devices are hard-switched with abrupt changes of currents and voltages, which results in severe switching losses and noises. To achieve both high efficiency and high density, the converter needs to realize the soft switching operation.1) Among the various soft switching dc-dc converters operating at a high frequency, the LLC resonant converter is widely used because of following several advantages.

The LLC resonant converter has higher conversion efficiency at an overall input voltage range. The converter can realize the Zero-Voltage Switching (ZVS) turn-on of main switches and the Zero Current Switching (ZCS) turn-off of the rectification diodes, so that the converter can work at a higher switching frequency and the power density may increase. The ZCS operation can also be realized for the rectification diodes of the converter so that its recovery problem is solved. Another advantage of the LLC resonant converter is that all essential parasitic elements, including junction capacitances of all semi-conductor devices and the leakage inductance of the transformer are utilized to achieve soft-switching.2–6) Therefore, the power density of the converter will be increased. Its circuit schematic is shown in **Fig. 1**.

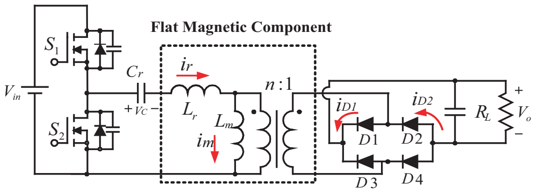

Fig. 1 LLC Resonant Converter.

The LLC resonant converter can operate at a high frequency with high efficiency because of soft switching operations. However, by operating the converter using a flat transformer at a high frequency, the transformer generates heat because its losses increase in proportion to the switching frequency and is inversely proportional to a section area of the magnetic components.

This paper presents design steps for a high switching frequency LLC resonant converter incorporated with two flat integrated magnetic components. Operations, analysis, and design considerations of flat transformers for reduction temperature are presented in this paper. Finally, analysis in winding and core losses of transformers and experimental results are shown to confirm the validity of the proposed converter.

2. Analysis of Circuit Topology

2.1 AC Analysis of Resonant network

The operating characteristics of resonant network can be

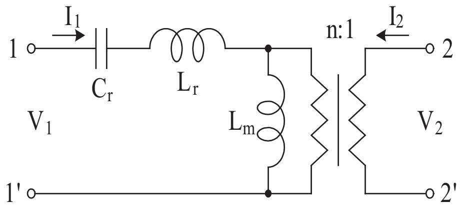

Fig. 2 AC equivalent model of LLC resonant converter.

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evaluated by AC analysis based on the Fundamental Element Simplification (FES) method. And it is analyzed by using the f-matrix. The ac equivalent model of the bi-directional LLC resonant converter is shown in **Fig. 2**.

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} 1 & sL_r + \frac{1}{sC_r} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{1}{sL_m} & 1 \end{bmatrix} \begin{bmatrix} n & 0 \\ 0 & \frac{1}{n} \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \quad (1)$$

From eq. 1 the operating characteristics of forward direction can be derived as following equations of 2 - 5.

$$R_{ac} = \frac{8}{\pi^2} R_L \quad (2)$$

$$Z_o = \frac{1}{n^2} \frac{sL_m(s^2L_rC_r + 1)}{s^2(L_m + L_r)C_r + 1} \quad (3)$$

$$Z_{in} = \frac{s^3L_mL_rC_r + s^2(L_m + L_r)C_rn^2R_{ac} + sL_m + n^2R_{ac}}{s^2L_mC_r + sn^2C_rR_{ac}} \quad (4)$$

$$M_F = \frac{s^2L_mC_rnR_{ac}}{s^3L_mL_rC_r + s^2(L_m + L_r)C_rn^2R_{ac} + sL_m + n^2R_{ac}} \quad (5)$$

Output impedance: Z_o, Input impedance: Z_{in} and Voltage conversion ratio: M_F

Figure 3 show the output impedance and input impedance characteristics of the LLC resonant converter using eq. 4 and 5. As shown in **Fig. 3** of output impedance, the two resonance peaks appear at fsr (series resonant peak) and fpr (parallel resonant peak). On the other hand, only one resonance peak appears in the input impedance. One of the chief advantages of series resonant converter is soft switching operation (ZVS turn-on of primary side switches and ZCS turn-off of secondary switches). In order to achieve the soft switching operation, the switching frequency range should be set optimal. For the ZCS operation of secondary side switch network, the switching frequency range fs is fs<fsr. Moreover, the switching frequency range of fs is fs>fzin (fzin : peak frequency of input impedance) for ZVS operation of primary side switch network. Hence, the switching frequency range for soft-switching operation (ZVS ZCS) is fzin<fs<fsr.

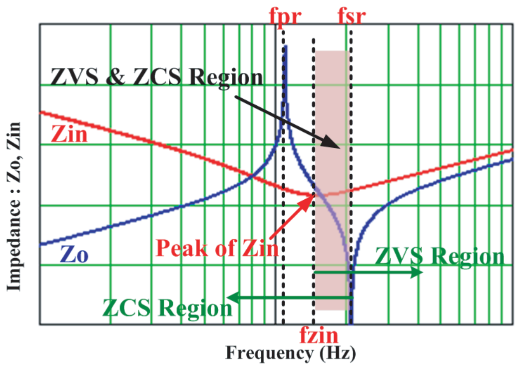


Fig. 3 Impedance characteristics.

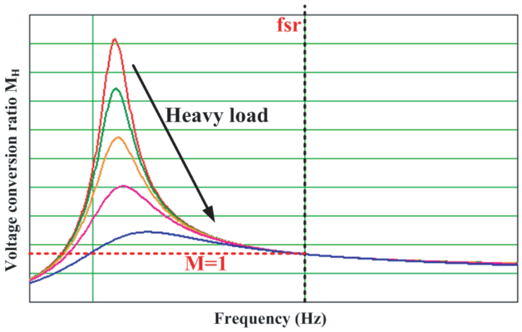


Fig. 4 Voltage conversion ratio.

Figure 4 shows the voltage conversion ratio. As shown in **Fig. 4**, the peak of conversion ratio is dumped at heavy load, and the peak frequency is sifted to high frequency side. The movable range of the peak frequency is fpr<fs<fsr. From these discussions, in the forward mode, the operating characteristics depend on load resistance largely. Moreover, the operating characteristics also depend on L_m, L_r, C_r.

2.2 Analysis of circuit operation

The key waveforms are shown in **Fig. 5** where, i_r and i_{LM} are the current flowing through the resonant tank and the parallel inductor, respectively, i_{D1} and i_{D2} are the current flowing through the rectification diodes and V_c is the voltage across the resonant capacitor. In a half switching cycle, the operation of the LLC resonant converter can be divided into two modes. The equivalent circuit of the operation mode is shown in **Fig. 6**.

State 1

This state begins when the primary resonant current i_r flows through S_1. During this mode, the transformer voltage is clamped at the output voltage. The magnetic energy of L_m is linearly charged with the output voltage, so it does not participate in the resonant operation during this mode.

This state ends when i_r is the same as i_{LM}. The output current reaches zero.

State 2

At the end of state 2, the magnetizing and primary resonant currents are equal. The output current reaches zero.

During this period, since output is separated from the primary side, L_m participates in the resonant operation. The resonant current flows by a resonant tank of L_m in series with L_r resonant with C_r.

This state ends when S_1 is turned off.

For the next half switching cycle, the operation is same as analyzed above.

3. Design of the LLC Resonant Converter

3.1 Design of resonant network

First, we must know the operation conditions of the LLC resonant converter before designing the converter. Specifications of power supply in plasma display panel are as follows:

- Input voltage : 320V-400V
- Output voltage : 180V-200V
- Output current : 2.3A

In a LLC resonant converter, the ZVS turn-on for the main switch is very important to obtain high efficiency. To operate under the ZVS condition, MOSFETs parasitic capacitors should be discharged by the magnetizing current within the dead time. The boundary of magnetizing inductance can be obtained as:

$$L_m \leqq \frac{t_d V_o n}{4 f_s 2 V_{in} C_j} = \frac{T t_d}{16 C_j} \tag{6}$$

For 120kHz switching frequency and 400ns dead time, together with 276pF C_j, we can calculate the magnetizing inductance to be less than 370uH.

The switching frequency range is decided by the operation condition as follows:

$$0.45 \leqq G_{dc} \leqq 0.625$$

where, G_{dc} is the DC voltage conversion ratio of LLC resonant converter.

Therefore, we design a converter with the peak voltage gain of 0.65.

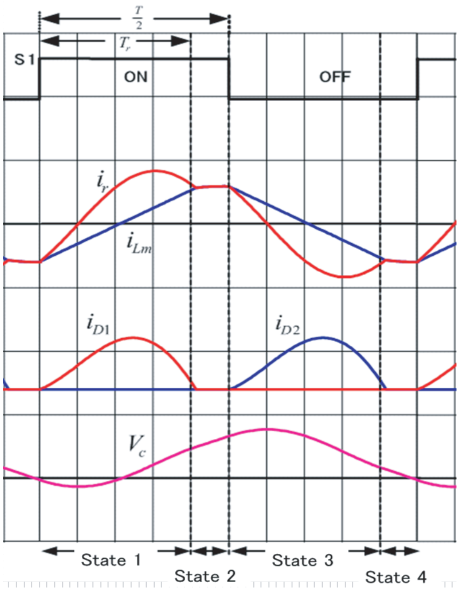
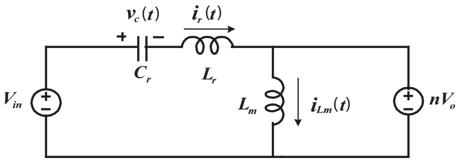
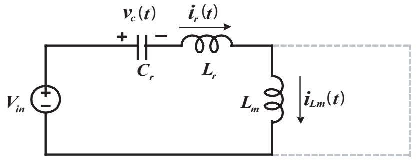


Fig. 5 Operation waveforms of the converter.



(a) State 1



(b) State 2

Fig. 6 Operating states of LLC resonant converter.

The value of peak gains can be obtained using simulation tool and equation (5) and depicted in **Fig. 7**, which shows how the gain varies with Q for different k values. The two parameters of k and Q are as follows.

- The ratio of magnetizing inductance to resonant inductance : $k = \frac{L_m}{L_r}$
- Quality factor : $Q = \sqrt{\frac{L_r}{L_m}} \cdot \frac{\pi^2}{8n^2 R_L}$

It appears that higher peak gain can be obtained by reducing k or increasing Q values. After designing the magnetizing inductance, k and Q combinations are decided to obtain a peak voltage gain of 0.65. From **Fig. 7**, to get the peak voltage gain of 0.65, the magnetizing inductance should be less than 300uH. However, if the magnetizing inductance is too small, large current flows through the main switches, so the main switch turn-off loss will increase because the main switches operate hard-switching turn-off. Therefore, the switching frequency range should be as small as possible, which requires a minimum k value.

3.2 Analysis of transformer loss

Core losses involve the magnetic properties of the core material, which exhibits power losses in the form of hysteresis and eddy currents within the core itself.

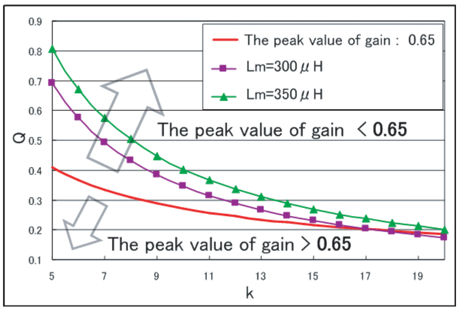


Fig. 7 Peak gain versus Q for different k values.

The core loss is calculated using the result of simulation. The best combination between the accuracy and simplicity seems to be the empirical Steinmetz equation in given below.[7,8)]

$$P_v = C_m \cdot f^{\alpha} \cdot B^{\beta} \tag{7}$$

where,

P_v : core loss per volume of the magnetic core.

f : switching frequency.

B : the maximum flux density.

C_m, α, β : empirical parameters related to the magnetic core.

In this paper, the core loss is calculated by the empirical Steinmetz equation. C_m, α, and β are decided by a datasheet of the magnetic core. Moreover, winding losses have to be considered for overall losses of transformers. Winding losses come from the resistance in the conductive material. This loss has both dc and ac components. The dc component is proportional to the length and inversely proportional to the cross-sectional area of the wire used. If the device is carrying a current with an ac component, there are also losses due to eddy currents and the proximity effects if multiple turns are used. The winding loss $P_{winding}$ is calculated from equation 8.

$$P_{winding} = I^2_{r\_rms} \cdot R_{pri\_ac} + I^2_{sec\_rms} \cdot R_{sec\_ac} \tag{8}$$

where, I_{r_rms} is the rms value of the resonant current, I_{sec_rms} is the rms value of the current through a transformer secondary side, and R_{pri_ac} and R_{sec_ac} are the ac resistance of transformer primary and secondary winding. R_{pri_ac} and R_{sec_ac} can be measured through an impedance analyzer.

3.3 Construction of transformers

By using one flat transformer in the LLC resonant converter, temperature of the transformer becomes too high because transformer loss increases in proportion to the switching frequency and is inversely proportional to a section area of the transformer. Therefore, to drop the temperature of the transformer, we built up the power module using two flat transformers.

For designing a converter using two transformers, it is important to connect to primary and secondary winding wires. The 4 patterns are considered by the connecting combination as shown in **Fig. 8**. In addition, the condition of two transformers is the same by dividing voltage and current evenly.

In case of high voltage application such as PDP TV, the core loss of the transformer is considerably higher than the wire loss of the transformer. Moreover, it increases in flux density at the central part of the core because the thickness of the central part of the core is lower than the other parts. This is the reason why the operating temperature of flat transformers generates heat. Therefore, the primary and secondary winding wires of two flat transformers should be connected in series. **Figure 9** shows the losses for a transformer in cases of using one and two transformers calculated using equations 7, 8.

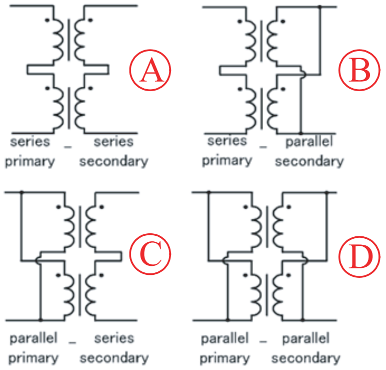


Fig. 8 The 4 connect patterns of two transformers.

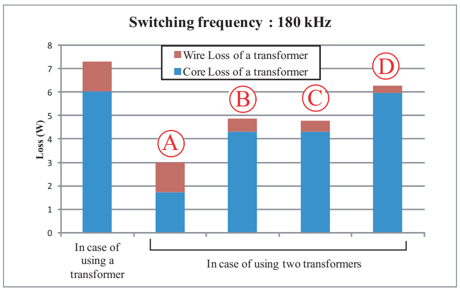


Fig. 9 Comparison between the losses for a transformer in cases of using one and two transformers.

Next, the winding loss and core loss depending on the number of the winding wire turns and switching frequency are estimated by using equations 7, 8 as shown in **Fig. 10**. As breakdown of overall losses of flat transformer, the core loss decrease considerably when the number of the winding wire turns is 25 turns, because the flux density of the core becomes small. And, the core loss decrease a little as the converter operates at higher frequency. However, the winding loss increases at higher switching frequency.

4. Experimental Results

In order to show validity of design consideration, an experimental prototype converter of the 440W half-bridge LLC resonant converter has been built and tested. Comparison between proposal and tradition prototypes are shown in **Fig. 11**. The low-profile power module of a thickness of about 14mm could be built up by using flat magnetic components and devices. The power density of the converter increases to 1.86W/cm^3.

The efficiency curve of the LLC resonant converter using one flat magnetic components is shown in **Fig. 12**. The average temperature inside the enclosure was maintained at 26 ℃. The temperature of the transformer rises up to 131 ℃.

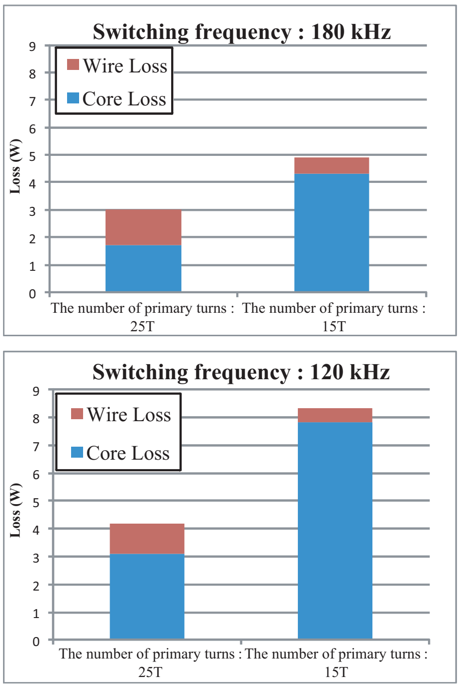
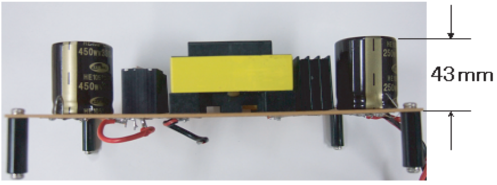


Fig. 10 Loss breakdown of flat transformer in LLC resonant converter depending on the number of the winding wire turns and switching frequency.

Next, the temperature of the transformers depending on the number of primary winding turns and switching frequency are confirmed. The operating temperature of the transformer is measured by the thermal camera.

Operating the converter at 180 kHz switching frequency, the temperature change of the transformer versus flux density is shown in **Fig. 13** and the parameters of the converter are listed in **Table 1**. As a result, when the number of primary winding turns is 25 turns, the temperature of the transformer rises to 67 ℃.

Operating the converter at 120 kHz switching frequency, the temperature change of the transformer versus flux density is presented in **Fig. 14** and the parameters of the converter are listed in **Table 2**. As a result, when the number of primary winding turns is 25 turns, the temperature of the transformer represses to 66.5 ℃. And, **Fig. 15** shows the temperature characteristics of the transformers when the converter operates for about 40 minutes. From **Fig. 15**, the temperature of the core is almost same in case of the number of the wire turns is 25 turns. However, the temperature of the winding wire at 180 kHz switching frequency is a little higher than one at 120 kHz switching frequency. The efficiency curve for different load conditions depending on the flux density and switching frequency is shown in **Fig. 16**.



(Tradition prototype)

(Proposal prototype)

Fig. 11 Comparison between proposal and tradition prototypes.

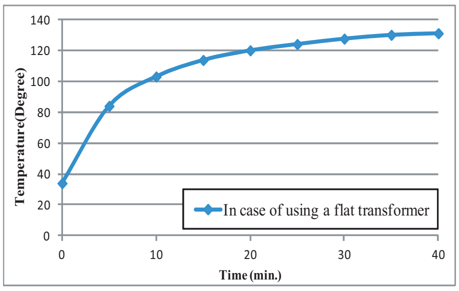


Fig. 12 The temperature change of the transformer by using one flat transformer.

Table 1 Parameters of circuit (switching frequency : 180 kHz).

Signs	Parameters	Values
n	Transformer turns ratio	1.05
V_{in}	Input voltage	400V
V_o	Output voltage	190V
I_o	Output current	2.3A
L_m	Magnetizing inductance	170uH
L_r	Resonant inductance	11uH
C_r	Resonant capacitance	69nF
f	Switching frequency	180kHz

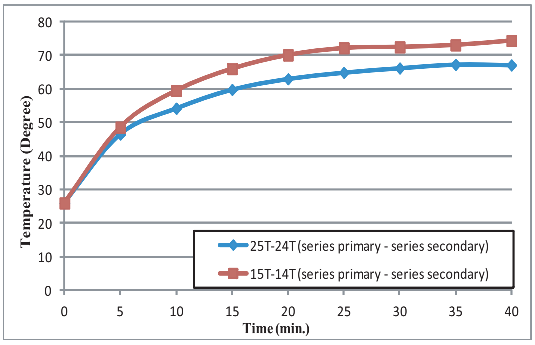


Fig. 13 The temperature changes of transformer depending on flux density (180 kHz switching frequency).

5. Conclusion

In this paper, the design consideration of a low-profile LLC resonant converter is considered to reduce the operating temperature of the flat transformer. The power module using two

Table 2 Parameters of circuit (switching frequency : 120 kHz).

Signs	Parameters	Values
n	Transformer turns ratio	1.05
V_{in}	Input voltage	400V
V_o	Output voltage	190V
I_o	Output current	2.3A
L_m	Magnetizing inductance	300uH
L_r	Resonant inductance	17uH
C_r	Resonant capacitance	94nF
f	Switching frequency	120kHz

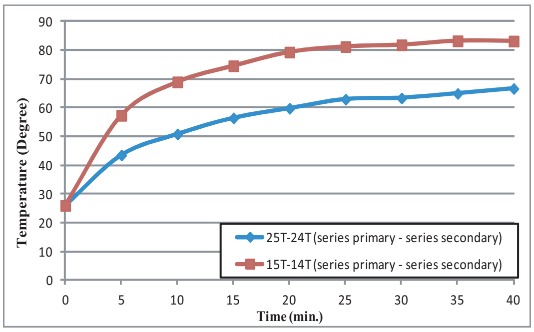


Fig. 14 The temperature changes of transformer depending on flux density (120 kHz switching frequency).

flat transformers is considered to drop the temperature of the transformer. In case of high voltage application such as PDP TV, the core loss of the transformer is considerably higher than the wire loss of the transformer. Therefore, the primary and secondary winding wires of two flat transformers should be connected in series to decrease the core loss per a flat transformer. Next, the loss of the flat transformer depending on the switching frequency and the number of primary winding turns is studied. As the number of primary winding turns is 25 turns when operating the converter at 120 kHz switching frequency, the temperature of the transformer rises to 66.5 ℃ and an overall efficiency of 96.5 % was measured.

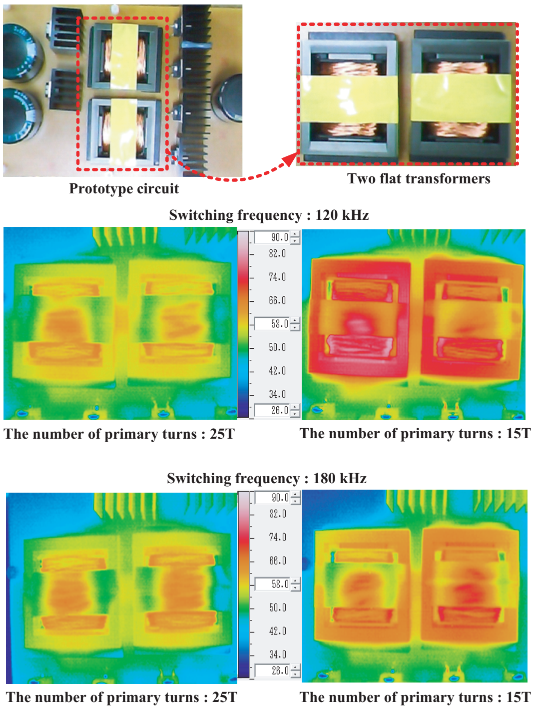


Fig. 15 Temperature characteristic of two flat transformers depending on flux density and switching frequency.

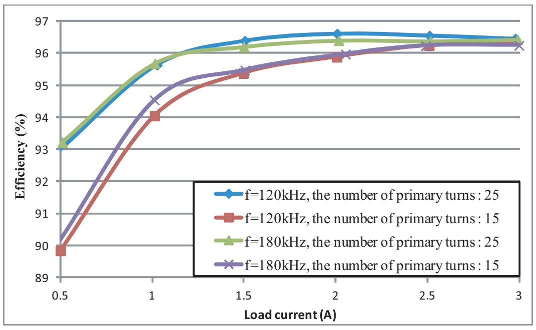


Fig. 16 Conversion efficiency of LLC resonant converter depending on flux density and switching frequency.

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