1. Introduction

Due to the rapid development of the electronics industry and the rising awareness of energy saving and carbon reduction, the high conversion efficiency and compact size of the volume is an inevitable trend. The power converter will develop towards newer and more advanced switching power converter. Energy conservation and the use of a large number of electronic products and frequency conversion equipment make electromagnetic interference and harmonic a growing problem [1-2], thereby affecting the overall efficiency and peripheral products. So in the former stage of converter circuit add power factor correction technology, which will be able to effectively improve the energy conversion efficiency [3-6].

When switching power converter switch is turned on or cut off, it instantly generates a very high voltage and current stress, easy to cause serious switching loss when the power switch is switched [7-8], from which also electromagnetic interference problems are derived. This drawback can use soft switching with zero voltage switching, ZVS and zero current switching technology, ZCS technology to improve [9-11]. In 1988 C.Q. Lee and R. Liu presented LLC series resonant converter, LLC-SRC [12-18]. Because the LLC resonant converter has the advantage of soft switching, the maximum efficiency can be up to 90% or above [19-20]. Today LLC resonant converter is receiving attention gradually. So far the literature has still continued to be raised for discussion [21-25], but on account of the frequency conversion control, EMI filter design difficulties and low light-load efficiency become the main drawback.

To overcome these shortcomings, this paper has developed a high power factor, high efficiency two-stage AC - DC power converter. This paper proposes a two-stage AC - DC power converter. The first stage is boost active power factor correction circuit. The latter stage is near constant frequency LLC resonant converter. In addition to traditional LLC high efficiency advantages, light-load conversion efficiency of this power converter can be improved. And it possesses high power factor and near constant frequency operating characteristics, can significantly reduce the electromagnetic interference. This paper first discusses the main structure and control manner of power factor correction circuit. And then by the LLC resonant converter equivalent model proceed to circuit analysis to determine the important parameters of the converter circuit elements. Then design a variable frequency resonant tank. The resonant frequency can change automatically on the basis of the load to reach near constant frequency operation and a purpose of high efficiency. Finally, actually design and produce an AC – DC power converter with output of 190W to verify the characteristics and feasibility of this converter. The experimental results show that in a very light load (9.5 W) the efficiency is as high as 81%, the highest efficiency of 88% (90 W). Full load efficiency is 87%. At 19 W ~ 190 W power changes, the operating frequency change is only 0.4 kHz (AC 110 V) and 0.3 kHz (AC 220 V).
discontinuous mode. When the voltage is near zero, it is the discontinuous mode. The output diode has zero current switching characteristics, which can reduce the loss of diodes reverse recovery time. The rest are continuous mode, which can reduce switching loss. Therefore, this paper uses a fixed off time control method.

![Fig. 1 Architecture of boost power factor correction](image)

Fixed off time allows the majority of the power factor correction circuit to operate in continuous conduction mode, resulting in high performance. But it can use a simple peak control method, does not require a proprietary controller, and just add some passive components to achieve the purpose. In a typical fixed-frequency mode, when duty cycle is more than 50%, it will generate sub-harmonic oscillation, causing system instability and slope compensation must be made. Theoretically fixed off time control method duty cycle can reach 100%, while we do not have to do slope compensation, reducing material costs, as shown in Fig. 3.

In addition, a fixed off time also has the advantage of dynamic performance uplift. The internal current control loop responds sensitively to shocks arising from changes of load in the inductive current. External voltage control loop is not affected, and thus the power factor is effectively improved.

**3. Near constant frequency LLC resonant converter**

Although the LLC resonant converter already has many advantages, there are still some shortcomings. E.g., with changes in the load switching frequency varies, causing electromagnetic interference filter design problems, and poor conversion efficiency at light loads. Fig. 4 is a traditional style of LLC resonant converter gain curve. It can be seen from figure that when slowly loading from lighter loads frequency also will slowly decline.

![Fig. 2 Inductance current waveform of off time control method](image)

![Fig. 3 Current state diagram of fixed frequency control method and fixed off time control method in time of duty> 50%](image)

![Fig. 4 Conventional LLC resonant converter gain curves](image)

![Fig. 5 Architecture of near constant frequency LLC resonant converter used herein, in which resonant tank has a variable inductor.](image)

![Fig. 6 Gain curve](image)
3.1 Principle of variable resonant tank

The principle of variable resonant tank is mainly to design an inductor whose resonant inductive value can also change accordingly with the changes in the loads. To achieve this goal, we develop a special core gap capable of partial core saturation. When the load increases, the core saturation region increases, the resonant inductive value also changes accordingly. Fig. 7 is a schematic diagram of the core with an air gap of variable resonant inductor.

3.2 Design of variable resonant inductive value

This article concerns to facilitate the design and production of the air gap, so choose the EI-30 of TDK as resonant inductor, and based on a traditional-style LLC resonant converter design according to the following steps:

1. Inductance value $L_{r,\text{full}}$ of variable inductance of resonant tank when fully loaded

\[
L_{r,\text{full}} = \frac{1}{\left(\frac{f_{s,\text{full}}}{2\pi C_r}\right)^2}
\]

(1)

Wherein, $f_{s,\text{full}}$ is switching frequency in time of full load. $C_r$ is resonant capacitance values.

2. Calculate the actual production’s light load resonant inductive value:

\[
L_{r,\text{light}} = L_{r,\text{full}} - L_{LK}
\]

(2)

Wherein, $L_{LK}$ is main transformer leakage inductance values.

3. Redraw the gain curve graph and calculate $f_r$ and $f_m$ of the light load and heavy load.

4. Check if the light load and heavy load intersection point is close to the set gain. If the difference is too large, it can be adjusted. Adjustment methods are the following two fashions:

(A) Adjust the core air gap of variable resonant inductance, so that the light load and heavy load gain curve intersection point is close to the set gain value.

(B) Adjust the turn ratio, and make the gain value rise or fall while approaching a light load and heavy load gain curve intersection.

4. Design example

This article designs a set of two stage high power factor high-efficiency AC - DC 190W power supply, whose specifications are shown in Table 1. The main structure of the circuit is shown in Fig. 8. And actually measure to validate feasibility of the article proposed method. Wherein, the power factor correction circuit specifications are as shown in Table 2. The controller uses ST Microelectronics’ L6562. Table 3 shows the LLC resonant converter specifications. The controller uses ST Microelectronics’ L6599.

| Table 1 Specifications of implemented circuits |
|-----------------------------------------------|
| **AC/DC 190W Power Supply**                  |
| Nominal Input Voltage $V_{\text{in(RMS)}}$    | 90 to 264VAC               |
| Nominal Output Voltage $V_{\text{out}}$       | 19VDC ± 1%                |
| Nominal Output Power $P_o$                    | 190W                      |
| Estimated Efficiency $\eta$                   | 90%                       |
| PFC Maximum Switching Frequency $f_{SW,max}$  | 100kHz                    |
| LLC Switching Frequency $f_s$                 | 65kHz                     |

| Table 2 Power factor correction circuit specifications |
|-------------------------------------------------------|
| **PFC Circuit Specification**                         |
| Nominal Input Voltage $V_{\text{in(RMS)}}$            | 90 to 264VAC              |
| Nominal Output Voltage $V_{\text{out}}$               | 380VDC                    |
| Nominal Output Current $I_{\text{out}}$               | 0.526A                    |
| Estimated Efficiency $\eta$                           | 95%                       |
| Maximum Switching Frequency $f_{SW,max}$              | 100kHz                    |
| Nominal Output Power $P_o$                            | 200W                      |
| Ripple Factor $k_r$                                   | 40%                       |
Table 3 Near constant frequency LLC resonant converter circuit

| Specification | | |
|---|---|
| Nominal Input Voltage \(V_{in}\text{(RMS)}\) | 380V DC |
| Nominal Output Voltage \(V_{out}\) | 19V DC |
| Nominal Output Current \(I_{out}\) | 10A |
| Estimated Efficiency \(\eta\) | 95% |
| Full Load Switching Frequency \(f_s\) | 90kHz |
| Resonant Frequency \(f_r\) | 110kHz |
| Nominal Output Power \(P_o\) | 190W |

4.2 Experimental results and discussion

This paper presents the high power factor high efficiency AC-DC converter. The efficiency of its latter stage employing near constant frequency architecture is compared with that of its latter stage using traditional LLC resonant converter, as shown in Table 4. Fig. 9 and Fig. 10 is efficiency comparison curves diagram between near constant frequency and traditional LLC resonant converter. It can be seen from the figure that in a very light load (5%, 10% load, DC 110V) efficiency reaches more than 81%. Under full load efficiency reaches 87%. The maximum efficiency is 88%, a significant improvement in efficiency.

Table 4 Comparison with the efficiency of traditional LLC resonant converter [26]

| Load(%) | Proposed | Reference |
|---|---|---|
| \(P_o(W)\) | | |
| \(E_r(110V)E_r(220V)\) | | |
| 5 | 9.5 | 0.81 | 0.72 | Without Measured |
| 10 | 9.0 | 0.82 | 0.79 |
| 20 | 8.1 | 0.86 | 0.84 |
| 30 | 7.3 | 0.87 | 0.86 |
| 40 | 6.8 | 0.87 | 0.87 |
| 50 | 6.3 | 0.87 | 0.88 |
| 60 | 5.9 | 0.87 | 0.88 |
| 70 | 5.5 | 0.87 | 0.88 |
| 80 | 5.2 | 0.86 | 0.88 |
| 90 | 4.9 | 0.85 | 0.88 |
| 100 | 4.5 | 0.84 | 0.87 |

Fig. 9 Efficiency comparison graph between 110 V and a traditional LLC converter [26]

Fig. 10 Efficiency comparison curve graph between 220 V and a traditional LLC converter [26]

Fig. 11 and Fig. 12 are from the very light load to full load LLC switching frequency curve graph when the input is 110 V and 220V. The operating frequency change of the converter is less than 0.4 kHz, close to the constant frequency state.

5. Conclusion

This article combined active power factor corrector with near constant frequency LLC resonant converter to achieve the purpose of high power factor high efficiency, the actual completion of high efficiency high power factor AC-DC 190 W power converter. The former and latter stage circuits have the same characteristics. That is, by the principle of a simple structure without increasing components, it can significantly improve performance. In terms of a power factor correction device, when the measurement of the input AC voltage is 110 V and 220 V, it is able to meet the high power factor. Regarding the latter stage near constant frequency LLC resonant converter from very light load to full load, when the switching frequency is almost unchanged, power switch can also achieve zero voltage switching.
reduce the power switch losses, effectively improve the efficiency from light loads to very light load. The near constant frequency control significantly reduces electromagnetic interference.

REFERENCES

[1] N. Mohan, T. M. Undeland, and W. P. Robbins, Power Electronics: Converters Applications and Design (Wiley, ed. 3, 2003)

[2] S. Kim, P. N. Enjeti, “A Modular Single-Phase Power Factor Correction Scheme With a Harmonic Filtering Function’’ IEEE Transactions on Industrial Electronics, 50, 328-335 (2003) DOI: 10.1109/TIE.2003.809400

[3] B. Andreycak, “Controlled ON-Time, Zero Current Switched Power Factor Correction Technique” Texas Instruments Incorporated (2001)

[4] S. Basu, T. M. Undeland, “Inductor design considerations for optimizing performance & cost of continuous mode boost PFC converters” Proc. Twentieth Annual IEEE. Applied Power Electronics Conference and Exposition (APEC 05), pp. 1133-1138, March (2005) DOI: 10.1109/APEC.2005.1453140

[5] C. C. Huang, “Study and Implementation of a 250-W Partially Zero-Voltage-Switching Quasi-Resonant Boost-Type Power Factor Corrector,” M.S. thesis, Dept. Electron. Eng., Taiwan Tech Univ., Taipei, Taiwan, 2009.

[6] C. L. Chen, “Study and Implementation of an Active-Clamp Flyback Converter with Power Factor Corrector Turn-Off Feature,” M.S. thesis, Dept. Electron. Eng., Taiwan Tech Univ., Taipei, Taiwan, 2009.

[7] R. L. Steigerwald, “High-frequency resonant transistor DC-DC converters” IEEE Transactions on Industrial Electronics, IE-31, 181-191 (1984) DOI: 10.1109/TIE.1984.350066

[8] R. L. Steigerwald, “Analysis of a resonant transistor DC-DC converter with capacitive output filter” IEEE Transactions on Industrial Electronics, IE-32, 439-444 (1985) DOI: 10.1109/TIE.1985.350122

[9] F. C. Lee, “High-frequency quasi-resonant converter technologies” Proceedings of the IEEE, 76, 377-390 (1988) DOI: 10.1109/5.4424

[10] J. A. Sabate, R. W. Farrington, M. M. Jovanovic, and F. C. Lee, “Effect of switch capacitance on zero-voltage switching of resonant converters” Proc. 23rd Annual IEEE. Power Electronics Specialists Conference (PESC ‘92), pp. 213-220 July (1992) DOI: 10.1109/PESC.1992.254670

[11] J. S. Glaser, A. F. Witulski, and R. G. Myers, “Steady-state analysis of the constant-frequency clamped series resonant converter” IEEE Transactions on Aerospace and Electronics Systems, 30, 135-143 (1994) DOI: 10.1109/7.250414

[12] R. Liu, C. Q. Lee, “Analysis and Design of LLC-Type Series Resonant Converter” Electronics Letters, 24, 1517-1519 (1988) DOI: 10.1049/el:19881036

[13] C. H. Chan, “Implementation and Study of LLC Resonant Converter with Low Current Ripple,” M.S. thesis, Dept. Electric. Eng., Chienkuo Tech Univ., Changhua, Taiwan, 2009.

[14] S. C. Chen, “Near Constant-Frequency LLC Resonant Converter,” M.S. thesis, Dept. Electric. Eng., Chienkuo Tech Univ., Changhua, Taiwan, 2011.

[15] Y. C. Chen, “Design and Implementation of LLC Resonant Converter,” M.S. thesis, Dept. Electric. Eng., Chienkuo Tech Univ., Changhua, Taiwan, 2009.

[16] W. I. Hsu, “Realization Study of Synchronous-Rectified LLC Series-Resonant Half-Bridge Converter,” M.S. thesis, Dept. Electron. Eng., Taiwan Tech Univ., Taipei, Taiwan, 2005.

[17] S. Y. Yang, “Design and Implementation of 500W Half-Bridge LLC Series-Resonant Converter,” M.S. thesis, Dept. Electron. Eng., Taiwan Tech Univ., Taipei, Taiwan, 2007.

[18] C. M. Huang, “Design of a High-Efficiency Half-Bridge LLC Series-Resonant Converter,” M.S. thesis, Dept. Electron. Eng., Taiwan Tech Univ., Taipei, Taiwan, 2007.

[19] D. Fu, B. Lu, and F. C. Lee, “1MHz High Efficiency LLC Resonant Converters with Synchronous Rectifier” Proc. IEEE. Power Electronics Specialists Conference (PESC 07), pp. 2404-2410, June (2007) DOI: 10.1109/PESC.2007.4342388

[20] C. H. Chang, “Realization Study of Synchronous-Rectified LLC Series-Resonant Half-Bridge Converter,” M.S. thesis, Dept. Electric. Eng., Kun Shan Tech Univ., Tainan, Taiwan, 2007.

[21] E. S. Kim, H. K. Lee, Y. S. Kong, and Y. H. Kim, “Operating Characteristics in LLC Resonant Converter with A Low Coupling Transformer” Twenty Second Annual IEEE Applied Power Electronics Conference, (APEC 07), pp. 1651-1658, March (2007) DOI: 10.1109/APEX.2007.357740

[22] Y. Ang, C. M. Bingham, M. P. Foster, and D. A. Stone, “Modelling and Regulation of Dual-Output LLC Resonant Converters” Proc. 33rd Annual Conference of the IEEE. Industrial Electronics Society (IECON 07), pp. 2130-2135, November (2007) DOI: 10.1109/IECON.2007.4460232

[23] Y. Ma, X. Xie, Z. Qian, “Frequency-Controlled LLC Resonant Converter with Synchronous Rectifier” 7th International Conference on Power Electronics and Drive Systems, pp.1442-1445 (2007) DOI: 10.1109/PEDS.2007.4487894

[24] A. J. Forsyth, G. A. Ward, and S. V. Mollov, “Extended fundamental frequency analysis of the LLC resonant converter” IEEE Transactions on Power Electronics, 18, 1286-1292 (2003) DOI: 10.1109/TPEL.2003.818826

[25] C. M. Hung, “Study and Implementation of Buck-Fed LLC Resonant Converter,” M.S. thesis, Dept. Electric. Eng., Chienkuo Tech Univ., Changhua, Taiwan, 2010.

[26] W. C. Huang, “Analysis and Implementation of a Half-Bridge LLC Resonant Converter with Front-End Power Factor Correction,” M.S. thesis, Dept. Electric. Eng., Tatung Univ., Taipei, Taiwan, 2009.

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