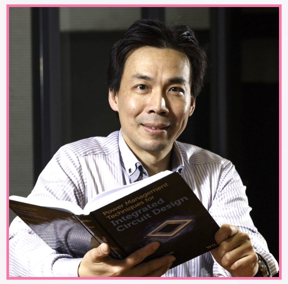
✦ D24-001 ✦

符合能源之星計畫與80plus鈦金標準應用於綠能產業之高效率LLC轉換器

A High-efficiency LLC Converter for the Green Energy Industry Achieving Energy Star and 80 Plus Titanium Standard

隊伍名稱｜鑽石大賞 Diamond Award
隊　　長｜陳麒聿 / 陽明交通大學電控工程研究所
隊　　員｜邱柏睿 / 陽明交通大學電機工程研究所
王資文 / 陽明交通大學電機工程研究所
烏孝權 / 陽明交通大學電機工程學系

✦ 指導教授 ✦



陳科宏｜陽明交通大學電機工程學系

臺灣大學電機工程學士、碩士、博士，現為陽明交通大學電機工程學系講座教授以及IEEE Fellow。曾於1996至1998年任臺北飛利浦公司兼職IC設計人員，1998至2000年任Avanti擔任項目經理，從事電源管理IC的設計。成立陽明交通大學混合信號和電源管理IC實驗室，在IEEE頂尖期刊（JSSC及TPE）和會議（ISSCC及VLSI symposium）上有卓越的貢獻，並擁有多項專利。

研究領域

電源管理積體電路設計、混合訊號電路設計、液晶顯示器（LCD）驅動器設計、氮化鎵驅動器設計

✦ 作品摘要 ✦

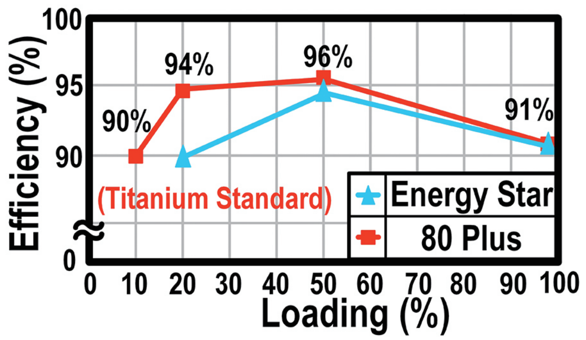
隨著綠能產業發展以及環保意識抬頭，對於電源供應器的效率有著更高的要求，特別是伺服器、通訊裝置和資料中心等高耗能的硬體設備，即便只提升1%的效率即可降低大量功率損耗。能源之星計畫（Energy Star）和80 plus鈦金標準（80+ Titanium Standard）分別對於電源供應器輕載下的效率要求達90%以上，以減少廢熱，而傳統硬切換的直流轉換器（DC-DC converter）受限於開關損耗，無法達到要求。使用電感和電容串聯的諧振轉換器（LLC-series resonant converter）則透過一次側零電壓切換（zero voltage switching）和二次側零電流切換（zero current switching）大幅降低開關損耗，進而提升整體效率。本研究使用單晶片的氮化鎵（GaN）單晶片，實作LLC converter，並提供最高24V電壓與5A電流。以下將逐一探討GaN之優勢、設計困難與解決方法，如以下詳述。

氮化鎵（GaN）高電子遷移率電晶體（HEMT）具有低寄生電容、低導通電阻（RON）和高功率密度的特性，因此基於GaN HEMT的功率轉換器可以實現低功耗和高開關頻率，故近年來比傳統矽（Si）電晶體更受歡迎。

然而，GaN HEMT缺乏P型半導體（P-type semiconductor），因此採用單晶片整合（monolithic integration）的傳統設計使用電阻來取代PMOS的功能，但也因此增加靜態電流。後續改進的設計雖然使用耗盡型氮化鎵（depletion-mode GaN）串聯電阻來限流，但多條的漏電路徑仍然使靜態電流無法進一步降低。

LLC converter在穩態下有更高的效率，然而在軟啟動（Soft start-up）時卻會面臨過壓，導致元件損壞，並產生巨大功耗。原因為此時輸出電壓還沒建立，變壓器（transformer）視為短路，又開關頻率約等於諧振頻率，所以諧振電容（Cr）和諧振電感（Lr）會開始諧振。

基於上述問題，本研究提出了混合式閘級驅動器（Hybrid gate driver），在降低靜態電流的同時，也有足夠的驅動力去開關功率元件，另外有自動預充技術（Auto precharge technique），以確保驅動器可以正常運行，最後是三階段軟啟動箝位技術（Three-phase soft startup clamping technique），在軟啟動時保護功率開關和被動元件不被高壓損毀，圖二為本研究電路架構。



圖一 兩個商用標準之效率規格。

✦ Abstract ✦

With the development of the green energy industry and the rise of environmental awareness, there are higher requirements for power supply efficiency, especially for power-consuming hardware devices such as servers, communication devices, and data centers. Even a 1% increase in efficiency can reduce a large amount of power consumption. The Energy Star and the 80 plus Titanium Standard require power supplies to achieve over 90% efficiency at light loads in order to reduce waste heat. The efficiency of traditional hard-switching-based DC-DC converters is limited by switching loss and cannot meet the requirements. In contrast, the LLC-series resonant converter (LLC-SRCs), which adopts inductors and capacitors in series, significantly reduces switching loss through zero-voltage switching on the primary side and zero-current switching on the secondary side. Therefore, the efficiency is improved. In this study, a GaN-based LLC converter provides a maximum voltage of 24V and a current of 5A. The advantages, design challenges, and solutions are discussed in the following.

Compared to conventional Si-based transistors, Gallium nitride (GaN) high-electron mobility transistors (HEMTs) have become a more popular choice in recent years. Due to their low parasitic capacitance, low on-resistance (RON), and high power density, the power converters based on GaN HEMTs can achieve low power consumption and high switching frequency.

However, since there is no P-type semiconductor in the GaN process, conventional monolithic GaN designs adopt a pull-high resistor to replace PMOS, which increases the quiescent current. A later design uses a depletion-mode GaN in series with a resistor to limit the current, but the multiple leakage paths cannot further reduce the quiescent current.

LLC converters operate efficiently in a steady state. However, during the soft start-up period, the components of the LLC converters face high voltage stress, which can cause serious damage to these components and significant power consumption. The reason is that the output voltage has not yet been built up, so the transformer is seen as short-circuited. In addition, the switching frequency is approximately equal to the resonant frequency, the resonant capacitance and the resonant inductance will start to resonate.

Based on the problems mentioned above, this study proposes a hybrid gate driver to reduce the quiescent current and have a strong driving ability to turn the power switches. In addition, the proposed auto-precharge technique ensures that the driver can function properly. Finally, the three-phase soft start clamping technique keeps the power switches and the passive components from being damaged by high voltage during soft start.

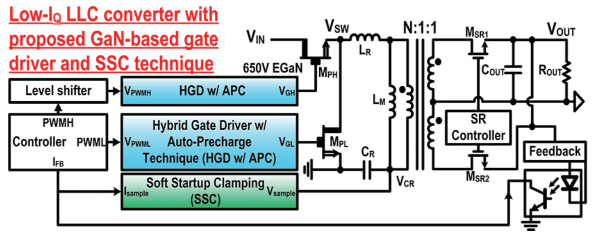


Fig. 2 System architecture.