國立臺灣大學電機資訊學院電機工程學系

博士論文

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Doctoral Dissertation

應用於串列匯流排電力傳輸之變頻峰值電流控制返馳式轉換器自調式控制器研製

An Adaptive Controller Development for Flyback Converters with Variable-Frequency Peak-Current Control in USB-PD Application

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本論文係 鄭景翔 君（學號 D04921024）在國立臺灣大學電機工程學系完成之博士學位論文，於民國 108 年 2 月 22 日承下列考試委員審查通過及口試及格，特此證明。

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中文摘要

具串列匯流排電力傳輸（USB-PD）規格的返馳式轉換器廣泛用於許多低功率充電器應用中。為了在整個負載範圍內實現高電能轉換效率，該應用經常使用可根據負載狀況調整開關切換頻率的變頻峰值電流控制（VFPCM）。然而，由於過去無文獻提出針對 VFPCM 控制的準確小信號模型來克服 USB-PD 寬輸出電壓範圍操作所引起的不穩定問題。再者為確保所有工作條件下轉換器之穩定性，在補償器設計上，必須考慮控制對輸出轉移函數的最壞情況進行設計。不幸的是，該設計方式犧牲了其他工作條件下環路增益的交越頻率，導致該轉換器在其他工作條件下，負載暫態響應變差。

為解決此問題，本文首先針對 VFPCM 控制提出一種新穎且精確的小訊號模型，用於分析 USB-PD 充電器應用中的環路增益變化。接著，根據該小訊號模型，發展出具恆定交越頻率的自調式變頻峰值電流控制（AVFPCM），以減輕穩定性和負載暫態響應之間的設計取捨，並同時保有變頻特性以減少轉換器輕載的電能損耗。最後，透過模擬軟體與實驗電路，驗證所提出的小訊號模型和 AVFPCM 控制之有效性。

關鍵字—返馳式轉換器、變頻峰值電流控制、串列匯流排電力傳輸、小訊號模型、恆定交越頻率

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Abstract

A flyback converter with Universal Serial Bus Power Delivery (USB-PD) specification is widely used in many low-power adaptor applications. To achieve high efficiency for the entire load range of operations, a variable-frequency peak-current-mode (VFPCM) control, which adapts the switching frequency according to the load conditions, is often used in this application. However, in the past, there was no small-signal model reported for the VFPCM control to overcome the instability problem caused by a wide output-voltage-range operation in USB-PD specification. Besides, to ensure stability in all working conditions, the loop gain has to be compensated based on the worst case of control-to-output transfer function. Unfortunately, the crossover frequencies of loop gain in other working conditions are sacrificed, resulting in poor transient response.

In this dissertation, a novel and accurate small-signal model for VFPCM control is firstly proposed to analyze the loop gain variation in a USB-PD charger application. Next, in accordance with the novel small-signal model, an adaptive variable-frequency peak-current-mode (AVFPCM) control with constant crossover frequency is developed to mitigate the trade-off between stability and transient response while maintaining the variable frequency characteristic to decrease light load power consumption. Finally, the

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simulations are conducted and a hardware experimental circuit is built to verify the validity of the proposed small-signal model and the AVFPCM control.

Index Terms— Flyback converter, variable-frequency peak-current mode, universal serial bus power delivery, small-signal model, constant crossover frequency.

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