Abstract

Multilevel flying capacitor boost converters offer high power density and efficiency at high voltage gain. However, balancing the flying-capacitor voltages is critical for maintaining efficient and reliable operation. Fixed frequency digital current mode control (DCMC) architectures are simple to implement and aim to achieve fast transient with active flying-capacitor balancing; however, they require external ramp compensation. Event-based constant on-time and off-time DCMCs offer inherent current loop stability and superior dynamic performance. Standard continuous-time small-signal models fail to capture flying-capacitor dynamics and to predict fast-scale instability considering sampling delay effects while aiming for higher closed-loop bandwidth. Therefore, the challenges remain in developing accurate converter model and controller design techniques to ensure closed-loop stability while achieving fast transient performance.

This thesis proposes fixed and variable frequency DCMC architectures in a three-level flying capacitor (3LFC) boost converter to achieve fast transient performance with flying-capacitor voltage balancing. A unified discrete-time framework is proposed by considering the largest state vector dimension and large-signal models of the converter are derived for all possible structural configurations within a switching cycle. Discrete-time small-signal transfer functions are derived to carry out closed-loop stability analysis and investigate the sampling delay effect under fixed-frequency and variable-frequency DCMCs. A hybrid controller design approach is proposed using the design insight of continuous-time models and the accuracy of discrete-time models. A digital multi-mode control architecture is proposed, which further improves the dynamic response using a large signal designed controller and results in higher light load efficiency with the proposed pulse skip modulation (PSM) technique. A 12 V to 48 V, 100 W, 100 kHz hardware prototype is developed and all the analytical investigations are verified experimentally.

Keywords: Multilevel, flying-capacitor, boost converter, digital control, multi-mode, discrete-time model, fast-scale stability, constant off-time, constant on-time.