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High-Gain Transformer-less Multiphase Hybrid Boost SMPS with Digital Per-Phase Current-Programing

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***Abstract* - This paper introduces a multiphase hybrid boost converter with digital current-programmed controller for high conversion ratio, voltage step-up applications. The controller provides tight output voltage regulation while maintaining real-time current balancing capabilities for superior thermal distribution and converter efficiency. The controller includes a system governor unit which facilitate additional control aspects that are important for multiphase operation such as phase shedding, soft-start mechanism, and system protection. The SMPS operation is validated experimentally on a four-phase 12V-to-300V multiphase prototype with maximum output power of 250W, power density of 2.5kW/Liter.**

Keywords – SMPS, Digital control, High Voltage, Multiphase, Hybrid Boost, Step Up.

I. Introduction

A focal point of state-of-the-art SMPS is system miniaturization and obtaining higher overall system power density [1]-[5]. Smaller SMPS that maintain the same output power is the key to enable power solutions that can be either implemented in mobile applications [6]-[7] or to increase the total power output for a given volume. The overall SMPS size in high conversion ratio boost type converters is highly dependent on the selected topology. Traditional solutions for high conversion ratio high-power SMPS include either resonant converters [8]-[10], or hard switched topologies [11]-[13], which often rely on a transformer to obtain the desired voltage gain. The implementation of such a high-power transformer requires substantial volume, and therefore, increases system size and reduces the SMPS power density. Transformer-less boost type topologies [14]-[17] eliminate the need for a bulky magnetics to achieve the desired voltage conversion ratio that often comes at a cost of more complex design and components stress.

Another SMPS miniaturization technique is using multiphase converters. In multiphase converters with load sharing capabilities [18]-[20], each phase of the SMPS is required to provide less per-phase power, which translates into reduced components stress and size. Load sharing increase the system efficiency [21]-[23] and enables system scalability by adding additional phases if higher power is required. Operating a multiphase system, requires to address additional control aspects beyond traditional system's state-variable regulation. Phase synchronization and current balancing are required for proper operation of the multiphase converter. In order to further improve the performance of the multiphase converters, phase shedding and phase interleaving [24]-[25] are used to enhance system efficiency over wide range of loading conditions.

The objective of this study is to introduce a high conversion-ratio, digital current-programmed interleaved multiphase hybrid boost converter as shown in Fig. 1. Each boost phase is a high efficiency transformer-less single-switch dual-inductor hybrid boost converter as shown in [15]. The new multiphase converter utilizes an Average Current Mode (ACM) control scheme, which provides inherent current sharing and load-distribution capabilities among the phases. The ACM controller reduces the per-phase component stress and allows to further increase the converter overall power density. The multiphase converter operates in an interleaved manner to take advantage of enhanced output voltage ripple cancelation. This paper further highlights the

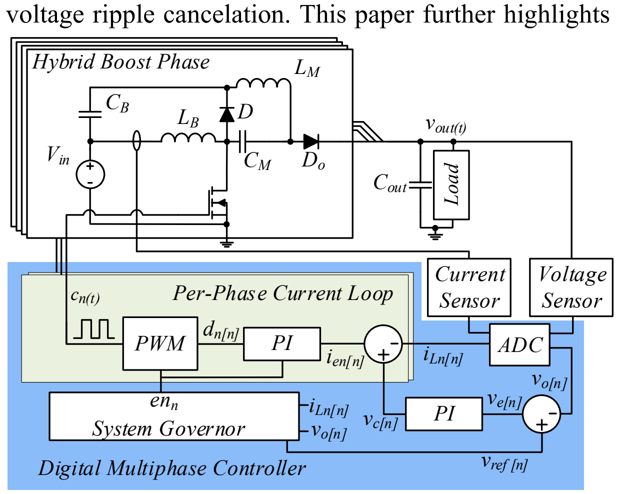

Fig. 1. Simplified schematic diagram of a transformer-less single-switch multiphase boost converter with dual loop ACM controller.

practical challenges and constraints that are associated with the implementation and miniaturization of the multiphase hybrid boost converter (MHBC).

The rest of the paper is organized as follows, Section II describes the multiphase boost converter operation and control scheme. Section III covers the operation and control features executed by the multiphase system governor. Experimental verification of the MHBC is provided in section IV. Section V concludes the paper.

II. MHBC Controller Principle of Operation

The high conversion ratio SMPS developed in this study which consists of a multiphase hybrid boost converter and a multiphase digital dual-loop ACM controller is presented in Fig. 1. The digital controller is structured around a dual-loop current-programmed linear compensation scheme and operates in a fixed-frequency pulse width modulation. By operating under fixed frequency regime, it enables simpler power stage design procedure, requires only a relatively simple analog front-end and provides high static efficiency. Good thermal distribution between the phases is also obtained by maintaining balanced currents among the phases, which is highly important in the context of multiphase converters. The single-phase variation of the hybrid boost converter [15] with dual-loop control scheme is demonstrated in Fig. 2. The hybrid boost topology was selected due to its highly efficient power conversion capabilities and low component stress in high conversion ratio applications. Since this topology doesn't require the use of a bulky transformer to achieve the desired conversion ratio, a higher power density is feasible in comparison to other transformer-based topologies. In this study the dual-loop control architecture is implemented by a high bandwidth inner current loop that directly controls the boost stage inductor (L_B) current and a slower outer voltage loop that regulates the converter output voltage.

In this study the inner current loop is realized by an ACM control approach, this is done to reduce the analog hardware requirements and the controller design complexity in comparison to a peak current mode controller implementation. The principle of operation of the introduced ACM controller is described with the aid of Fig. 3, which shows the conceptual block diagram of the ACM controller. Since this study focuses on a digital implementation of the controller, the description is carried out with sample-data domain notations. The outer voltage loop creates a digital reference $v_c[n]$ for the inner current loop based upon the error signal $v_e[n]$, which is calculated form the output voltage sampled voltage $v_{out}[n]$ and the voltage loop reference signal $v_{ref}[n]$.

The current error $i_e[n]$ can be calculated using the sampled average boost inductor current $i_{LB}[n]$ and the voltage loop digital reference. The current error $i_e[n]$ is fed as the input for the current loop compensator, which in turn generates the duty command $d[n]$ for the DPWM module, and a pulse width modulated signal $c(t)$ is formed.

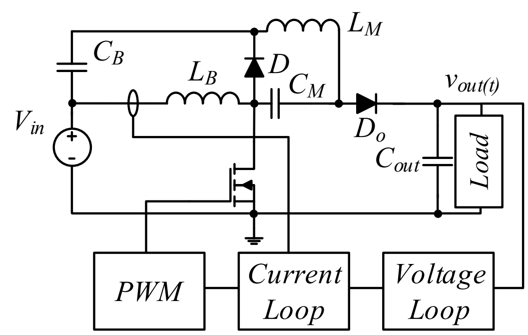

Fig. 2. Dual-loop single-phase ACM hybrid boost converter.

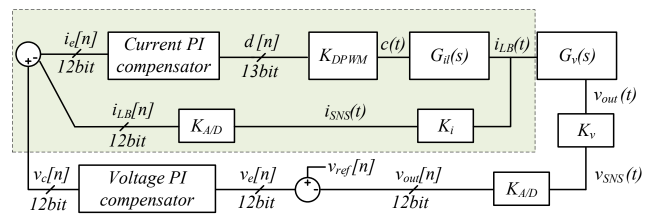

Fig. 3. Conceptual block diagram of the hybrid boost converter dual-loop ACM control system.

The MHBC configuration where multiple single-phase converters (Fig. 2) are connected to a single output stage, this requires minor adaptation of the control scheme to accommodate the additional phases and support load sharing between the phases. Active current balancing is required in multiphase operation to compensate for component non-idealities and practical implementation variation between the phases, these factors greatly increase the current mismatch between the phases when the same duty cycle command is applied to each phase. In the multiphase implementation of the ACM controller the inner current loop (inner frame of Fig. 3), which is described above, is multiplied on a per-phase basis. Each of the current loops are provided with the same $v_c[n]$ command, therefore the boost inductors currents $i_{LB}(t)$ are equalized by the control loops and current balancing is achieved. Since the per-phase current equalization is obtained inherently by the current loop operation no additional control loop is required.

In addition to the adaptation of the regulation controller for multiphase operation, phase interleaving is also highly beneficial for the multiphase converter by reducing component stress, and to further enhance the converters

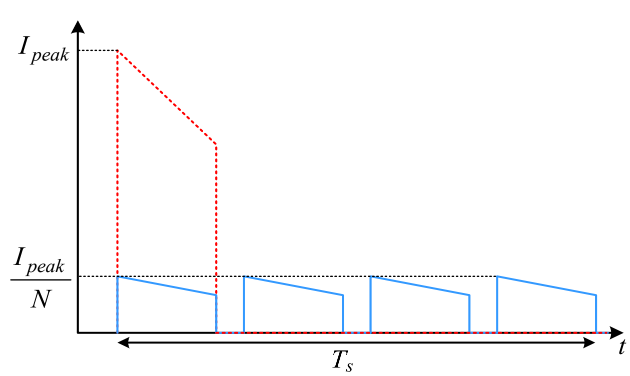

Fig. 4. MHBC output current with phase interleaving (solid) and without phase interleaving (dashed).

efficiency. Phase interleaving is achieved by time offsetting the PWM signals for each single-phase converter to spread equally within the switching period. Fig. 4 shows the output current of the MHBC with phase interleaving (solid line) and without phase interleaving (dashed line). As can be seen the peak output current of the converter without phase interleaving is significantly higher.

This is crucial in high power operation where a larger, more robust, output capacitor specialized for power applications is required to withstand the increased current ripple. Moreover, the RMS value of the output current without phase interleaving is larger as well, this translates to increased conduction losses of the converter which can curtail the converter's efficiency.

Another aspect of the multiphase implementation of the MHBC is the prevention of current flow back to either of the phases from the common output stage, making a specific phase an additional load instead of a power supply. This can also negatively affect system efficiency or cause system failure by overloading the remaining phases. This problem is solved inherently by the hybrid boost converter topology with the implementation of D_o diode which prevents current backflow to the phase.

III. System Governor

In addition to the regulation requirements performed by the digital multiphase controller, unique control features such as phase shedding, soft-start, and protection attributes are required by the MHBC controller. In this study all the additional control features are carried out by the system governor (Fig. 1). The phase shedding feature is responsible for optimizing the operational phases count according to the load status. By doing so the converter's efficiency can be increased in low, and medium load conditions where fewer phases can provide the desired load power while cutting back on drive losses. A phase shedding procedure, transitioning from a four-phase operation to a three-phase operation is demonstrated in Fig. 5. In this example the fourth phase is shed in a time optimal manner where the PWM signal to the phase is replaced with constant off state of the transistor, this forces the inductor current i_{LB1} to reach zero at minimal possible time. After the phase is shed, the load current is spread equally among the remaining phases increasing each phase average current from I_{old} to I_{new}. Although time optimal phase shedding provides the fastest optimization of the converter efficiency it can introduce non-negligible output voltage deviation during the transition. In systems where time optimal phase shedding is prohibited by regulation requirements, the duty cycle command can be ramped down in a controlled manner to allow the controller to tightly regulate the output voltage [26] at a cost of prolonged phase shedding operation.

Another control feature managed by the system governor is the soft-start procedure, where the output voltage is raised in a supervised manner by the controller. Soft-start procedure is necessary in boost type converters to limit the peak current of the boost inductor when the output voltage doesn't reach its nominal value. The ACM control scheme, which was

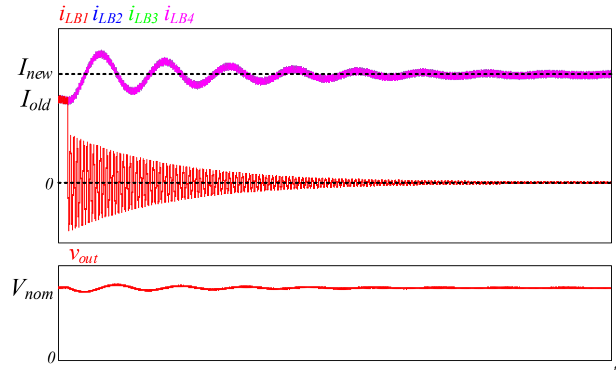

Fig. 5. Time optimal phase shedding procedure of four-to-three phase transition during light load operation in MHBC.

Table I – Experimental Prototype Parameters

Parameter	***Value/Type***
Input voltage V_{in}	12V
Nominal output voltage V_{nom}	300V
Maximal output Power P_{max}	250W
Transistors	Vishay SUM90142E
Boost inductor L_B	22µH
Link inductor L_M	22µH
Flying capacitors C_B C_M	22 µF
Output capacitance C_{out}	110µF

discussed in the previous chapter naturally limits the boost inductor current i_{LB} by limiting the maximum voltage loop output. The system governor controls the output voltage ramp up procedure by dynamically adjusting the voltage loop reference over time during start-up.

System protection is managed by the system governor since the system governor unit collects all the system state variables information for its other functions. Over and under voltage protection as well as over current protection are implemented. During these events the controller operation is halted, and the system is turned off and enters soft-start procedure. In this study an additional per-phase thermal protection is introduced using on board thermal sensors that reports back directly to the system governor, which can shut-down system operation at the occasion of system overheating.

IV. Experimental Results

The digital multiphase controller introduced in this study has been validated using a 12V-to-300V four-phase MHBC. An experimental prototype with all the analog front-end peripherals has been built and tested. The MHBC converter operates at 300kHz and is rated for maximum output power of 250W, the rest of the converter parameters are shown in Table I.

The digital controller has been implemented on a Microchip dsPIC33CK64MP103 alongside its analog front-end circuitry. Fig. 6 shows the experimental prototype setup, which comprises a four-phase HMBC designed for

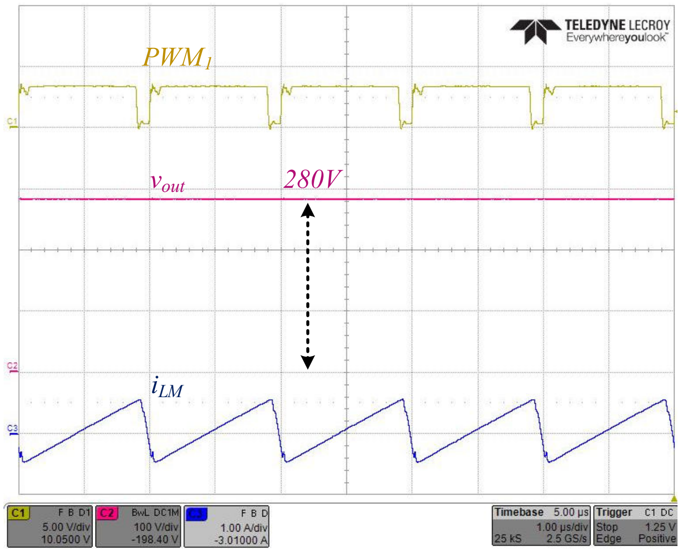

Fig. 7. Steady-state waveforms of a single-phase configuration hybrid boost converter (Gain = 23, Pout = 35W).

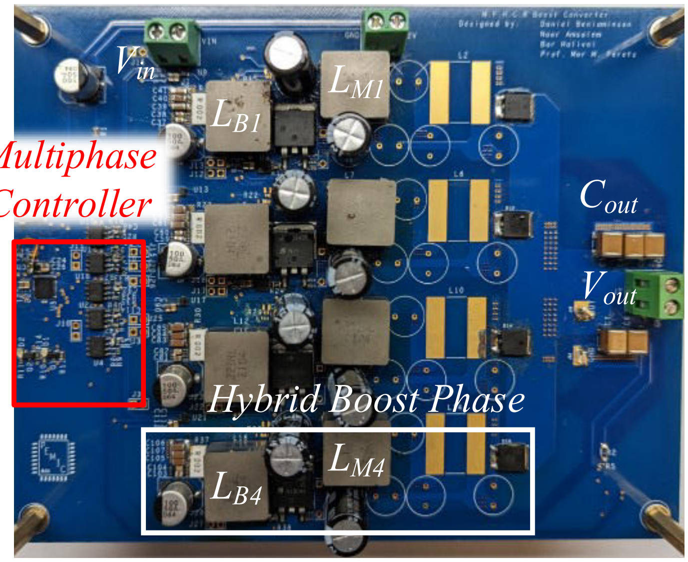

Fig. 6. Four-phase 12V-to-300V MHBC experimental setup, including all the front-end peripherals and digital controller.

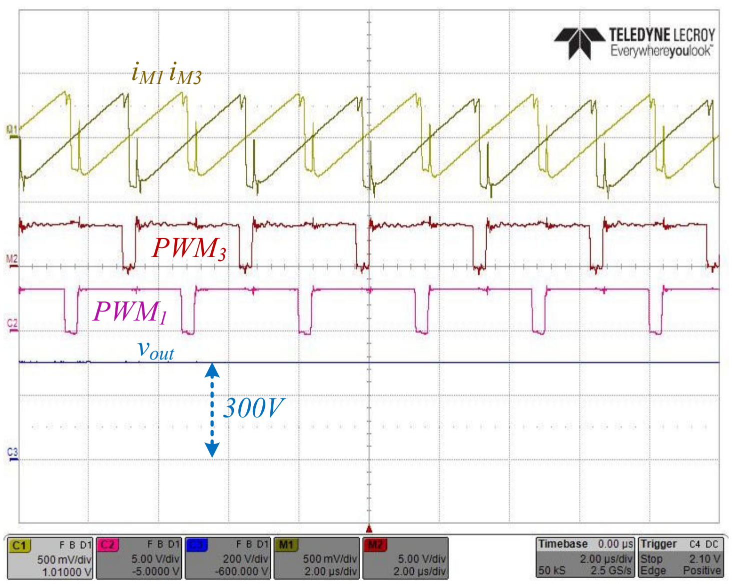

Fig. 8. Four-phase operation of the converter at and output voltage of 300V(Gain = 25, Pout = 250W).

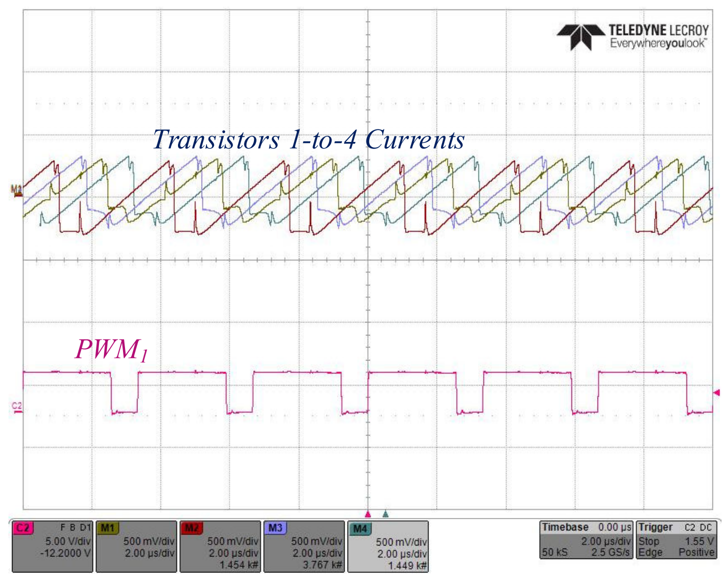

Fig. 9. Four-phase operation of the converter at half-load of 175W and output voltage of 300V.

maximum power of 250W and output voltage up to 350V. The converter phases are compact to provide increased overall power density of 2.5kW/Liter and minimize the overall system. The small converter also minimizes the differences between the phases routing and the resultant parasitic components within the system. The replicated structure of the phases also induces the system design procedure and reduce the complexity of designing higher phase count converters. The phase replication also equalizes the per-phase parasitic components and cuts down system losses.

Fig. 7 shows the experimental prototype waveforms during steady-state operation of a single phase at output power of 35W. The converter increases the output voltage to 280V form a 12V input. The link inductor current is shown, as can be seen the converter operate in CBCM mode that supports higher efficiency. At single phase operation the hybrid boost converter achieves peak efficiency of 94% at output voltage of 174V (Gain = 14.5) and 84% at 300V (Gain = 25). This demonstrate the efficiency decrease as more gain is required, pushing the converter's duty ratio closer to 1.

The operation of the full HMBC converter can be seen in Fig. 8. Here, the transistor currents of phases 1 (i_{M1}) and 3 (i_{M3}) is shown alongside their corresponding PWM signals. The currents are measured by a Rogowski current probe and demonstrate good current sharing and phase interleaving of half switching cycle. As can be seen the output voltage is 300V at maximum output power of 250W.

The current balancing capabilities of the ACM controller are demonstrated in Fig. 9, showing all the four phases transistor currents. The currents are measured at output voltage of 300V and output power of 175W. The transistor currents are inherently balanced due to the controller architecture, this contributes to obtain excellent thermal balancing between the phases.

V. Conclusion

A multiphase hybrid boost converter with digital current-programmed ACM controller has been introduced and demonstrated using a four-phase experimental prototype. The digital controller is realized based on a dual-loop ACM control scheme with inherent current balancing capabilities. Phase shedding, soft-start and protection features have been implemented to facilitate multiphase operation with enhanced performance. A 12V-to-300V four phase MHBC experimental prototype has been built and tested for maximum power rating of 250W, power density of 2.5kW/Liter, and efficiency of 83%.

Acknowledgments

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