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Analysis and Design of Single Inductor Multiple Output Resonant Buck Led Driver

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Abstract--Traditional LED drivers with multiple converters for powering up multiple strings in parallel suffer from high system volume and cost. This paper proposes a compact digitally controlled single-inductor multiple-output resonant buck LED driver operating in continuous conduction mode (CCM) with time-multiplexing control which independently optimizes local bus voltages for power loss reduction. In addition, a single time-shared control loop is used for current regulation in multiple parallel strings, resulting in reduction of errors. The power conversion efficiency varies from 84% at light loads to 93% at heavy loads. The advantages of the proposed SIMO LED driver include reducing the controller design complexity by eliminating loop compensation, driving more LED strings without limiting the maximum current rating, digital dimming without additional switches and optimization of local bus voltage. The simulated results of the proposed system are done by MATLAB SIMULINK platform.

***Keywords*— Continuous conduction mode (CCM), time multiplexing control, single-inductor dual-output (SIDO), single-inductor multiple-output (SIMO).**

I. INTRODUCTION

An LED driver is essentially a current source which maintains a constant current required for achieving the desired color and luminous flux from an array of LEDs. A number of highly efficient switching LED drivers have been reported in the literature and their primary objective is to achieve high power conversion efficiency [1]–[11]. Besides efficiency, another important consideration is the scalability of the existing single-inductor dual-output (SIDO) switching converter to drive multiple independent LED strings in a single-inductor multiple-output (SIMO) topology for reduced cost and smaller form factor [12].

The fast market growth of multiple-voltage battery operated portable applications such as digital cameras, PDAs, cellular phones, MP3 players, Displays etc. demands for more and more efficient power management systems. Since multiple voltage rails are required on a Power Management IC (PMIC), several such converters are normally used in a device for obtaining different voltage levels. If a PMIC supplies N independent voltage rails, *N* such converters are required. A solution for this issue is to use a single-inductor serving to multiple outputs. In this area, DC-DC switching converters play a critical role in keeping long battery life while still providing stable supply voltage together with the required driving capability. Hence, Resonant based digitally controlled Single-inductor dual-output (SIDO) dc–dc converters operating in continuous conduction mode (CCM) are proposed due to its reduced cost and smaller form factor in comparison with using multiple single output converters. Based on the time-multiplexing control scheme, a theoretical upper limit of the total number of outputs in a SIMO buck switching LED driver for various backlight LED current values can be derived analytically. The extension of this SIDO architecture to SIMO is formally examined.

The rest of this paper is organized as follows. Section II introduces the proposed resonant based digital controller for a SIDO switching buck LED driver operating in CCM. Section III provides a theoretical analysis on the scalability of the proposed digital control scheme from SIDO to SIMO and suggests a general formula for determining the theoretical upper bound in the total number of outputs in SIMO.Section IV shows MATLAB simulation results that are used to verify the theoretical model. Section V concludes my research effort.

II. RESONANT BASED DIGITAL CONTROL FOR SIDO LED DRIVER

A SIDO switching converter with time-multiplexing control scheme operating in DCM was first reported in [11]–[13]. With such kind of time-multiplexing control scheme, a SIDO converter can easily be extended to drive multiple outputs and it exhibits negligible cross regulation in DCM. It uses an analog-based controller with

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dominant pole compensation for stability and time-multiplexing control in DCM is employed to suppress cross regulation among the LED strings. The DCM operation, however, is usually accompanied with ringing noise generated by the LC tank when the inductor current returns to zero. This inherent noise source degrades the performance of the driver. Unlike conventional pulse width modulation (PWM) based analog controllers, the proposed digital controller utilizing resonant control does not require any compensation circuits because of its inherent stability [12], hence Simplifying the control loop design and reducing the component count and cost. FIGURE I show the system architecture of the proposed resonant based digitally controlled SIDO buck switching LED driver. In the proposed design, an system clock is used to synchronize the buck LED driver which switches at a fixed frequency. Fast comparators are used to control the on-time and off-time of the power switches by monitoring the inductor current.

A major drawback of the previously proposed SIMO LED driver operating in DCM [12] is that since the LED current is discontinuous, the LED could potentially be operating close to its absolute maximum current rating, thereby increasing the current stress and possibly shortening the operating lifetime of the LED. In their approach, the LED current scales with the number of LED strings in SIMO. Hence, the maximum current rating of the LED unnecessarily restricts the maximum achievable number of LED strings which can be implemented in SIMO. In the proposed design, the LED current is always continuous and the LED can be regulated very close to the target average current value which is much lower than its maximum current rating. During the time interval when the output switch is OFF, the output capacitor, acting as a constant current source, continues to discharge its current to the corresponding LED string. When the switch is ON, the power stage is reconnected to the LED string and the inductor current is transferred to the output capacitor and the LED string simultaneously.

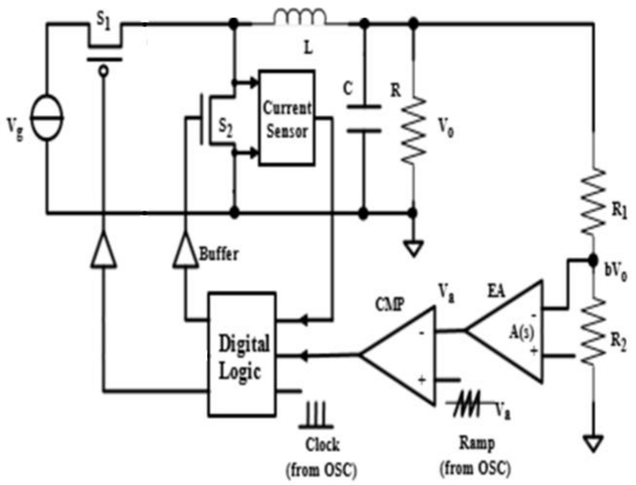

Fig I: System architecture of the digitally controlled SIDO Resonant Converter

The current-sense feedback control ensures that the LED current is maintained at the desired dc level. Hence, a time-continuous current is supplied to the LED string. Consequently, the LED current does not scale with the number of LED strings in the proposed SIMO architecture, making it possible to drive more LED strings without inducing too much stress on the LEDs.

The working principle of the proposed SIDO resonant buck LED driver is represented by the diagram shown in FIGURE II. The two independently driven LED strings share the same inductor L and the two main power switches (S1 , S2) of the resonant buck converter. The switches enable the charge stored in the inductor to be distributed between the two outputs in a time-multiplexed fashion. Since an LED is essentially a current driven device, The current-sense voltage is then compared with the reference voltage (Vrefa , Vrefb) to generate the corresponding logic signals which determine the opening or closing of the two switches in a SIDO resonant buck converter. The system clock defines the switching frequency. The rising edge of the system clock triggers the ON duty cycle (D1aTs , D1bTs) by charging up the inductor during which S1 is ON and S2 is OFF. The inductor current continues to increase until it hits the peak current limit at which point the converter enters (D2aTs , D2bTs) where S1 is OFF and S2 is ON. The inductor discharges its current to the corresponding output until the zero-crossing of the inductor current is detected and the switching sequence repeats itself.

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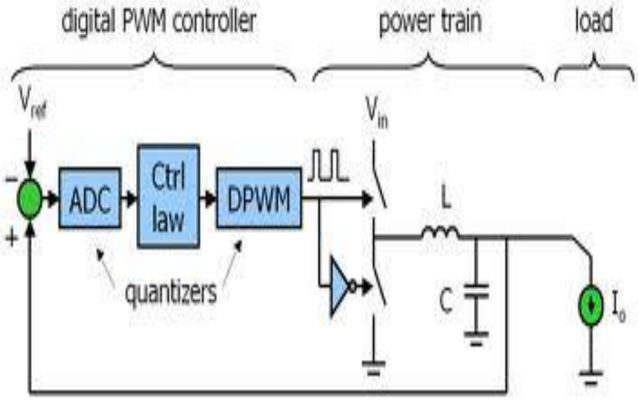

Fig II: Working principle of proposed SIDO resonant buck LED driver

For balanced load condition, the current between the two LED strings is identical and each string consists of two LEDs connected in series. The switching frequency is 100 kHz and the input voltage V_{in} is 10V. The simulation results show that the LED current in either of the two strings is regulated successfully to the target steady- state dc value of 60 mA with a minimum current ripple. The steady-state output voltage for the first and second LED string is approximately 6.045 V with a small voltage ripple. The digital dimming control signals essentially modulate the dc current level flowing through the corresponding LED string.

Using the proposed SIDO buck LED driver in FIGURE I as an example and assuming the LED current is 60 mA in each string, the output voltage is Voa = 6.04 V. The total power consumption of the load P_{LOAD} , including the LED string and current-sense resistor, is $P_{LOAD} = \max(V_{oa}, V_{ob}) \times I_{LED}$.

III. EXTENSION FROM SIDO TO SIMO BUCK LED DRIVER

Having demonstrated the feasibility of the proposed SIDO buck LED driver, it is natural for us to extend it to SIMO with N independently driven LED strings. FIGURE IV gives the design structure of the proposed SIMO system. In particular, the theoretical maximum number of LED strings Nmax is determined. To simplify the analysis, the balanced load condition is assumed.

Based on the time-multiplexing control scheme [5], energy is being transferred from the dc supply to each individual output exactly once within a total of N switching phases. FIGURE V shows the PWM control circuit of the proposed SIMO system. During the subsequent (N – 1) × Ts phases, the output capacitor continues to discharge to the corresponding LED string. Hence, the total discharging time for the output capacitor t_{dch} can be expressed as

$$t_{dch} = (N-1)T_S \qquad (1)$$

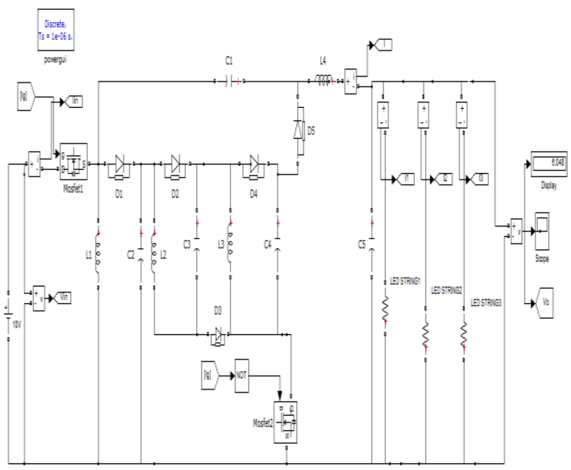

Fig IV: Circuit Design of Proposed SIMO System in Continuous Conduction mode

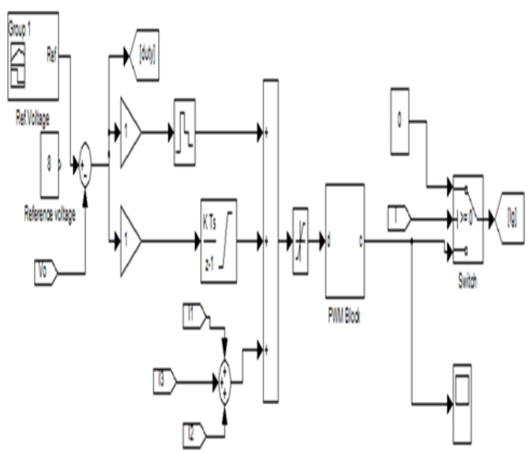

Fig V: PWM control circuit of the proposed SIMO system

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the voltage across the output capacitor V_C (t) is the same as the output voltage which is expressed as the charge q(t) divided by the capacitance value C_O

$$V_c(t) = \frac{q(t)}{C_o} \quad (2)$$

Here $i_c(t) = I_{LED}$

$$\Delta V_c(t) = \Delta V_o(t) = V_c(t) - V_o(t)$$
$$= \frac{I_{LED}\, t_{dch}}{C_o} \quad (3)$$

Hence, the total discharging time t_{dch} can be expressed as

$$t_{dch} = \frac{C_o \Delta V_o}{I_{LED}} \quad (4)$$

Where Δvo is the output voltage drop due to the discharging of the output capacitor. The LED ripple current ΔI_{LED} usually ranges from 10%p-p to 40%p-p of the dc forward current as recommended by the LED manufacturers. The output voltage ripple ΔV_o is, therefore, i.e.,

$$\Delta V_o = n \times \Delta V_{LED} \quad (5)$$

Suppose Δv_{omax} represents the maximum output voltage ripple allowed. Equation (4) can, therefore, be rewritten as

$$t_{dch} \leq \frac{C_o \Delta V_{omax}}{I_{LED}} \quad (6)$$

Hence, the theoretical maximum possible number of LED strings in SIMO, N_{max} is given by

$$N_{max} = \frac{C_o \Delta V_{omax}}{I_{LED} T_s} + D_1 + D_2 \quad (7)$$

The output power of the converter is expressed in the following:

$$P_o = \int_0^{KT} V_o^2\, dT = \sqrt{K}\ V_s \quad (8)$$

Where V_S -- Input voltage
T -- Chopping period
t_1 -- On-time
F -- Chopping frequency
K $= \frac{t_1}{T}$ = Duty cycle of chopper

The Power conversion efficiency of resonant converter is given by,

$$\eta = \frac{P_o}{P_i} \quad (9)$$

In fact, the LED current is the dominant factor for determining the maximum possible number of outputs under the scalable CCM-based SIMO scheme. By knowing the maximum LED current required for a particular application, the theoretical maximum achievable number of independently driven LED strings can be estimated.

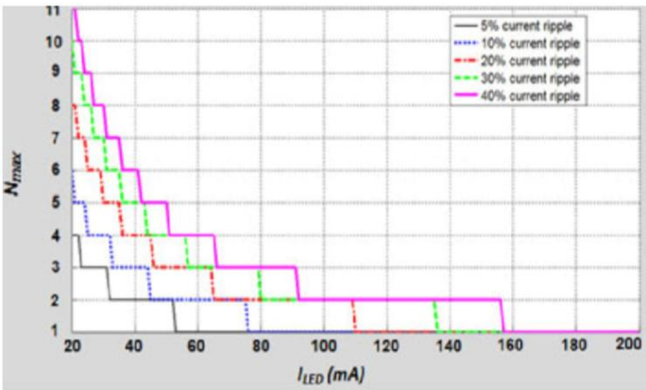

Fig VI: Plot of theoretical maximum number of LED strings in SIMO (Nmax) versus the LED current (I_{LED}) in the scalable CCM-based SIMO scheme

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FIGURE VI shows a plot of Nmax versus I_{LED} for Δi_{LED} ranging from 5%P-P to 40%P-P. As an example, assuming balanced load and two LEDs connected in series per string, a scalable BCM-based SIMO scheme is investigated with these parameter values: L = 100 µH, Co =300 µF, Vg = 10 V,and Vo = 6 V. The relationship between Nmax and I_{LED} can be obtained by using for different values of output voltage ripple Δvomax. Based upon the I–V curve and/or SPICE model of the particular LED used, the corresponding output voltage ripple ΔV_{omax} can be determined from the LED current ripple requirement Δi_{LED} . This plot is beneficial to a practical SIMO design in two ways. First, for a given LED current and current ripple requirement, the theoretical maximum number of LED strings viable under the scalable BCM-based SIMO scheme can be extracted directly from the plot. Second, the maximum LED current allowed in order for a SIMO to remain at the same scaling level can also be obtained from the plot. On the other hand, it is useful to study how the LED current affects the maximum achievable number of outputs in SIMO. By knowing the maximum LED current required for a particular application, the theoretical maximum achievable number of independently driven LED strings can be estimated in advance.

Table I. Design Specification of a SISO Buck Led Driver in CCM

Design parameter	value	unit
Input voltage V_{in}	12	V
Output voltage V_o	6.045	V
LED forward current I_L	60	mA
Switching frequency f_s	100	kHz
Inductor (L)	100	µH
Output capacitor (C)	300	µF
Maximum LED current ripple Δi_{LED}	40	$\%_{p-p}$
Maximum voltage ripple Δv_o	4	$\%_{p-p}$
Duty cycle	≳ 50	%

IV. SIMULATION RESULTS

The scalable CCM-based SIMO scheme were constructed and simulated in MATLAB simulink tool. The design specification of a single-inductor single-output (SISO) buck converter is shown in Table I. The theoretical model suggests that Nmax CCM = 1, meaning only one LED string is viable. FIGURE VII shows the simulated steady-state waveforms of the output voltage Vo of a SISO buck LED driver. The simulated steady-state LED current I_{LED} is approximately 60 mA which meets the design target. The simulated LED current ripple Δi_{LED} which satisfies the maximum ripple requirement. Now, the SISO buck LED driver is transformed into SIDO by adding a second LED string. FIGURE VIII shows the simulated steady-state waveforms from the resulting SIDO buck LED driver. A third LED string is added to the SIDO buck LED driver to transform it into SIMO consisting of three independently driven LED strings. The LED current in each string remains unchanged at 60 mA as in the SISO or SIDO case. According to FIGURE VI, the theoretical model suggests that for I_{LED} = 60mA, a scalable CCM-based SIMO scheme with a maximum of three LED strings is feasible under the 40%p-p current ripple constraint.

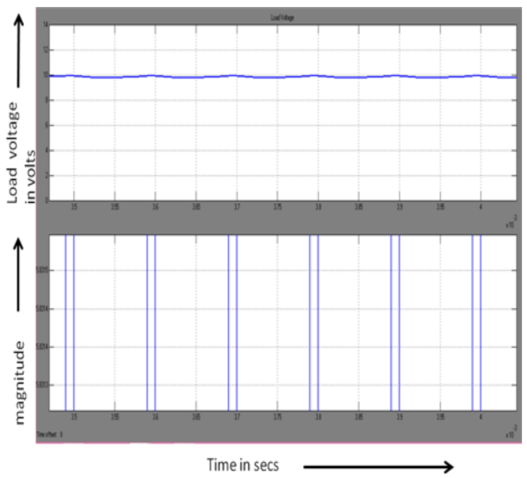

Fig VII: Simulated waveforms for SISO output corresponding gate pulse waveform

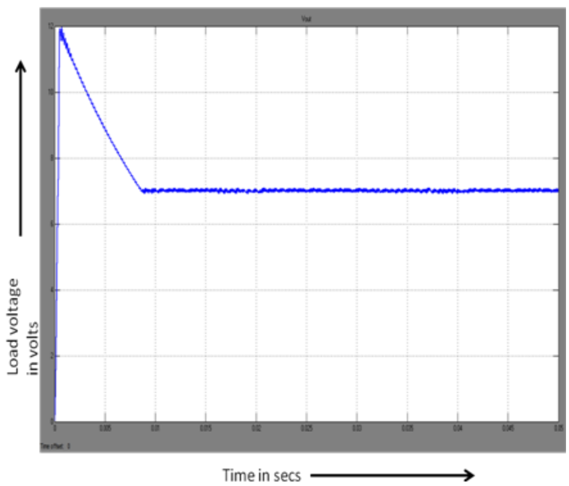

Fig VIII: Simulated Waveform for voltage and the output voltage of SIDO LED string

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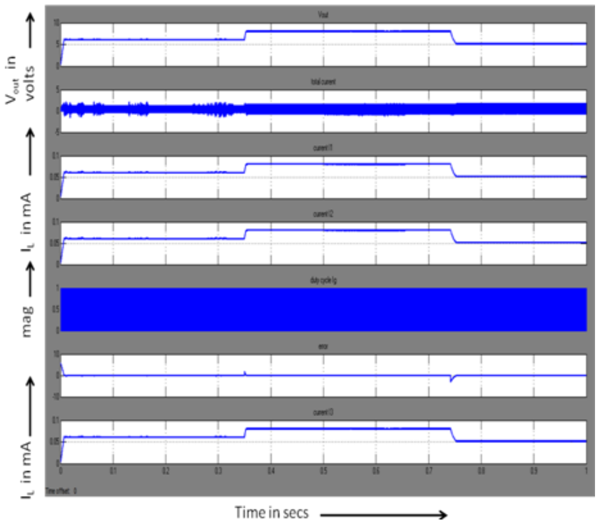

Fig IX: Simulated steady-state waveforms of three-string SIMO Resonant LED driver Operating in CCM within the time period (0 – 1) sec

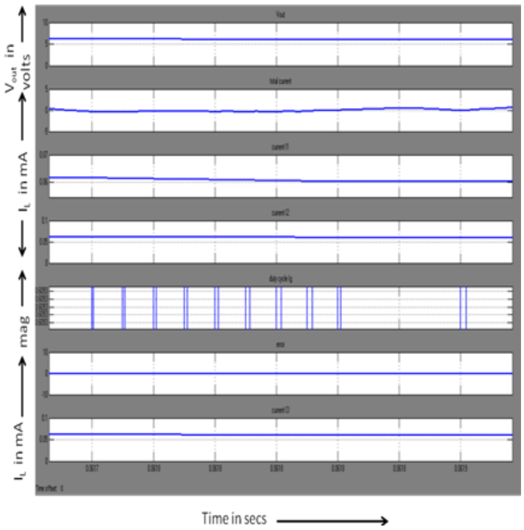

Fig X: simulated steady- state waveforms of three-string SIMO Resonant LED driver operating in CCM Within the time period (0 – 0.3) sec

The proposed SIDO converter is also capable of delivering unequal currents to the two LED strings simultaneously. FIGURE X shows the simulated waveforms from the resulting SIMO resonant buck LED driver. The output voltage reaches its target steady-state value of 6.045 V and current in each LED string is 0.06A under balanced load condition which is shown in the FIGURE X.

V. CONCLUSION

The scalability of the proposed SIDO buck LED driver to SIMO is closely examined. The simulation results were shown to be consistent with those obtained from the theoretical model for the same design parameter values. The digital control scheme does not require loop compensation which simplifies the control loop design and reduces component count. In addition, the proposed SIMO architecture offers the advantage of driving a larger number of parallel LED strings. Local bus voltage and current optimization in each individual LED string compensates for the variability of the LED's forward voltage, which reduces power loss and LED costs. FIGURE VII shows the simulated steady-state waveforms from the resulting SIDO LED driver. According to FIGURE VI, the theoretical model suggests that for I_{LED} = 60mA, a scalable CCM-based SIMO scheme with a maximum of three LED strings is feasible under current ripple constraint. The switching period T_S is chosen to be 10µs which corresponds to a switching frequency of 100 kHz. FIGURE X shows the simulated waveforms from the resulting SIMO resonant buck LED driver. As a sanity check, the theoretical model suggests that a maximum possible number of three independently driven LED strings can be achieved in the scalable CCM-based SIMO scheme.

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