ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal

Proportional-Integral (PI) Compensator Design of Duty-Cycle-Controlled Buck LED Driver

T.Madhukar Reddy
M.Tech-Power Electronics,
Department of EEE,
SRTIST Nalgonda,Telangana.

B.Ravi Kumar
Associate Professor,
Department of EEE,
SRTIST Nalgonda,Telangana.

ABSTRACT

A discrete time-domain modelling and design for the duty-cycle-controlled buck light-emitting diode (LED) driver is presented in this paper. The discrete time-domain equation representing the buck LED driver is derived and linearized about the equilibrium state. Also the switching control law, the proportional integral (PI) compensator is used here as an example of the error amplifier, is linearized about the equilibrium state. The linearized buck LED driver and the control law are then combined to arrive at a linearized duty-cycle-controlled buck LED driver. The root locus method is employed to analyze the dynamic performance of the closed-loop system. Based on the modelling result, a practical design equation for the PI compensator is derived. Experimental results are presented to verify the validity of the proposed PI compensator design.

INTRODUCTION

Over the past few years, light-emitting diode (LED) technology has emerged as a promising technology for residential, automotive, decorative, and medical applications. This is mainly caused by the enhanced efficiency, energy savings and flexibility, and the long lifetime. Today, LEDs are available for various colours and they are suitable for white illumination. The luminous flux of LEDs is mostly determined by the LED forward current. Controlling the current accurately is a challenge when each LED has a large manufacturing tolerance in its forward voltage. Therefore, the regulated constant current control is needed to achieve constant brightness of LEDs.Recently, many works, which include power factor correction methods, current sharing for LED strings, and thermal design, have been done for power LED applications.

Small-signal linearized modelling for the current regulated LED driver is of crucial importance in many applications not only for assessing stability and dynamic characteristics but for designing compensators. Numerous attempts have been made to characterize the switching converter system. The average concepts successfully used in the modelling of power converters.

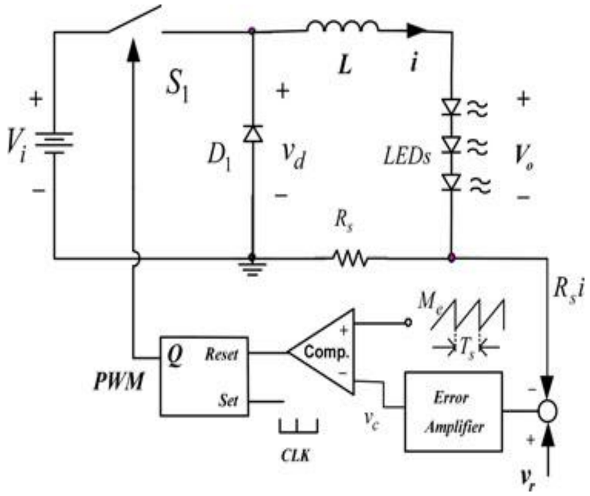


Fig.1Duty-cycle-controlled buck LED driver with constant-frequency controller.

ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal

The low-frequency response can be well predicted by the average models. However, one common issue of the average models is that they cannot predict sub harmonic oscillations in current-mode control. Exact discrete-time model can accurately predict responses. This numerical technique is not useful to be used in practical design. In order to extend the validation of the average models to the high-frequency range, modified average models are proposed based on the results of discrete-time analysis and sampled-data analysis.Allmentioned modelling approaches are related to voltage regulated converters. Very little work has been done in the area of modelingand control to improve dynamic performance of the current regulated LED driver.

In this paper, the systematic discrete time-domain approaches adapted to modelling and designing feedback compensator for the duty-cycle-controlled buck LED driver shown. Root-locus analysis is used to derive the stability boundaries and the practical design equation for selecting the optimum proportional-integral (PI) gains of the error amplifier. Experimental results are presented to confirm the validity of the proposed design method.

DESIGN GUIDELINES

Bode plots have been commonly used to assess the stability of the closed-loop system by finding the phase margin, but these plots cannot give information on the dynamic behaviorof the individual state variables. On the other hand, root-locus analysis can provide the engineer with the stability and the transient performance of the individual state variables related to the location of the roots of the characteristic equation. To analyze the stability and dynamic characteristics of the closed-loop system, the eigenvalues of the system matrix misevaluated. The eigenvalues of A is the solutions of

$|A - zI| = 0$ (14)

Where I is the identity matrix. The following root-locus analysis is performed for Rs= 1.

The root locus as a function of the P gain $kp$for kni= 0.2,D = 0.45, and Sr= 0.82 is shown in Fig. 2. Corresponding pole locations between the s-plane and the z-plane are shown. The eigenvalues $\lambda 1$ and $\lambda 2$ in the z-plane are mapped to s1and s1 , and s2 in the s-plane, respectively. Unlike the peakcurrent-controlled buck LED driver reported in, this dutycycle-controlled buck LED driver is unstable for kip= 0.

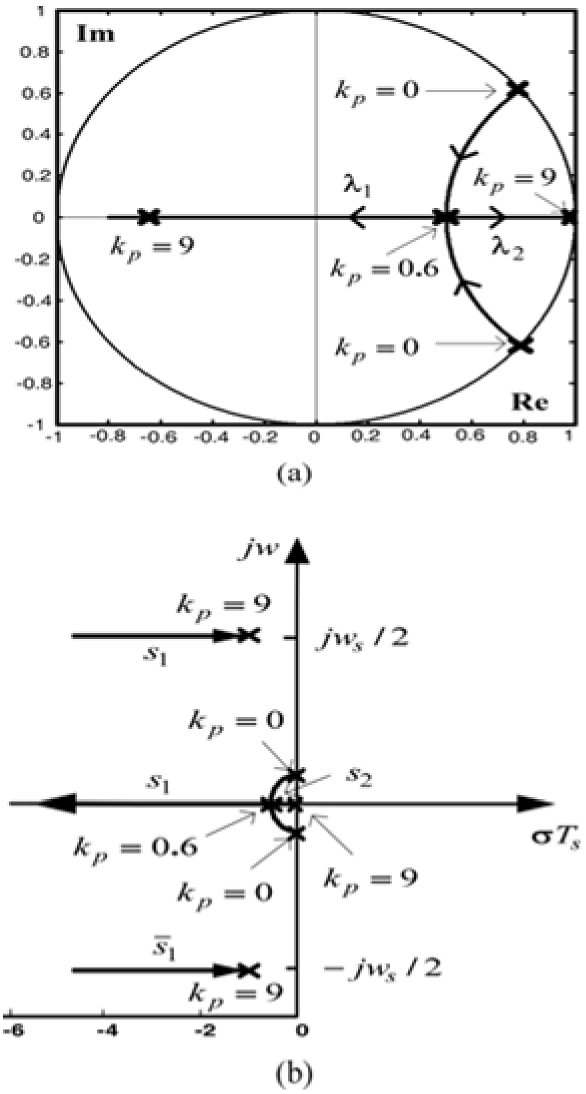


Fig. 2 Root locus as a function of the *P* gain *kp*: (a) in the *z*-plane and (b) in the *s*-plane (kni= 0.2, D = 0.45, Sr= 1.0D 1−D = 0.82).

The Eigen value $\lambda 1$ is dominated by the inductor current state. The transient response of $\lambda 1$ after a disturbance is underdampedwhen $kp$is between 0 and 0.6. At kp= 0.6, the system response is critically

ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal

damped. And then, $\lambda 1$ moves toward the origin of the unit circle with increasing *kp*, which means the inductor current becomes faster. When *kp*is greater than 0.6, the transient response of the inductor current is over damped. Increasing *kp*much further, the current response is under damped with a natural resonant frequency equal to *fs/*2 due to the negative real value of $\lambda 1$. On the other hand, the eigenvalue $\lambda 2$ is dominated by the capacitor voltage state of the error amplifier. The transient response of $\lambda 2$ is under damped when *kp*is between 0 and 0.6due to the two complex roots. Then, $\lambda 2$ moves toward the unit circle with increasing *kp*, which means the capacitor voltage becomes slower. The capacitor voltage is over damped when *kp*is greater than 0.6. The relationship between the *s*-plane poles and the *z*-plane poles is

$z = esTs|s=\sigma\pm jw= e\sigma Ts\pm wTs$.

The detailed information about the time response of the discrete system can be found in. The root locus as a function of the *I* gain *kni*for *kp*= 0.84,*D* = 0.4, and *Sr*= 1.0 is shown in Fig. 5. When the *I* gain *kni*is increased from 0 to 0.27, the transient response is changed from over damped to critically damped, and the overall system

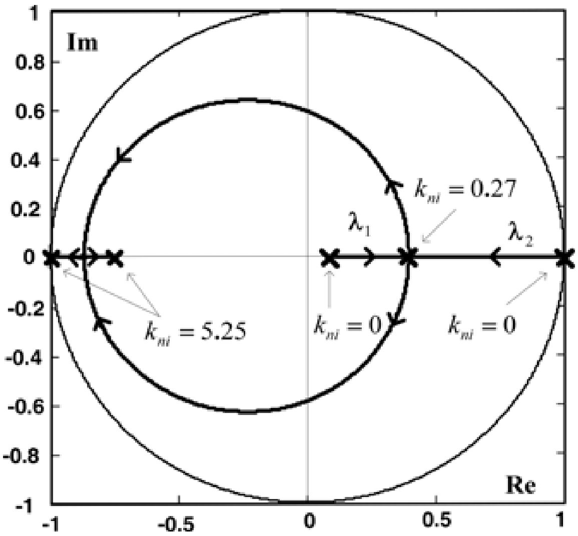


Fig. 3 Root locus as a function of the *I* gain *kni*(*kp*= 0.84, *D* = 0.4,*Sr*= 1.5*D*1−*D* = 1.0).

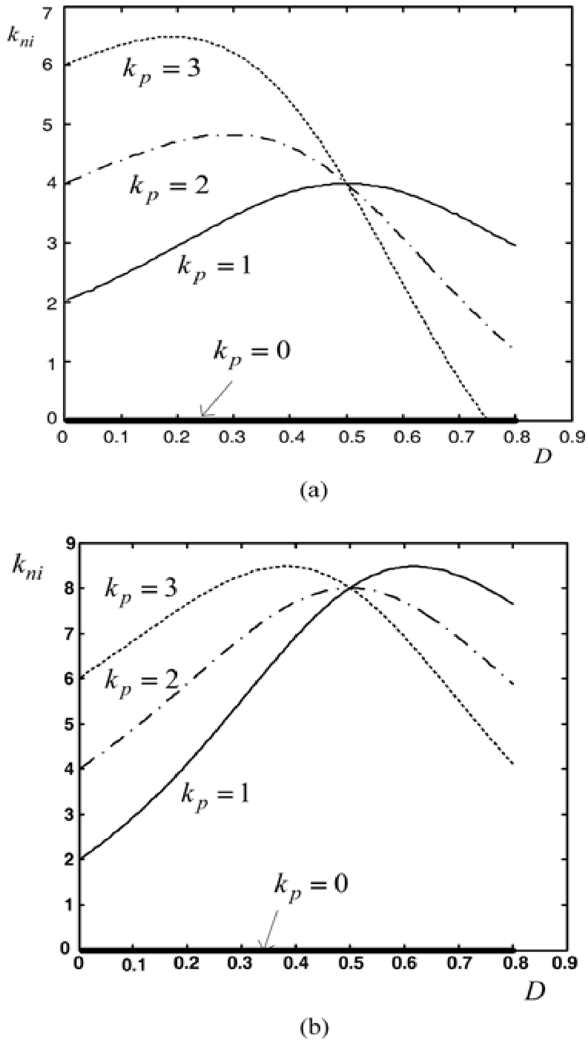
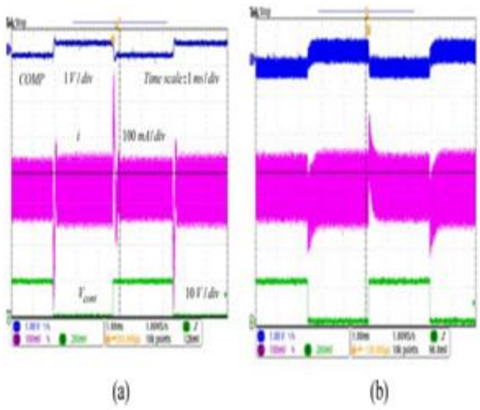
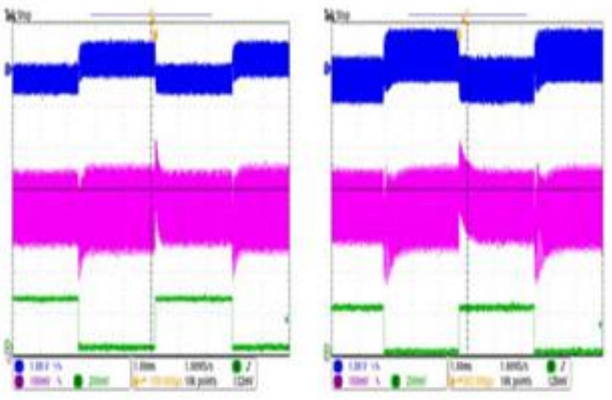


Fig. 4Theoretical stability boundaries of *kni*as a function of *D*. (a) *Sr*=1.0*D*1−*D* .(b) *Sr*= 2*D*1−*D* .

EXPERIMENTAL EVALUATION



ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal



(c) (d)

Fig. 5. Transient responses for step load change between 3 and 5 LEDs (*Vi*=40 V, *kni*= 0.2, *R_2* = 12 *k*, *C_1* = 10 nF). (a) *kp*= 0.1 (*R_1* = 0.5 *k*).(b) *kp*= 0.84 (*R_* 1 = 4.2 *k*). (c) *kp*= 1.3 (*R_1* = 6.5 *k*). (d) *kp*=2.0 (*R_1* = 10 *k*).

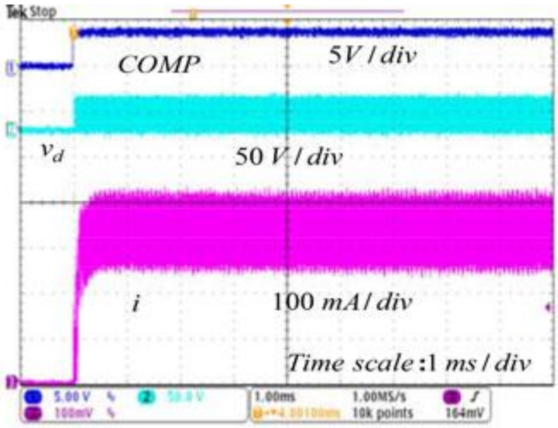
The constant switching frequency is 100 kHz. The normal operating range of *D* in the converter is between 0.2 and 0.6. In the experiment, the ramppeak-to-peak amplitude Δ*V* is 1.7/3 ≈ 0.567 V, which is generated with 13of the oscillator peak-to-peak amplitude 1.7 V. The ramp slope*Me*is Δ*V/Ts*= 0.567 × 100 × 103. The control IC is CS3842. *S* is IRF 840 and *D*1 is DSEI12-06A.Here, we use pure-white LEDs, Z-POWER w42182, whichhas a typical current of 350 mA. This LED forward voltage varies from 3.0 to 4.0 V, for a nominal of 3.25 V. The output voltage is approximately (3.25 V × 5 LEDs in series)

16.25 V. *Sri* is

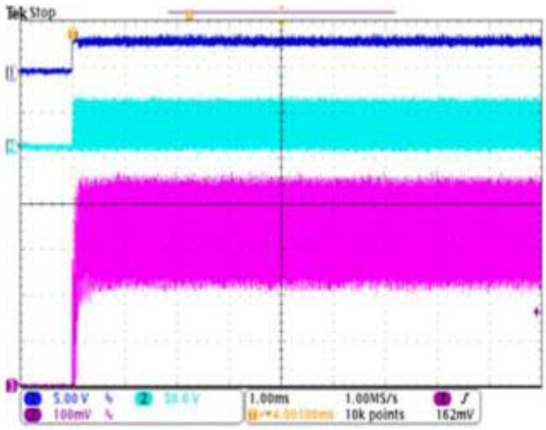
$$\frac{M_e}{(V_o R_s/L)}\frac{1}{k_{ni}} = \frac{0.567\times100\times10^3}{\{16.25\times1/(430\times10^{-6})\}}\frac{1}{k_{ni}} = \frac{1.5}{k_{ni}}$$

for*Rs*= 1Ω, and *Sr*is 1.5*D*/1−*D* . Setting *kni*= 0.2, *Sri* is 7.5., $\frac{k_p}{k_{ni}}$ is $(1-2D)+\sqrt{2(1-D)(S_{ri}\frac{2D}{1-D}-D)} = 4.0$ for the maximum *D* = 0.6. The designed *kp*is selected to be 0.84, which is slightly greater than 0.8 for *kni*= 0.2. The integralgainis*ki*= *kni/Ts*= 0.2 × 100 × 103 = 20 000. The PI gains are distributed throughout the feedback path between the current sense and the comparator input. The gain of LM324 is1.2*k*+7.4*k*/1.2*k* = 7.16. The function of LM 324 is converting the sensed *Rs*ito the internal reference voltage of the error amplifier.The average value of the output voltage of LM 324 isequal to the reference voltage of the error amplifier input, whichis 2.5 V in the datasheet [29]. From the datasheet, the internalgain between COMP and the comparator input is 13. Theoverall proportional gain *kp*and integral gain *ki*are 7.16/3× *R_1*/*R_2*and 7.16/3× 1/*R_2 C_1*, respectively. For the designed integral gain*ki*= 20 000, the values of *R_2* and *C_1* are chosen to be 12 k and 0.01 μF. For the designed proportional gain *kp*= 0.84, thevalue of *R_1* is chosen to be 4.2 k.

With five LEDs connected in series, which provides a typical loading voltage of approximately (3.25 V × 5 LEDs in series)

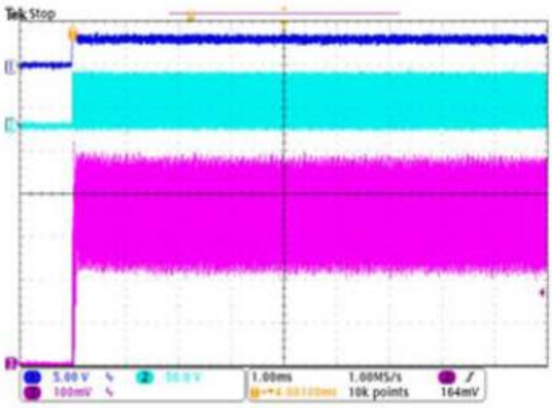


(a)

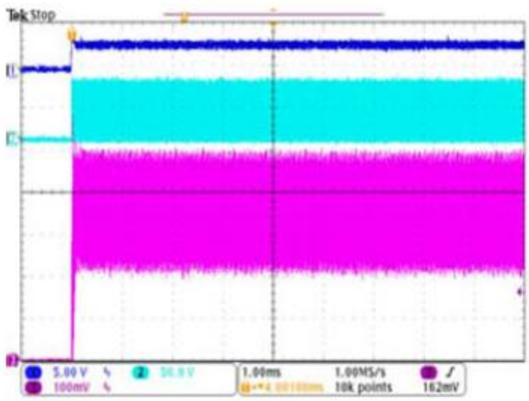


(b)

ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal



(c)



(d)

Fig.6Start-up transient responses with increasing the input voltage(*Vo*≈ 16.25 V, *kp*= 0.84, *kni*= 0.2). (a) *Vi*= 30*V* (*Sr*≈ 1.77).(b) *Vi* = 50*V* (*Sr*≈ 0.72) (c) *Vi*= 60*V* (*Sr*≈ 0.56) (d) *Vi* = 70*V*(*Sr*≈ 0.45).

16.25 V, the LED currents are measured for start-up transience with increasing *P* gain as shown. As the *P* gain increases from *kp*= 0.1 to *kp*= 1.3, the transient response ofthe LED current changes from under damped to over damped response, and then, to a slower and poor transient response due to the slower error amplifier state for*kp*= 2.0. This experimental response shows a good agreement with the prediction of the root-locus analysis.

CONCLUSION

A discrete time-domain modelling and analysis for the duty cycle-controlled buck LED driver has been presented. The discrete time-domain equation that represents the static and dynamic behaviour of the buck converter is derived and linearizedabout the equilibrium state of the buck converter. Also the duty cycle control law is linearized about the equilibrium state. Thelinearized buck converter and the linearized duty cycle control law are then combined to arrive at a linearized duty-cyclecontrolledLED driver.

The PI compensator is used as an example of the error amplifier. Increasing *P* gain from zero, the transient response of the inductor current state changes from under damped to overdamped,and then, to under damped with natural resonant frequency equal to half of the switching frequency. The duty-cyclecontrolledbuck LED driver is always unstable for *kp*= 0. The stable integral gain range is very wide for a given *P* gain. Impractical design, it is desirable that the transient response of the inductor current should be critically damped or slightly overdampedto avoid an oscillatory LED current. Based on thisconcept, the PI gains can be determined at the maximum *D*in the range of operating region. Therefore, for a good transient response, the *P* gain *kp*slightly greater than or equal to *kni*{(1−2*D*max)+_2(1−*D*max)(*Sri*2*D*max1−*D*m ax−*D*max)}can be selected. Selecting the PI gains of the error amplifier according to this practical design equation is very easy and useful for the design engineer. Experimental results are presented to confirm the validity of the proposed PI compensator design.

REFERENCES

[1] D. G. Lamar, M. Arias, A. Rodriguez, A. Fernandez, M. M. Hernando,and J. Sebastian, “Design-oriented analysis and performance evaluation of a low-cost high-brightness LED driver based on flyback power factorcorrector,” IEEE Trans. Ind. Electron., vol. 60, no. 7, pp. 2614–2626, Jul. 2013.

[2] Seoul Semiconductor Co., LTD. (2009). Z-power LED series–technicaldatasheet for X4218X.[Online].Available:http://www.seoulsemicon.com/kr/html/main/

[3] C. B. Park, B. H. Choi, J. P. Cheon, and C. T. Rim, “Robust active LEDdriver with high power factor and lowtotal harmonic distortion compatiblewith a rapid-start ballast,” J. Power Electron., vol. 14, no. 2, pp. 226–236,Mar. 2014.

[4] H. H. Chou, Y. S. Hwang, and J. J. Chen, “An adaptive output currentestimation circuit for a primary-side controlled LED driver,” IEEE Trans.Power Electron., vol. 28, no. 10, pp. 4811–4819, Oct. 2013.

[5] Q. Hu and R. Zane, “Minimizing required energy storage in off-line LED drivers based on series-input converter modules,” IEEE Trans. PowerElectron., vol. 26, no. 10, pp. 2887–2895, Oct. 2011.

[6] W. Chen and S. Y. R. Hui, “Elimination of an electrolytic capacitor inAC/DC light-emitting diode(LED) driver with high input power factorand constant output current,” IEEE Trans. Power Electron., vol. 27, no. 27, pp. 1598–1607, Mar. 2012.

[7] Y. X. Qin, H. S. H. Chung, D. Y. Lin, and S. Y. R. Hui, “Current source ballast for high power lighting emitting diodeswithout electrolytic capacitor,”in Proc. IEEE Ind. Electron. Conf., 2008, pp. 1968–1973.

[8]J.M.Alonso,J.Vina,D.G.Vaquero,G.Martinez, andR.Osorio, “Analysisand design of the integrated double buck-boost converter as a high-powerfactordriver for power-LED lamps,” IEEE Trans. Ind. Electron., vol. 59,no. 4, pp. 1689–1697, Apr. 2012.

[9] F. Zhang, J. Ni, and Y. Yu, “High power factor AC-DC LED driver withfilm capacitors,” IEEE Trans. Power Electron.,” vol. 28, no. 10, pp. 4831–4840, Oct. 2013.

[10] Q. Luo, S. Zhi, C. Zou, W. Lu, and L. Zhou, “An LED driver withdynamic high-frequency sinusoidal bus voltage regulation for multistringapplications,” IEEE Trans. Power Electron., vol. 29, no. 1, pp. 491–500,Jan. 2014.

[11] X. Wu, C. Hu, J. Zhang, and C. Zhao, “Series-parallel autoregulatedcharge-balancing rectifier for multioutput light-emitting diode driver,”IEEE Trans. Ind. Electron., vol. 61, no. 3, pp. 1262–1268, Mar. 2014.

[12] X. Wu, Z. Wang, and J. Zhang, “Design considerations for dual-outputquasi-resonant flyback LED driver with current-sharing transformer,”IEEE Trans. Power Electron., vol. 28, no. 10, pp. 4820–4830, Oct. 2013.

[13] K. H. Loo, Y. M. Lai, and C. K. Tse, “Design and analysis of LCCresonant network for quasi-lossless current balancing in multistring ACLEDarray,” IEEE Trans. Power Electron., vol. 28, no. 2, pp. 1047–1059,Feb. 2013.

[14] J. Patterson and R. Jane, “Series input modular architecture for drivingmultiple LEDs,” in Proc. IEEE Power Electron. Spec. Conf., Athens,Greece, Jun. 2008, pp. 2650–2656.

[15] S. Y. R. Hui and Y. X. Qin, “A general photo-electro-thermal theory forlight emitting diode (LED) systems,” IEEE Trans. Power Electron., vol.24, no. 8, pp. 1967–1976, Aug. 2009.

[16] R. D. Middlebrook, “Modeling current-programmed buck and boost regulators,” IEEE Trans. Power Electron., vol. 4, no. 1, pp. 36–52, Jan. 1989.

[17] G. K. Schoneman and D. M. Mitchell, “Output impedance considerationsfor switching regulators with current-injected control,” IEEE Trans. PowerElectron., vol. 4, no. 1, pp. 25–35, Jan. 1989.

[18] F. C. Lee, R. P. Iwens,Y.Yu, and J. E. Triner, “Generalized computer-aided discrete-timemodeling and analysis of dc-dc converters,” IEEE Trans. Ind. Electron. Contr. Instrum., vol. IECI-26, no. 2, pp. 58–69, May 1979.

ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal

[19] R. B. Ridley, "A new, continuous-time model for current-mode control,"IEEE Trans. Power Electron., vol. 6, no. 2, pp. 271–280, Apr. 1991.

[20] F. D. Tan and R. D. Middlebrook, "A unified model for currentprogrammedconverters," IEEE Trans. Power Electron., vol. 10, no. 4,pp. 397–408, Jul. 1995.