Single-loop control scheme for electrolytic capacitor-less AC–DC rectifiers with PFC in continuous conduction mode

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A new simplified control scheme is proposed for AC–DC electrolytic capacitor-less converters operating in continuous conduction mode (CCM). The proposed method has a single-loop controller responsible for both regulation and power factor correction (PFC). In comparison with the two-loop conventional CCM current mode controller, the proposed scheme does not need a multiplier or extra sensors hence simplifying the control circuitry and its design procedures. Modelling of the closed-loop converter is addressed and experimental results are provided to show the feasibility of the control scheme.

Introduction: The crucial part that identifies the lifetime of an AC–DC converter is the bulky electrolytic capacitor (E-Cap). Single-stage AC–DC converters normally use an E-Cap to balance between the pulsating input power and the constant output power while minimising the current ripple at the double line frequency. This limits the lifespan of the converter to the own E-Cap lifespan which is typically between 1000 and 10,000 h at the maximum rating temperature range from 85 to 105°C. This is considerably lower than the lifespan of the devices driven by AC–DC converters such as in emerging LED and electrical vehicle applications. In addition, according to Arrhenius's law, the life of E-Cap is temperature dependent which is doubled when ambient temperature is 10°C lower. Even with temperature operation at 95°C, the lifespan is only pushed to 4000 h [1]. Consequently, eliminating the E-Cap is mandatory and many research efforts have devoted to this topic [2, 3].

In high and medium power applications, continuous conduction mode (CCM) is commonly used which results in better efficiency. In addition to the two-stage circuit, wherein the first stage is usually an AC–DC boost converter that operates in CCM as a power factor correction (PFC) pre-regulator and the second stage is a DC–DC converter for regulating the output voltage or current according to the load demand, a bulky E-Cap is usually used for DC coupling and performing power balance between the AC input and the DC output. Moreover, under CCM, the controller has two loops, namely, the outer voltage loop for output regulation and the inner current loop for PFC. For these reasons, PFC circuits for a high-power application should consider the system simplicity, lifetime, the component counts and the solution total cost. The LED drivers and EV battery chargers are two trend applications wherein the performance, lifetime, the component counts and cost are vital parameters for their AC–DC converters.

LED technology has several merits over the conventional lighting devices such as high efficiency, very long lifespan ($\sim 100,000$ h) and a lower power consumption. That is why it is being used in many lighting and display applications. The two main disadvantages that affect negatively the LED lighting industry and prevent the market penetration are the high cost of the LED driver and its lifespan. AC–DC LED drivers may have a lifespan shorter than the lifespan of LED chips if E-caps are used in their construction. Therefore, using a Film or ceramic capacitor is considered as an optimal solution for replacing the E-Cap. However, with Film and ceramic capacitors the low-frequency LED current ripple increases due to their low energy density. Fortunately, LED lamps can be driven by a relatively high-ripple current with a limited peak-to-average ratio without affecting their chromatic and lighting characteristics [4].

In this Letter, a simple compensation and control scheme is proposed for both PFC and sinusoidal current control in an AC–DC LED driver. The scheme can be applied indistinctly for different driver topologies such as buck, boost, flyback, Ćuk, SEPIC and buck–boost operating in CCM with both linear and non-linear loads. The proposed single-loop control technique takes the advantages of eliminating the bulky E-Cap and replacing it with Film one to increase the converter's lifetime. The compensation technique processes the error signal between the LED current and a suitable reference by using a typical one-zero two-poles type II compensator. In this way, a single-loop high bandwidth second-order compensation scheme is used to achieve the same results of a typical two-loop control scheme that is conventionally used for regulation and PFC.

Modelling of the power stage: The complete circuit diagram of the considered system is shown in Fig. 1. The dashed block in this figure can be any chosen single-switch topology. Here, we use an AC–DC rectifier based on a canonical boost converter topology loaded by an LED for designing and validating the proposed single-loop. The converter operates in CCM and therefore the averaged state equations for the power stage can be expressed as follows:

$$\frac{dv_C}{dt} = -\frac{v_C - V_F}{Cr} + \frac{1}{C} i_L (1-d) \tag{1}$$

$$\frac{di_L}{dt} = -\frac{V_F + r i_o + v_d}{L}(1-d) + \frac{v_{in}}{L} \tag{2}$$

where v_C is the average output capacitor voltage, V_F is the forward LED voltage, $r = r_F + r_s$, r_F being the LED internal resistance and r_s the current sensor resistance, C is the capacitance of the converter capacitor, i_L is the inductor current, i_o is the output current, L is the inductance of the inductor, v_{in} is the input voltage and v_d is the forward voltage drop of diode D when it turns on and d is the duty cycle of the PWM signal. The d-to-i_o transfer function for the system is given by

$$G_{id}(s) = \frac{(D-1)(V_F + rI_o)}{LC} \frac{\frac{I_o L}{(V_F + I_o r)(D-1)^2} s - 1}{s^2 + \frac{1}{rC} s + \frac{(D-1)^2}{LC}} \tag{3}$$

where D and I_o are the DC values of the duty cycle d and the output current i_o, respectively.

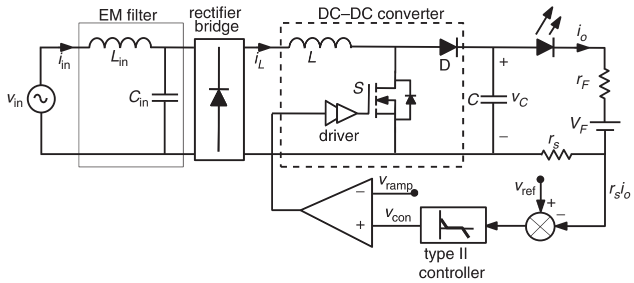

Fig. 1 *Unified circuit diagram of the AC–DC rectifier with the proposed single-loop control scheme*

Modelling the single-loop LED current controller: The conventional current mode controller in a boost converter under CCM is used for reshaping the input current to perform PFC. This is usually done by using two control loops, the first one is an inner current loop, wherein sensing both the inductor current and the rectified sine voltage to generate the reference current. The second loop is an outer controller, wherein the output voltage or current is sensed and then processed by a low bandwidth compensator with a cutoff frequency less than 50 Hz for regulating the output voltage or current [5, 6]. Here, both regulation and PFC are achieved by using a single-loop control. In particular, a typical type II compensator is used for controlling the LED current by processing the error $v_{ref} - r_s i_o$. Its transfer function is as follows:

$$G(s) = \kappa_p \frac{\omega_c (1 + s\tau)}{s\tau (s + \omega_c)} \tag{4}$$

where κ_p is the proportional gain, τ is the time constant and ω_c is the cut-off angular frequency. The output of this controller is the control signal v_{con} which is compared with the periodic ramp modulating signal v_{ramp} with frequency f_s and amplitude V_M to generate the duty cycle d.

Controller design: The transfer function G_{id} of the boost converter has a right half-plane zero and two poles. Thus, the compensation design should be carefully tackled. The type II compensator has one zero and two poles, one at zero frequency (integrator) for the regulation. The other pole is placed at a relatively high frequency (1 kHz) to attenuate the high frequency switching harmonics. Fig. 2 shows the bode diagram of the total loop gain of the system. Using the bode plot depicted in this figure, a phase margin of about 103° and a gain margin of about 21 dB can be selected at a crossover frequency of about 1 kHz which is much better than the one that can be achieved using a two-loop control approach.

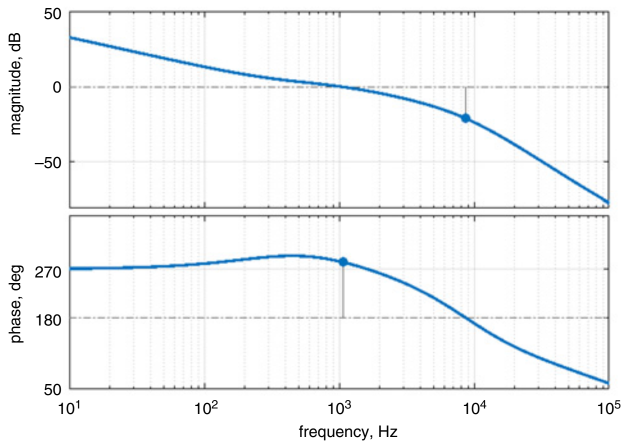

Fig. 2 *Bode plot for the total loop gain of the proposed single-loop LED boost driver*

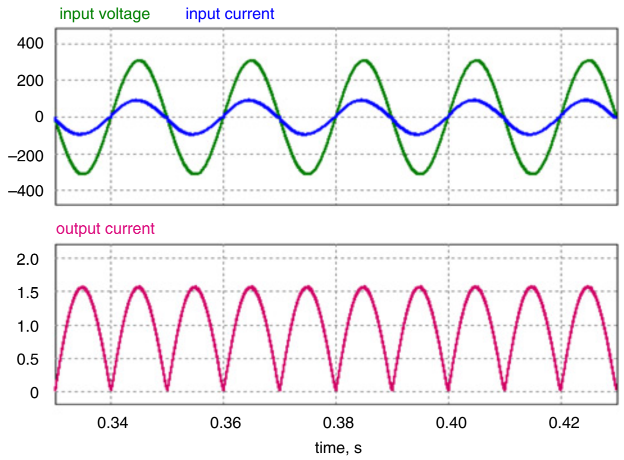

Fig. 3 *Simulated results showing the waveforms of the input voltage v_{in}, input current i_{in} and LED current i_o at 220 V*

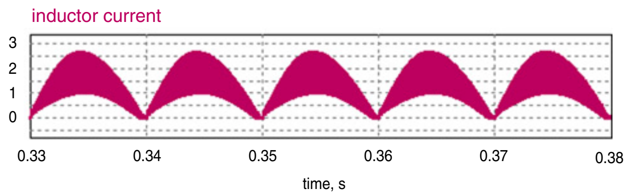

Fig. 4 *Simulated result showing the waveform of the inductor current i_L at 220 V*

Numerical simulations and experimental validation: To validate the feasibility of the proposed single-loop control approach, numerical simulations are performed on a case study of an AC–DC LED boost driver. Experimental measurements from a laboratory prototype of the same system are also provided. The system parameters for the AC–DC boost converter are as follows. The input voltage is a universal AC voltage with RMS value $V_{in} = 85$--240 V at 50 Hz, the output voltage is $V_o = 250$ V, the output current is $I_o = 1$ A, the switching frequency is $f_s = 100$ kHz, amplitude of the ramp signal $V_M = 5$ V, the controller gain $\kappa_p = 0.05$ and the time constant $\tau = 0.5$ ms, the input filter capacitor is $C_f = 0.5$ μF, the input filter inductor is $L_f = 160$ μH, the inductance of the inductor is $L = 260$ μH and the output Film capacitor from KEMET is $C = 1$ μF. Figs. 3 and 4 show the steady-state waveforms of input voltage v_{in}, input current i_{in} (scaled by a factor of 50), RMS output current i_o and RMS inductor current i_L at 220 V obtained from numerical simulations using PSIM© software. Figs. 5 and 6 show the steady-state experimental results waveforms for input voltage v_{in}, input current i_{in}, LED RMS current i_o and RMS inductor current i_L at 220 V. From simulations and experimental measurements, it can be observed that the average value of the LED current is regulated to its desired value, the line voltage and current are distortion free and on phase resulting on a PF of 0.99 hence complying with ENERGY STAR standard and also meeting the IEC61000 3-2 for harmonics distortion standard. The agreement between the numerical simulations and the experimental measurements is remarkable.

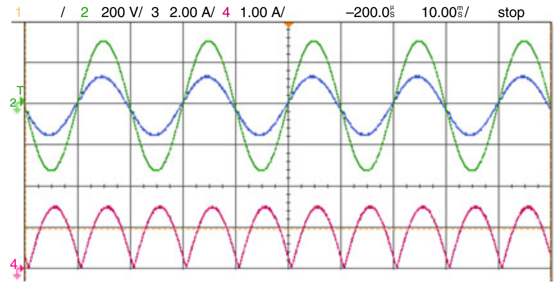

Fig. 5 *Experimental results showing waveforms of the input voltage v_{in}, input current i_{in} and load current i_o at 220 V*

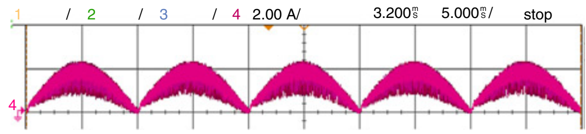

Fig. 6 *Experimental result waveform showing inductor current i_L at 220 V*

Conclusions: A simple and cost-effective single-loop control technique for both regulation and PFC has been presented for AC–DC rectifiers operating in CCM. The single-loop controller can be easily designed by simple analogue devices. Compared to the conventional two-loop control strategy, the proposed technique does not use a multiplier, an extra input current sensor nor a voltage sensor for the rectified sine wave source voltage. The numerical simulations and the experimental results have shown that the proposed method has similar performance as the conventional two-loop strategy and it complies with ENERGY STAR and IEC61000 3-2 standards for high and medium power converters such as those used in EV charging and LED driving applications.

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One or more of the Figures in this Letter are available in colour online.

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