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Assessment of the Current and Voltage Ripples of a Buck Converter as a Driver for LEDs Using a Non-Resistive Model

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Abstract: The main contribution of this paper is the assets of the current and voltage ripples in a buck converter with an LED load. The results indicate that the ripples are different and that it is possible to reduce the passive filter concerning the model of the LED as a simple resistance. The paper presents the design and simulation of a buck converter as a power supply for an LED lamp. Modeling the LED as a resistor and a voltage source (SVRM), the equations to calculate the components of the circuit using the SVRM model are presented, where the Fourier series and phasors are used to calculate the output filter. The equations are validated with SPICE simulations. The results indicate that the SVRM model for the LED load affects the calculation of the output filter of the buck converter as well as the voltage and current ripples, making it a more precise design alternative to the proposed development.

Keywords: LED lamp; buck; converter; SVRM model; PSPICE

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1. Introduction

The use of lighting represents a significant portion of energy consumption, accounting for 25% of the world's total electricity production. The use of Light-Emitting-Diode (LED) lamps are being more and more usual, mainly because of the attractive characteristic of LEDs such as high luminous efficacy, long lifetime, robustness, and small size when compared with a traditional lamp [1,2].

To take advantage of these benefits, all the circuits associated with the power supply of the LED must have maintained them. Efficiency, longevity, and minimal maintenance are critical factors to consider when designing the power supply assembly for LED lamps.

Many LED driver architectures have been developed to meet these requirements, while also satisfying the specific demands and limitations of diverse LED lighting applications. Typically, these LED drivers are derived and adapted from fundamental AC-DC and/or DC-DC converter topologies. However, it is common that the design of these topologies is based on the consideration of the LED as a resistive load, as is mentioned in [3–5]. This is not entirely correct, because it is assumed that the voltage and current ripples in the LED are the same, which is false due to the characteristics of the device itself, which leads to an inaccurate design [6].

The main contribution of this paper is the approach of a method that allows a determination of more precise equations to calculate the output filter elements of the DC-DC converter, by considering a model for the load represented by the LED in the circuit. By using this design methodology, it can be determined that it mainly influences the actual value of the capacitance required in the circuit. The proposed equations allow a more precise calculation of the value of the main components that will be used in the design of the circuit.

2. Materials and Methods

To determine and evaluate the output filter, the LED load that will be fed at the output is considered. Engineering modeling is primarily based on representation through equations that allow the representation of physical systems, as well as their behavior and response to different variables. However, to obtain models that allow us to represent a strong precision of the behavior in LED lighting converter systems, mathematical modeling must include equations that include the parameters that most closely resemble the real model of the system intended to analyze [7–9].

From the analysis of the literature, there is a tendency to simplify the design of power converters by representing LED charging as a resistor [10]. Representing the LED load as a resistor implies that parameters such as voltage and current ripples that influence the behavior of the circuit are not considered [11].

2.1. Model of a Load LED

The physical model of the LED is the well-known Shockley equation. However, this physical model is not very suitable for the design of power converters. A more simplified model involves modeling the converter load as a voltage and resistance source circuit to represent the LED load [12,13]. This paper focused on the operation of the DC-DC buck converter by modeling the LED as a serial voltage source with a resistor. With this analysis, equations are obtained that consider the voltage and current ripples that will influence the output capacitor. The proposed analysis for the output filter of the buck converter is based on the Fourier series and phasors to calculate the elements. The proposed solution guarantees accuracy in the calculation of design elements that are considered fundamental for any LED driver used in lighting systems. The present study aims to evaluate the impact of implementing the Source Voltage Resistor Model (SVRM) to model the LED load, specifically in terms of changes in current and voltage ripples. The SVRM model is composed of an ideal diode in series with a combination of a voltage source that represents the threshold voltage of the LED (V_{TH}) and its characteristic resistance (R_{LED}) represented in Figure 1.

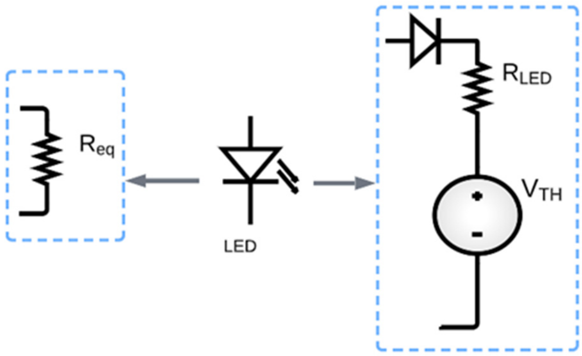


Figure 1. Resistive and SVRM LED model.

Within the literature, there are models available that replicate the behavior of LEDs, which take into consideration the impact of thermal effects. Such models have been documented in publications such as [10,12]. However, in applications for LED lighting systems, most of the proposed models model the output load (LED lamp) as a resistor, without considering the percentage error implied by this model, because the calculations are based solely on power and voltage, ignoring the actual current circulating in the circuit. As a result, the output waves observed in the circuit do not match those calculated by the modeling.

2.2. LED Linear Modeling

Similar to a conventional diode, the flow of current through an LED commences only when the threshold voltage (Vth) is surpassed. Subsequently, the current increases proportionally to the slope dictated by the characteristic resistance (R_{LED}). The characterization of the load is performed in this case by a strip of LED.

Figure 2 shows the behavior obtained from experimental data for a strip of 300 white LEDs of the brand Concept Car model 3528. The threshold voltage of the LED leads to a shift in its output voltage, consequently changing the correlation between the waveforms of current and voltage. As reported in the literature [14], the voltage of an LED is calculated using the Shockley equation, which is illustrated in Equation (1).

$$v_o = i_o R_s + \frac{E_g}{q} + \frac{nkT_j}{q} \ln\left(\frac{i_o}{C}\right) \tag{1}$$

where v_o is the LED voltage, R_s is the small signal resistance of the LED, i_o is the LED current, k is the Boltzmann's constant, E_g is the bandgap energy, T_j is the junction temperature, n is the ideality factor, C is a device parameter and q is the magnitude of the electronic charge. Based on the diode equation, it is evident that the connection between voltage (v_o) and current (i_o) is nonlinear. Nonetheless, Equation (1) is considerably more intricate compared to the SVRM, which serves as a linear approximation.

$$v_o = i_o R_{LED} + V_{th} \tag{2}$$

Equation (2) is simpler since it solely reflects the linear slope of the LED's constant behavior. The non-linear characteristics are incorporated through the use of an ideal SVRM diode, which restricts the flow of current in the opposite direction. The voltage threshold does not operate as a source, and current can only pass through once the voltage surpasses the threshold.

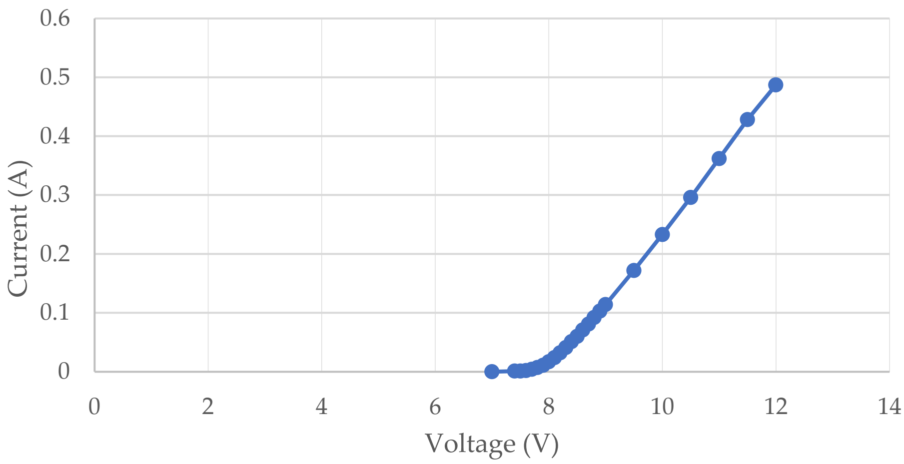


Figure 2. V-I curve of the LED strip model 3528.

2.3. Analysis of the Equation for Buck Converter with LED Load

The use of the SVRM model of LEDs has been examined and discussed in prior studies [15–17]. This section elaborates on the analysis conducted to simulate the performance of the proposed DC-DC buck converter as an LED driver and demonstrates the variances that emerge when the SVRM is treated as a load. It should be noted that the inclusion of the SVRM model parameters will have an impact on the complete analysis of the converter.

The analyzed circuit, consisting of a buck converter, is shown below in Figure 3. To calculate the parameters considering the SVRM model of the circuit, the average current in the LED is obtained by clearing Equation (3).

$$P = \frac{1}{T}\int_0^T i_{led} v_{led}\, dt = I_{led} V_{led} \tag{3}$$

where I_{led} and V_{led} are the average values of i_{led} and v_{led}, respectively. Clearing and substituting the current is obtained as a function of the power, as shown in Equation (4):

$$I_{led} = \frac{P}{V_{led}} \tag{4}$$

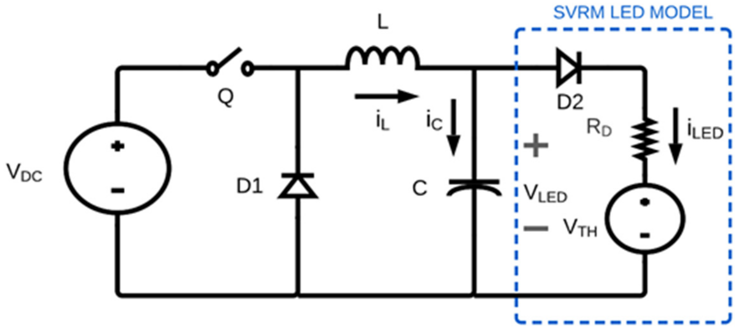


Figure 3. Buck converter circuit with SVRM model.

Subsequently, it is possible to calculate the value of the LED resistance from Ohm's law:

$$R_D = \frac{V_{led} - V_{th}}{I_{led}} \tag{5}$$

The duty cycle at which the converter will be operating is determined by Equation (6).

$$D = \frac{V_{led}}{V_{DC}} \tag{6}$$

2.3.1. Inductor Equation Analysis

The waveform of the current in the inductor L is assumed for a complete cycle, as shown in Figure 4. In this Figure, I_{led} represents the average value of the current i_L and Δi_L is the ripple.

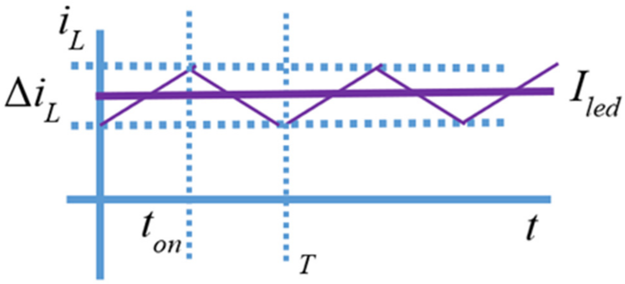


Figure 4. Inductor current waveform.

Analyzing the waveform in the inductor, the equation that defines this graph is:

$$v_L = L\frac{di}{dt} = v_{D1} - v_{led} \tag{7}$$

And

$$v_{D1} = \begin{cases} V_{DC} & 0 < t < t_{on} \\ 0 & t_{on} < t < T \end{cases} \tag{8}$$

Taking Figure 4 as a reference, if the switch (Q) is on $V_{D1} = V_{DC}$, assuming $v_{led} = V_{led}$ and equal to its average value:

$$V_{DC} - V_{led} = L\frac{\Delta i_L}{t_{on}} \tag{9}$$

The "on" time t_{on} from the definition of the duty cycle D can be expressed as:

$$D = \frac{t_{on}}{T} \therefore t_{on} = DT \quad (10)$$

Substituting these expressions, it is possible to determine an equation for the value L of the inductor, as developed in the following equation:

$$L = \frac{(V_{DC} - V_{led})t_{on}}{\Delta i_L} = \frac{(V_{DC} - V_{led})DT}{\Delta i_L} \quad (11)$$

$$L = \frac{(V_{DC} - V_{led})D}{\Delta i_L f_s} \quad (12)$$

Defining the current ripple in the normalized inductor:

$$r_{iL} = \frac{\Delta i_L}{I_{led}} \rightarrow \Delta i_L = I_{led} r_{iL} \quad (13)$$

where Δi_L is the current ripple in the inductor and I_{led} is the average current in the LED.

2.3.2. Capacitor Equation Analysis

To determine the value of the output capacitor C, the circuit shown in Figure 5 is analyzed, where i_{L1} represents the fundamental component of the current in the inductor i_L. This circuit can be analyzed using phasors and Fourier series. Since all the harmonics of the current in the inductor are filtered, only the fundamental component and the DC component pass.

$$\begin{aligned} I_L &= I_C + I_{led} \\ I_C &= 0 \\ I_L &= I_{led} \end{aligned} \quad (14)$$

where i_{L1} is the fundamental component of the current in the inductor, i_{R1} is the fundamental current component in the LED, i_{C1} is the fundamental component of the current in the capacitor, v_C would represent the voltage ripple in the capacitor. Solving by phasors we have a current divider:

$$\begin{aligned} \frac{I_{R1}}{I_{L1}} &= \left| \frac{-jX_c}{R_D - jX_c} \right| \\ \frac{I_{R1}}{I_{L1}} &= \frac{1}{a} = \frac{X_c}{\sqrt{R_D^2 + X_c^2}} \end{aligned} \quad (15)$$

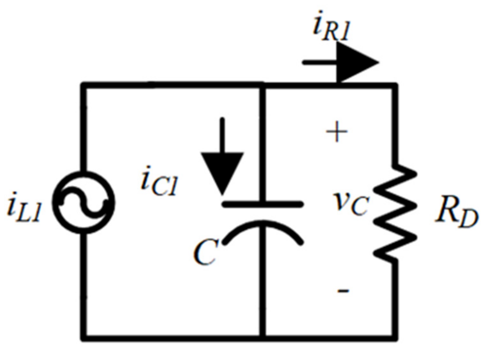


Figure 5. Circuit analysis for capacitor calculation.

In Equation (15), X_c represents the reactance of capacitor C for the fundamental frequency, I_{R1} represents the peak value of the fundamental component of the current in R_D, I_{L1} is the peak value of the fundamental component of the current in the inductor $L1$ and a is that both I_{R1} will be reduced concerning I_{L1}. The higher the value of a, the lower the ripple of voltage and current in the load. Clearing C from the above Equation (16) develops the following Equation (17):

$$\begin{aligned} &\frac{1}{a} = \frac{X_C}{\sqrt{R_D^2+X_C^2}} = \frac{\frac{1}{\omega C}}{\sqrt{R_D^2+\frac{1}{\omega^2 C^2}}} = \frac{1}{\sqrt{\omega^2 C^2 R_D^2+1}} \\ &\omega^2 C^2 R_D^2 = a^2+1 \end{aligned} \quad (16)$$

$$C = \frac{\sqrt{a^2+1}}{\omega R_D} = \frac{\sqrt{a^2+1}}{2\pi f_s R_D} \quad (17)$$

If $a >> 1$:

$$C \approx \frac{a}{2\pi f_s R_D} \quad (18)$$

2.3.3. Relationship between Voltage and Current Ripples in the LED

Taking Figures 4 and 5 as a reference, Equation (19) is established:

$$i_{L1} = I_{L1}\sin(\omega t+\phi) = I_{L1}\sin(2\pi f_s t+\phi) \quad (19)$$

where I_{L1} is the maximum current of i_{L1}. Defining the current ripple in the inductor as the peak-to-peak current of de i_{L1} yields:

$$\Delta i_L \approx I_{L1p-p} \approx 2I_{L1} \quad (20)$$

Clearing:

$$\Delta i_L = r_{iL} I_L = r_{iL} I_{led} = 2I_{L1} \quad (21)$$

Substituting Equations (20) and (21) establishes:

$$I_{L1} = \frac{r_{iL} I_{led}}{2} \quad (22)$$

Figure 6 shows the fundamental current in the LED i_{R1}. The value I_{R1} is the maximum value and Δi_{R1} is the peak to peak value of the waveform. From the waveform observed in the following Figure 6, and analyzing the circuit of Figure 5, Equation (23) is obtained.

$$v_{C1} = i_{R1} R_D = V_{C1}\sin(\omega t) = V_{C1}\sin(2\pi f_s t) \quad (23)$$

where V_{C1} is the maximum voltage of v_{C1}. Defining the voltage ripple in the capacitor as the peak-to-peak voltage of v_{C1}:

$$i_{L1} = I_{L1}\sin(\omega t+\phi) = I_{L1}\sin(2\pi f_s t+\phi) \quad (24)$$

where I_{L1} is the maximum current of i_{L1}. Defining the current ripple in the inductor as the peak-to-peak current of i_{L1} develops:

$$\Delta v_c \approx V_{C1p-p} = 2V_{C1} \quad (25)$$

$$r_v = \frac{\Delta v_C}{V_{led}} = \frac{2V_{C1}}{V_{led}} = \frac{2I_{R1} R_D}{V_{led}} \quad (26)$$

$$I_{R1} = \frac{r_v V_{led}}{2R_D} \quad (27)$$

Calculating the converter capacitor based on the voltage and current ripples yields:

$$\frac{I_{R1}}{I_{L1}} = \frac{1}{a} = \frac{X_c}{\sqrt{R^2+X_c^2}} = \frac{\frac{r_v V_{led}}{2R_D}}{\frac{r_{iL} I_{led}}{2}} = \frac{r_v V_{led}}{r_{iL} I_{led} R_D} \quad (28)$$

where:

$$a = \frac{r_{iL} I_{led} R_D}{r_v V_{led}} \tag{29}$$

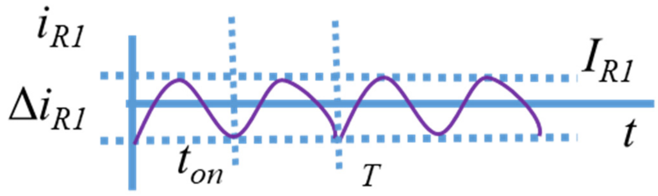


Figure 6. Fundamental component of the current waveform in the LED.

2.3.4. Component Selection from Conduction Losses

To carry out simulations of the proposed topology, it is sought to select a component that adjusts from the conduction losses as a percentage of the total power.

$$P_{cM} = \%P_M P \tag{30}$$

Driving losses can be expressed as:

$$P_{cM} = I_{MRMS}^2 R_{ds(on)} \tag{31}$$

where $R_{ds(on)}$ is the drainage-source resistance of the component during the power state:

$$R_{ds(on)} = \frac{P_{cM}}{I_{MRMS}^2} = \frac{\%P_M P}{I_{MRMS}^2} \tag{32}$$

The effective current is set as:

$$I_{MRMS} = \sqrt{\frac{1}{T}\int_0^T i_M^2 dt} = \sqrt{\frac{1}{T}\int_0^{t_{on}} I_L^2 dt} = I_L\sqrt{D} = \frac{P\sqrt{D}}{2V_{DC}} \tag{33}$$

If the losses are proposed as a percentage of the total power, it is possible to select the appropriate one for the converter. This is represented by Equation (34).

$$R_{ds(on)} = \frac{\%P_M P}{\frac{P^2 D}{V_{DC}^2}} \leq \frac{\%P_M V_{DC}^2}{PD} \tag{34}$$

3. Results

This section presents the results obtained from the equations proposed in the previous section. Specifically, a design for a buck converter is proposed using these equations for study purposes. It is notable to observe that the design with these equations considers the parameters of the behavior of the converter circuit with the AC and DC components that intervene in the operation of the source.

3.1. Design Specifications

The equations derived can be utilized to determine the necessary parameters for designing a converter intended for LED lamp applications. The necessary values of the components for the design of the buck converter can be determined. This converter will be connected to a load of LED strips, with the required operation specifications being shown in Table 1.

Table 1. Parameter specifications of the buck converter.

Parameter	Symbol	Value
Voltage on the LED	V_{LED}	12 V
Threshold Voltage	Vth	9.1 V
LED Resistance	R_D	7.76 Ω
Power	P	5.84 W
Switching frequency	f_s	100 kHz
Supply voltage	V_{DC}	24 V
Normalized voltage ripple	r_v	0.01
Normalized current ripple	r_{iL}	0.2

3.2. Equations for the Buck Converter

Once the operating characteristics of the converter and the required output characteristics are known, Table 2 presents the equations required to determine the necessary component values for designing the buck converter.

Table 2. Equations for the Buck converter.

Parameter	Equation	Value
LED Current	$I_{led} = \frac{P}{V_{led}}$	$\frac{35\ \text{W}}{12\ \text{V}} = 2.916\ \text{A}$
LED Resistance	$R_D = \frac{V_{led} - V_{th}}{I_{led}}$	$\frac{12\ \text{V} - 6\ \text{V}}{2.916\ \text{A}} = 2.057\ \Omega$
Duty Cycle	$D = \frac{V_{led}}{V_{DC}}$	$\frac{12\ \text{V}}{24\ \text{V}} = 0.5$
Inductor	$L = \frac{(V_{DC} - V_{led})D}{I_{led} r_{iL} f_s}$	$\frac{(24\ \text{V} - 12\ \text{V})0.5}{(2.916\ \text{A})(0.2)(10^5\ \text{Hz})} = 102.9\ \mu\text{H}$
Capacitor	$C = \frac{\sqrt{\left(\frac{r_{iL} I_{led} R_D}{r_v V_{led}}\right)^2 + 1}}{2\pi f_s R_D}$	7.8 µF
The losses in transistor	$R_{ds(on)} \leq \frac{\%P_M V_{DC}^2}{PD}$	$\leq \frac{(0.02)(24\ \text{V})^2}{(35\ \text{W})0.5} \leq 0.65$

For this case, we can observe in the equations of Table 2 that the values of the LED load intervene in the determination of the values required for the design of the converter. These equations not only consider the conditions that would be observed in a solely resistive load, but use the model that allows the parameterizing of the real conditions of the LED load, which allows the more accurate adjustment of the value of the components which are used when manufacturing the converter.

Relationship between Current Ripple and Voltage in the LED

To compare the ripples of current and voltage of the SVRM with the conventional resistive model of the LED. The analysis of the ripples with the resistive model was done. The resistive model of the LED is shown in Figure 7.

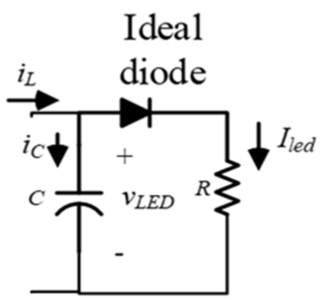


Figure 7. Resistive LED model.

Figure 7 model the LED as a resistance R, where i_L is the inductor current, i_C is the capacitor current and I_{led} is the current in the resistive model of the LED R.

As can be seen in the figure, from the circuit we can obtain the equations:

$$r_v = r_{iled} \tag{35}$$

Substituting the value in Equation (35) we obtain:

$$\begin{array}{l} r_v = \frac{\Delta v_C}{V_{led}} = \frac{2V_{C1}}{V_{led}} = \frac{2I_{R1}R_D}{V_{led}} \\ r_{iled} = \frac{2I_{R1}}{I_{led}} \end{array} \tag{36}$$

And the equation for the voltage in the LED is determined by Equation (38):

$$r_v = \frac{\Delta v_C}{V_{led}} = \frac{2V_{C1}}{V_{led}} = \frac{2I_{R1}R_D}{V_{led}} \tag{37}$$

$$r_{iled} = \frac{2I_{R1}}{I_{led}} \tag{38}$$

The topology for the circuit with SVRM model is shown in Figure 8. In this Figure, R_D and V_{th} represent the SVRM model of the LED.

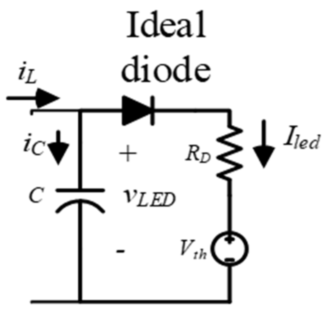


Figure 8. SVRM LED model.

It was determined by analyzing the equations that describe the circuit that is observed in Figure 8.

$$r_v \neq r_{iled} \tag{39}$$

From Equation (39) is obtained (40):

$$\frac{r_v}{r_{iled}} = \frac{\frac{2I_{R1}R_D}{V_{led}}}{\frac{2I_{R1}}{I_{led}}} = \frac{I_{led}R_D}{V_{led}} = \frac{I_{led}R_D}{V_{th} + I_{led}R_D} = \frac{1}{1 + \frac{V_{th}}{I_{led}R_D}} \tag{40}$$

when comparing Equations (36) and (40), we can see that there are different parameters involved that define these expressions, which shows that making use of the SVRM model for the LED load allows us to obtain different values than those that would be obtained using the traditional resistive model. The relevance of considering most of the variables that operate in a real way when designing the converter for the LED lamp is to be able to select the appropriate components that extend the useful life of the power supplies, considering the actual margin of error that will apply in the converter.

The equations for the LED model and the SVRM model, are shown in Table 3, where the equations required for each model are compared.

The design parameters for which the converter for the SVRM model is specified are in Table 1, and the parameters for the resistive LED model were the same, except the ripple of current, for in this case the ripple of voltage and current are the same of r_i = 0.01

In the following Table 4, a comparison is shown between the voltage and current ripples obtained when using the resistive model and the SVRM model.

Table 3. Comparison between equations for the resistive LED model and SVRM LED model.

Parameter	Resistive LED Model [18]	Value	SVRM Model	Value
Inductor	$L = \frac{(V_{in}-V_o)D}{\Delta i_L f_s}$	102.88 µH	$L = \frac{(V_{DC}-V_{led})D}{I_{led} r_{iL} f_s}$	102.9 µH
Capacitor	$C = \frac{V_o(1-D)}{8\Delta V_o L {f_s}^2}$	6.07 µF	$C = \frac{\sqrt{\left(\frac{r_{iL} I_{led} R_D}{r_v V_{led}}\right)^2+1}}{2\pi f_s R_D}$	7.8 µF
Resistor	$R = \frac{V_o}{I_o}$	4.1 Ω	$R_D = \frac{V_{led}-V_{th}}{I_{led}}$	2.05 Ω

Table 4. Comparison between current and voltage ripples for LED model and SVRM model.

Parameter	Resistive LED Model	SVRM Model
Output current	$I_o = \frac{V_o}{R_{eq}}$	$I_o = \frac{V_o - V_{th}}{R_{LED}}$
Ripple voltage	$r_v = \frac{2V_{ac}}{V_o}$	$r_v = \frac{2V_{ac}}{V_o}$
Ripple current	$r_i = \frac{2I_{ac}}{I_o}$	$r_{iLED} = \frac{2I_{ac}}{I_o} = \frac{2V_{ac}}{V_o - V_{th}}$
Ratio between voltage and current ripple	$k_r = \frac{r_i}{r_v} = 1$	$k_{rLED} = \frac{r_{iLED}}{r_{vLED}} = \frac{1}{1-(V_{th}/V_o)}$

3.3. Circuit Analysis in PSPICE

This paper evaluates the impact of the SVRM in the design of converter LED drivers. The study concludes that the LED load can be represented as a current source with two components, and by analyzing the output circuit (including the capacitor and load) through superposition, an accurate expression to calculate the output capacitor based on the current and voltage ripple percentages can be obtained. The equation used to evaluate the output capacitor for the SVRM was validated through PSPICE simulations.

The behavior analysis of a resistive LED model and an SVRM LED model was conducted through the development of a circuit for an LED driver utilizing a buck converter, illustrated in Figure 9, and implemented in PSPICE. For the purpose of comparison, the buck circuit was simulated with the resistive model Figure 9a and the SVRM model with Figure 9b.

By simulating the buck converter circuit with both the SVRM LED model and the resistive LED model as loads, it is possible to measure the current and voltage in the LED, as well as the current in the inductor. This allows for the verification of the desired ripple values and voltage and current levels across the LED.

Figure 10 shows the voltage graph at the output of the converter for both cases. Figure 10a shows the output votage for the SVRM model and Figure 10b shows the output voltage for resistive model. It is observed that it has an average level of approximately 11.55 V. It is also appreciated that it has a maximum level of 11.59 V and a minimum value of 11.503 V, which gives a ripple of 0.096 V. This is close to the desired value (0.01 normalized, which is equivalent to 0.12 V).

On the other hand, in Figure 11 the graphs obtained by measuring the output current in the converter load for both cases are shown. Figure 11a shows the output current of the SVRM model and, Figure 11b shows the output current for the resistive LED model. It can be observed in graph (a) that for the SVRM model, there is an average current of 2.71 A. It has a maximum peak value of 2.722 A and a minimum value of 2.675 A, which results in a ripple of r_{iLED} = 0.018. On the other hand, for the resistive LED model the current ripple is r_i = 0.010.

In Figure 12, the graphs corresponding to measuring the current flowing through the inductor for the resistor LED model and the SVRM LED model are shown. We can observe in Figure 12a that there is a maximum peak value of 2.998 A, and a minimum value of 2.3985 A, which results in a current ripple in the inductor of 0.5995 A, which is too close to the required value (0.2 normalized, which is equal to 0.583 A).

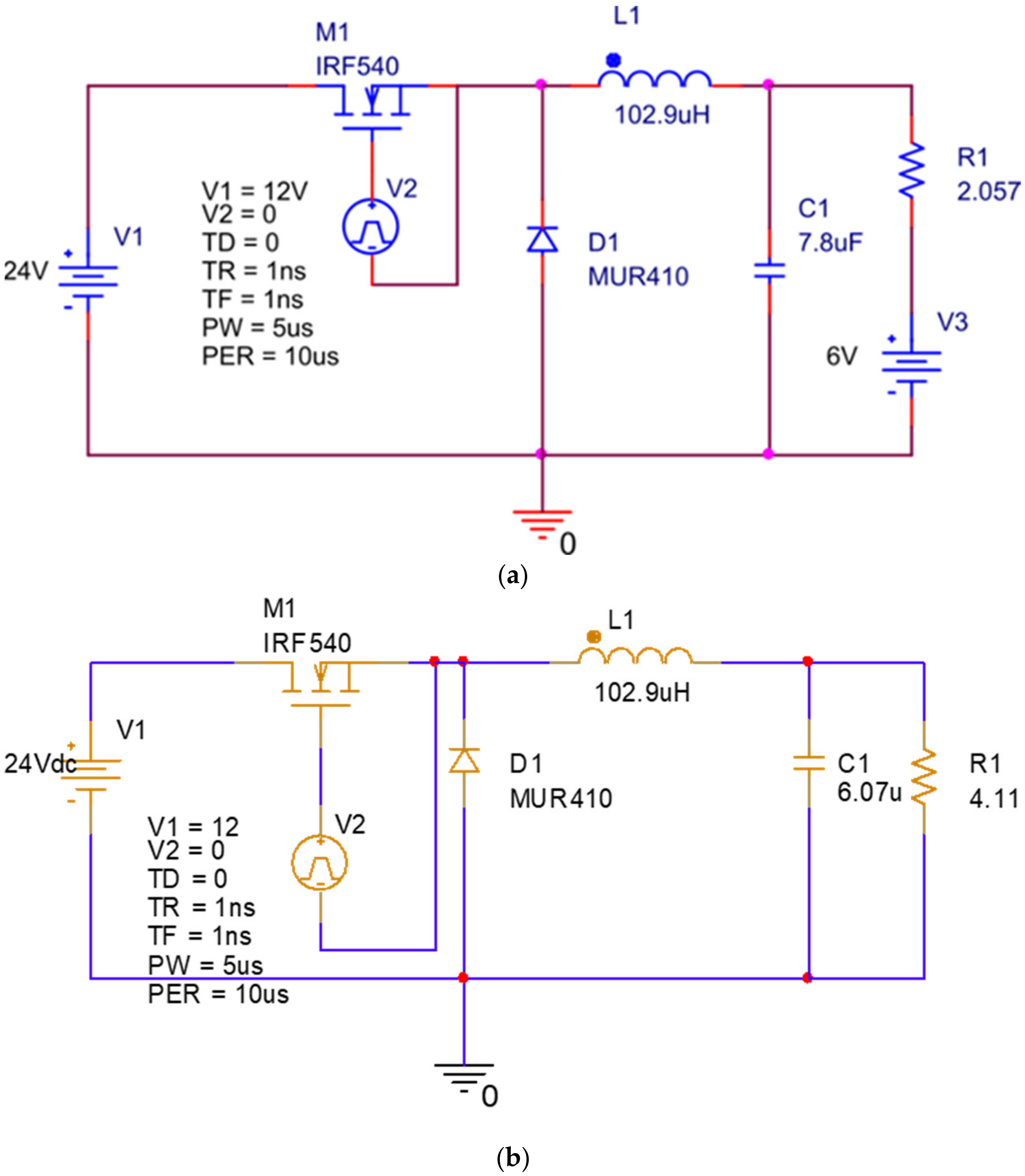


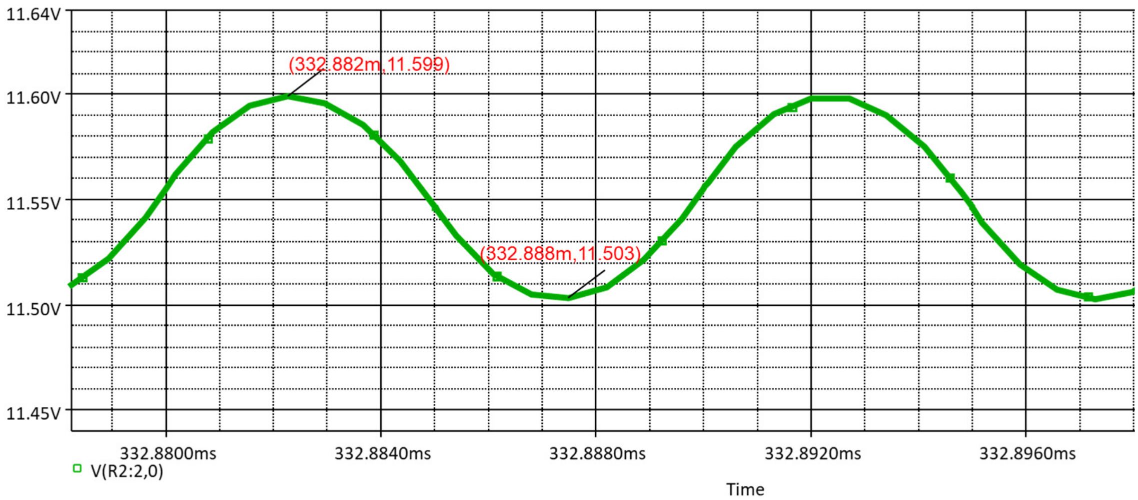
Figure 9. Buck converter simulated in PSPICE (**a**) Resistive LED model (**b**) SVRM LED model.

The following Table 5 shows the data obtained for each variable mentioned, both in simulation tests and the methodology presented in this document, as well as the percentage of error between both values obtained.

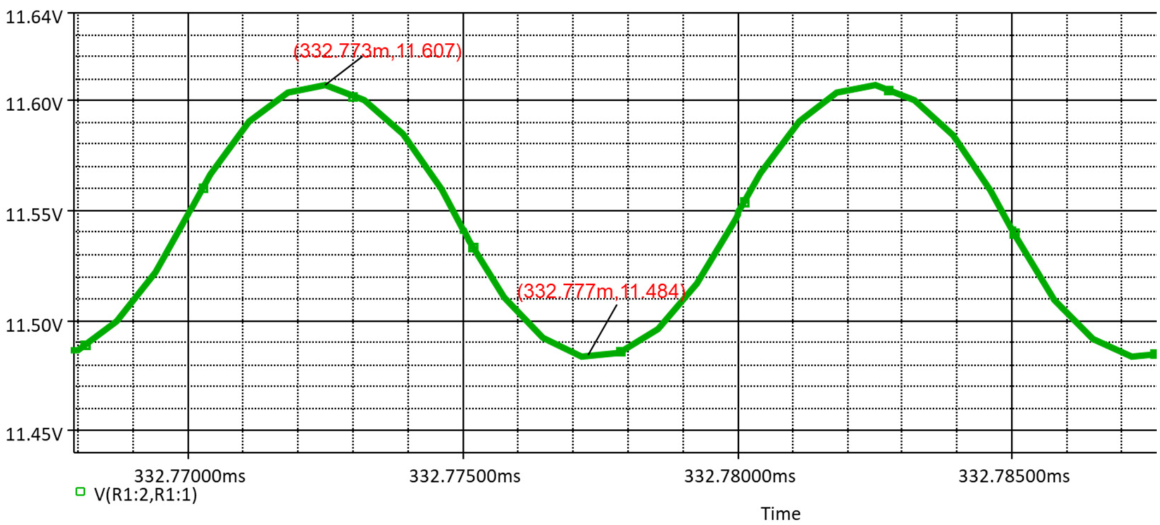
In Table 5 presented, we can analyze that the error percentages obtained are small, which helps to determine that it is possible to implement the design of this converter using these equations to calculate the components of the power supply for the LED lamp.

Table 5. Comparison between results calculations for LED model.

Value	Theoretical	Simulation	Error %
V_{avg}, V	12	11.8	1.66%
I_L, mA	97.4	101.03	3.69%
% R_{iL}	20%	20.73%	0.73%
% $R_{V\,LED}$	1%	0.8%	0.2%

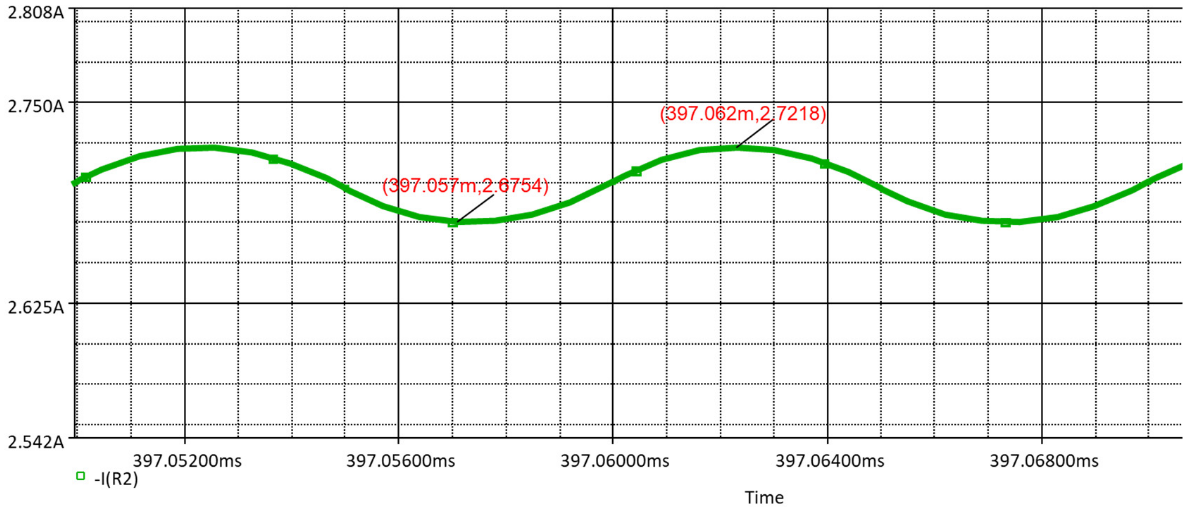


(**a**)

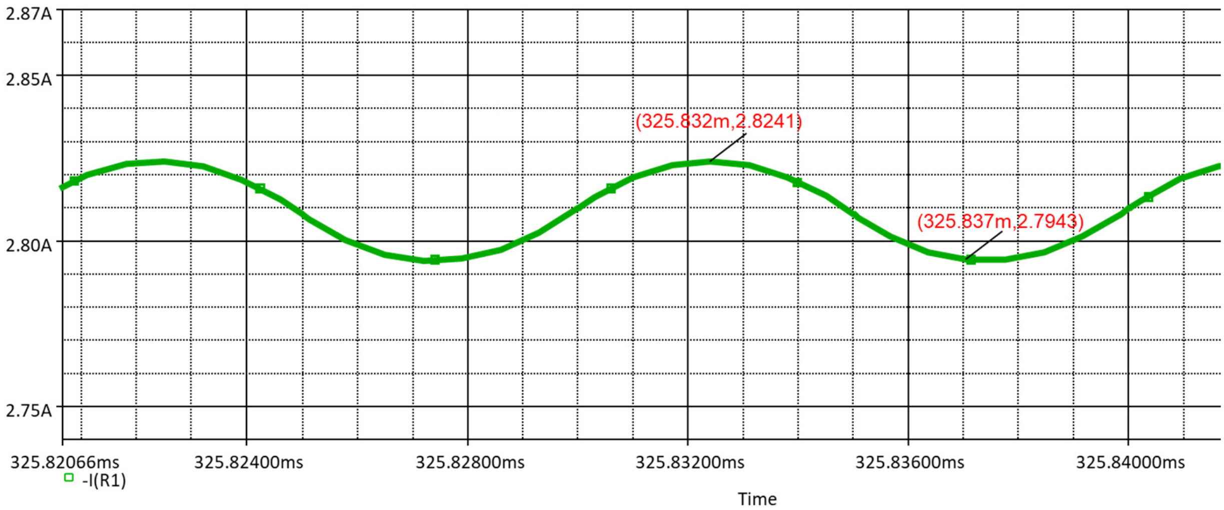


(**b**)

Figure 10. Buck converter output voltage graph (**a**) SVRM LED model (**b**) Resistive LED model.



(**a**)



(**b**)

Figure 11. Buck converter output current graph. (**a**) SVRM LED model (**b**) Resistive LED model.

The simulation of a buck converter with an LED as a load was presented. For this simulation and the design of the converter, the SVRM model of the LED was considered, which contemplates a resistance in series with a voltage source. This model is too close to the actual operating characteristics in the components, and in many cases is more than sufficient for the development of LED lamp power systems, as well as their possible controllers. With the development of this work, a method is proposed that allows us to analyze in greater detail the design of a buck converter, mainly in the output filter, managing to improve the precision in the values of the elements involved in the topology of the converter. If the current in the LED is very small, the difference between ripples will be greater, and analogously, the higher the current in the LED, the greater the difference between ripples. On the other hand, it can be observed that the average voltage and average current levels at the output vary from the specifications. This is mainly due to the losses that occur in both the interrupter and the diode. To compensate for these losses, it may be enough to increase the duty cycle.

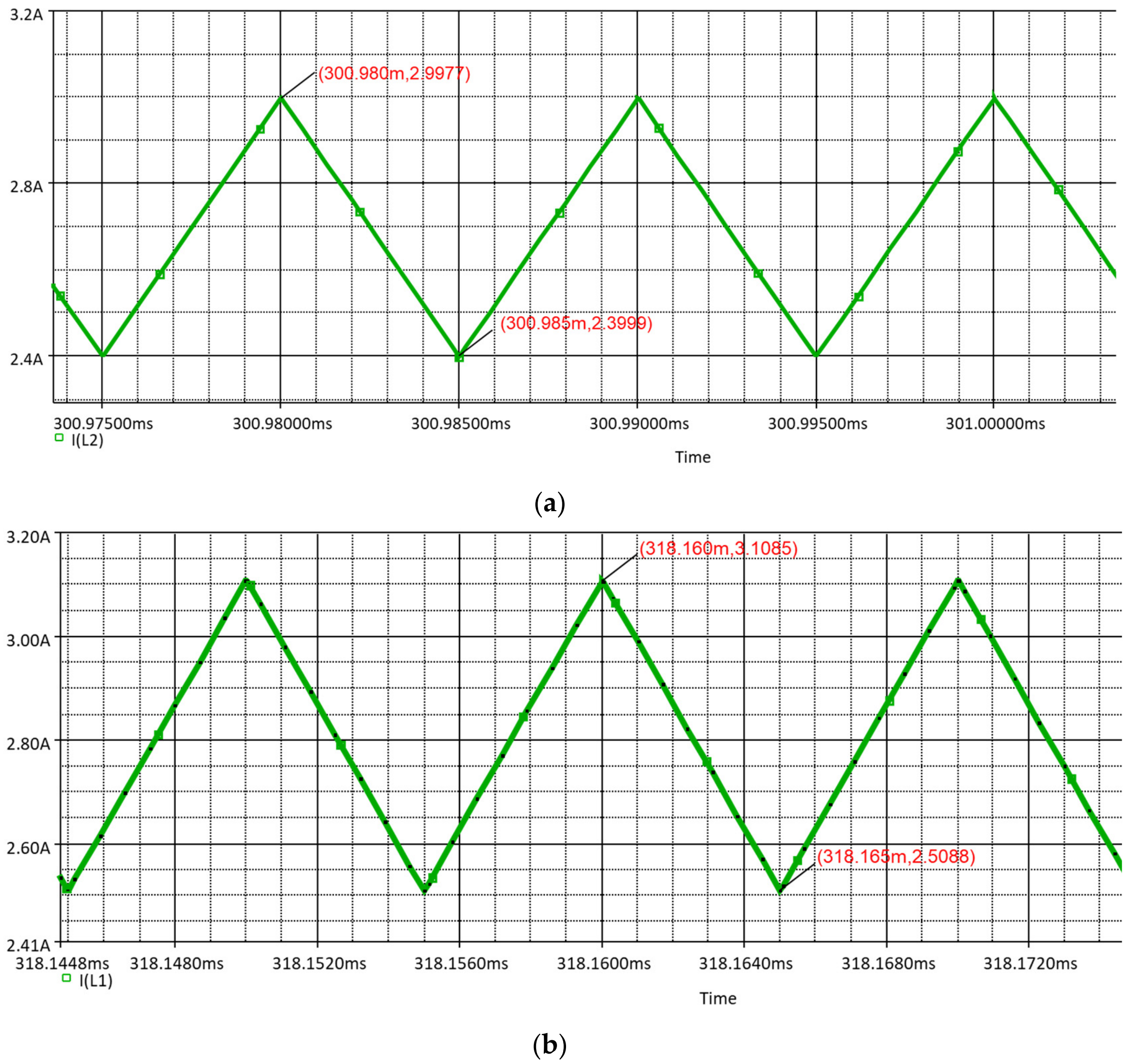


Figure 12. Graph of the current in the inductor of the buck converter. (**a**) SVRM LED model (**b**) Resistive LED model.

4. Discussion

This work presents an equation for the most accurate output capacitor for the value of the elements for the design of the buck circuit. The analysis of the RC filter is based on the Fourier series and a phasor analysis so the development proposed in the previous document applies to any DC-DC converter with an RC filter at the output and current source feeding the filter. It is demonstrated that, based on the V-I behavior of LEDs, the current and voltage ripples in the LED will always be different, with the current ripple always being greater than the voltage ripple.

In this study, the impact of SVRM on the design of LED lamp drivers has been examined. The analysis presented in the paper shows that the output of a buck converter, when driving an LED load, can be modeled as a current source with two components: a DC component and an AC component with a frequency that is twice the line frequency. By using superposition, it is possible to derive an equation that accurately calculates the required output capacitance based on the desired current and voltage ripple percentages. The equation used to evaluate the output capacitor for the SVRM was compared using SPICE simulations, obtaining an error of less than 3%. The analysis conducted in this study also demonstrated that the current ripple percentage is invariably higher than the voltage ripple percentage in the presence of an LED load (%RvLED < %RiLED). The dissimilarities between the models primarily pertain to the capacitance of the circuit, stored energy and voltage ripple percentage wherein the SVRM stores significantly more energy owing to the use of a larger capacitor, while the voltage ripple percentage remains minute owing to the voltage threshold.

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