

## Article

# Implementation of Rapid Prototyping Tools for Power Loss and Cost Minimization of DC-DC Converters

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Academic Editor: Gabriele Grandi

Received: 30 March 2016; Accepted: 20 June 2016; Published: 1 July 2016

**Abstract:** In this paper, power loss and cost models of power electronic converters based on converter ratings and datasheet information are presented. These models aid in creating rapid prototypes which facilitate the component selection process. Through rapid prototyping, users can estimate power loss and cost which are essential in design decisions. The proposed approach treats main power electronic components of a converter as building blocks that can be arranged to obtain multiple topologies to facilitate rapid prototyping. In order to get system-level power loss and cost models, two processes are implemented. The first process automatically provides minimum power loss or cost estimates and identifies components for specific applications and ratings; the second process estimates power losses and costs of each component of interest as well as the whole system. Two examples are used to illustrate the proposed approaches—boost and buck converters in continuous conduction mode. Achieved cost and loss estimates are over 93% accurate when compared to measured losses and real cost data. This research presents derivations of the proposed models, experimental validation of the models and demonstration of a user friendly interface that integrates all the models. Tools presented in this paper are expected to be very useful for practicing engineers, designers, and researchers, and are flexible and adaptable with changing or new technologies and varying component prices.

**Keywords:** rapid prototyping; design methodology; DC-DC converters; user centered design; user interface; design optimization

## 1. Introduction

### 1.1. Overview

As dependence on electronic appliances, digital products and computer systems in both industrial and household applications grows, the demand for power electronic converters is increasing. DC-DC converters continue to grow in popularity in all major electronics applications. Given the high demand for these converters, engineers are faced with a major challenge to design them in a very short period of time while still ensuring competitive cost. Rapid prototyping tools for converter development help solve this constraint and thus are of interest as both time- and cost-saving methods.

Existing literature indicates significant research related to power loss estimation of various power electronic components. Loss estimation, for example, is used in [1] to analyze how power loss can be redistributed in a power converter using a modulation technique. Another reason for the need for power loss estimation is when evaluating the effect of different material on device power losses, e.g., [2,3]. In other applications, e.g., [4], power loss estimation is central in evaluating the usability of a power electronic converter, and power loss is used as a metric when comparing various converters. Since temperature rise in semiconductors and other power electronic devices is mainly caused by power losses, power losses have also been used for thermal analysis and modeling of power electronic

systems, e.g., [5,6]. Therefore, power loss estimation is essential for new material, device, and converter evaluation, in addition to comparing various converters and designs where efficiency is a major figure of merit. Modeling of power electronic converters can be improved by loss and cost estimation, such as distributed power converters in a standalone DC microgrid [7], or DC microgrids for electric vehicle charging stations [8]. Also, essential application which relies on power converter topology can benefit from loss and cost estimation, like PFC converters for plug-in-hybrid electric vehicles [9], and novel bidirectional DC/DC converter topologies [10].

Several techniques have been implemented to find out power loss or cost models of specific components. A majority of this research has focused on selecting components for power electronic converters, e.g., [11]. Extensive research has been conducted for finding specific losses in semiconductors and magnetic components, e.g., [12]. Power loss estimation in semiconductors has also been extensively studied, e.g., [6,13] where power losses are correlated with temperature rise in the devices using thermal resistance datasheet values. Topology-specific power loss models also exist, which address specific component losses, e.g., power MOSFET losses in a buck converter [14], or system-level losses, e.g., boost converter [15]. Several methods to measure system-level power loss have also been proposed, e.g., [16,17]. Power losses in other parts of the converter, e.g., PCB losses [18–20] and gate drive losses [21], have been addressed but are only introduced in the Appendix A of this paper.

Cost consideration is the most important factor for industries which mass-produce power electronic converters, to achieve market success and competitiveness by reducing cost [22]. However, most existing literature mainly focuses on methods to predict costs of specific systems and avoids generalized cost models of power electronic devices and converters. For example, in [23] the cost models of a battery, inverter and converter were developed on the basis of power ratings of these sub-systems. Cost estimation and reduction techniques have been developed for a single component such as inductor or heat sink in [24]. Some cost models are also developed for switch-mode power supplies by considering component power losses, weight, manufacturing process and raw material cost fluctuations [25].

An important application of power loss and cost estimation is design optimization of power electronic converters. With a well-established power loss or cost model of various devices that can form the converter, an optimization problem can be established where the converter's power loss or cost are the figures of merit. Attempts for such analytical design approaches are [26], but mostly focus on power losses, especially semiconductor losses in [26]. Cost models and power loss models of specific devices which can be extended for integration in power electronic converters, have been presented in [27] but without converter design optimization.

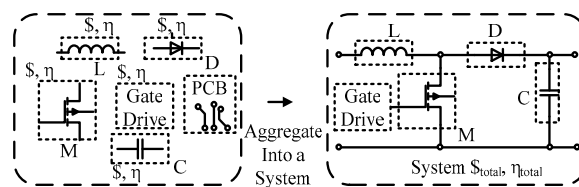
Therefore, generalized power loss models of major power electronic devices, as well as cost models of these devices, have not been shown in the literature for ease of integration for any power converter topology. For example, textbook models such as those presented in [16,28–30], are presented in an introductory way where they may not be easily integrated into any power converter topology. Research papers, on the other hand, present very specific models for devices or topologies but rarely provide a flexible model that can be integrated with different power converter topologies.

### 1.2. Proposed Approach and Contribution

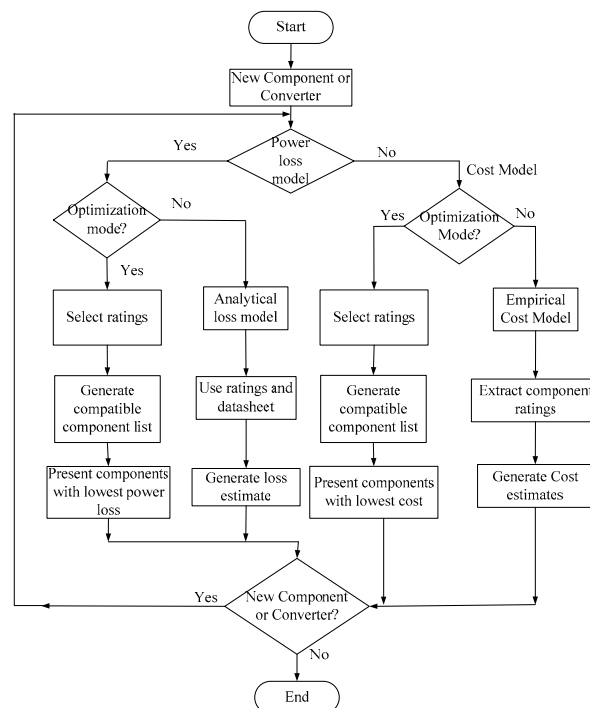
This paper presents a building-block approach, as demonstrated in Figure 1, towards modeling power loss and the cost of power electronic converters. Power loss models are based on converter voltage, current, power, and frequency ratings and operating conditions along with basic datasheet information. Cost models are based on average prices related to component ratings obtained using an extensive market survey and surface-fitting tools. It is important to note that component technology and cost profiles change over time as a result of changes in material and manufacturing techniques and thus this paper intends to develop power loss and cost modeling methodologies that can evolve with time and changes in technology.

The paper focuses on the building-block approach of the modeling of power loss and the cost of power electronic converters to achieve minimum power loss and cost design instead of the model

construction of single component. The proposed method provides a new tool and effective way where assembles the circuit from parts to an entirety to evaluate the power loss and cost of an entire converter. The overall process used in rapid prototyping tools for cost and power loss models in optimization and component-specific modes as proposed here is illustrated in Figure 2. The target of the models is to minimize the estimation error when comparing actual component power loss and cost values with the measured power losses or actual cost. Their main advantage is the ability to evaluate a large number of possible component combinations and achieve almost instantaneous cost and loss estimates. Thus a large quantity component library is generated as the basement of the models and the web based program of the rapid prototyping tool ensures the component library is up to date along with the newest marketing price and technology. From customer perspective, once the converter topology is chosen and desired power loss and cost are typed into the GUI interfacing panel, the rapid prototyping tool is able to search, chose the appropriate component and assemble the converter rapidly to save the time of customer to search and evaluate the component. Also, the rapid prototyping tool is able to optimize the results to minimize the power loss and cost with the change of the custom parameters such as topology, total cost and power loss.



**Figure 1.** Example illustration on how to aggregate component level models into a system (\$: Cost,  $\eta$ : Efficiency).



**Figure 2.** Procedure for the proposed rapid prototyping tools.

Rapid prototyping tools for DC-DC converters are of main interest here due to the converters' simplicity, wide range of their applications and since the methodology for developing models is of main interest rather than actual topologies.

The paper proceeds as follows: Section 2 shows generalized component-level power loss models. Section 3 discusses the application of generalized power loss models for several power electronic converters. Section 4 explains the concept behind cost model development and illustrates these models. Section 5 shows experimental results that validate the developed models. Section 6 explains rapid prototyping tools for model-based power loss minimization and presents tools for cost minimization. Section 7 concludes with the summary remarks and future work.

## 2. Generalized Component-Level Power Loss Models

Generalized power loss models of power electronic components are derived based on equivalent circuit models of each major component by considering component non-idealities and parasitic elements. The models presented here stem from existing models in textbooks and foundational research papers, e.g., [13,19,28–30] and others. Therefore, this Section is a summary of such models, while Section 3 presents these models when massaged for specific buck and boost converter topologies.

### 2.1. MOSFET Losses

In power electronic converters, MOSFETs operate as switching elements. Figure 3 shows a MOSFET model with its non-idealities.

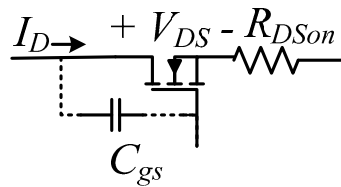


Figure 3. MOSFET model with non-idealities.

The MOSFET  $P_{CM}$  [28] is:

$$P_{CM} = R_{DS(on)} I_{Drms}^2 \quad (1)$$

where  $I_D$  is represented as shown in Figure 4 when the MOSFET operates as a switch.  $I_{Drms}$  can be computed by  $I_{Drms} = \sqrt{\frac{1}{T} \int_0^T \left( \frac{\Delta i}{DT} t + I_{Lavg} - \frac{1}{2} \Delta i \right)^2 dt} = \sqrt{\frac{1}{3} \Delta i^2 D + (I_{Lavg} - \frac{1}{2} \Delta i) \Delta i D + (I_{Lavg} - \frac{1}{2} \Delta i)^2 D}$ .

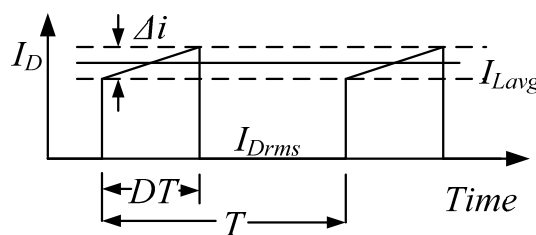


Figure 4. MOSFET drain current.

Switching losses of MOSFETs are mainly divided into two parts,  $P_{ON(M)}$  and  $P_{OFF(M)}$ . Because only steady state efficiency is concerned, voltage overshoot and diode reverse recovery effect won't be considered. The total switching loss  $P_{SW}$  is thus [31]:

$$P_{SW} = P_{ON(M)} + P_{OFF(M)} \quad (2)$$

where for a fixed  $f_{sw}$ :

$$P_{ON(M)} = \frac{1}{2} V_{DS} I_{Don} (t_r + t_{d(on)}) f_{sw} \quad (3)$$



$$P_{OFF(M)} = \frac{1}{2} V_{DS} I_{Doff} (t_f + t_{d(off)}) f_{sw} \quad (4)$$

The gate loss  $P_G$  is usually observed at  $C_{gs}$  [17]:

$$P_G = Q_{gs} V_{Supply} f_{sw} \quad (5)$$

Thus, total power losses in a MOSFET are:

$$P_{loss(MOSFET)} = P_{CM} + P_{SW} + P_G \quad (6)$$

## 2.2. Diode Losses

Diodes in power electronic converters act as rectifiers and uncontrolled switches. Figure 5 shows a diode model with its non-idealities.

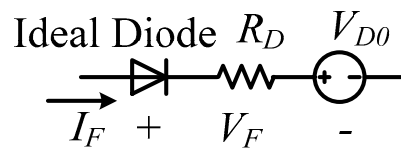


Figure 5. Diode model with non-idealities.

The diode conduction loss  $P_{CD}$  is modeled as:

$$P_{CD} = V_{D0}(1 - D) I_{Favg} + R_D(1 - D) I_{Frms}^2 \quad (7)$$

where typical values of  $V_{D0}$  and  $R_D$  are:

$$V_{D0} = V_{Dmax}/V_{Dtyp} \quad (8)$$

$$R_D = \Delta V_F / \Delta I_F \quad (9)$$

There are two switching losses of a diode—turn-on loss and turn-off loss. The turn-on loss is usually ignored because the diode starts conducting from an off-state.  $P_{SWD}$  is thus [6]:

$$P_{SWD} = \frac{1}{2} Q_{rr} V_{rr} f_{sw} \quad (10)$$

and the total diode power loss is:

$$P_{loss(Diode)} = P_{CD} + P_{SWD} \quad (11)$$

## 2.3. Inductor Losses

An inductor stores energy in its magnetic field. Figure 6 shows an inductor with non-idealities and Figure 7 shows a typical inductor current waveform in a DC-DC converter.

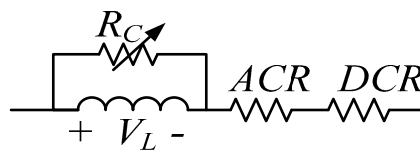


Figure 6. Inductor model with non-idealities.

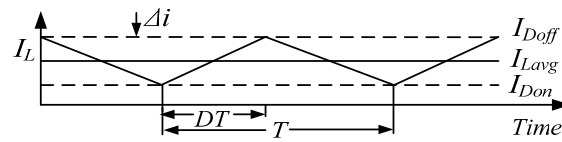


Figure 7. Inductor current waveform.

The core loss  $P_{CORE}$  is usually obtained by the Steinmetz equation [16,32] to be:

$$P_{CORE} = K_1 f^x B^y V_e \quad (12)$$

Note that modified Steinmetz equations are also common for core loss estimation, but if core loss coefficients are not supplied in a datasheet, a constant  $R_C$  can be used and  $P_{CORE}$  is estimated as:

$$P_{CORE} \approx \frac{V_L^2}{R_C} \quad (13)$$

The Steinmetz equation is used as an example, but the methodology is intended to support other forms of loss models. This is clear by using either Equation (12) or Equation (13) and can extend to more detailed models. Resistive losses can also be estimated as shown in [16,32],  $DCR$  and  $ACR$  are provided by datasheets or manufacturers:

$$P_{DCR} = I_{Lavg}^2 DCR \quad (14)$$

$$P_{ACR} = I_{Lrms}^2 ACR \quad (15)$$

Total power loss of an inductor is thus:

$$P_{loss(Inductor)} = P_{CORE} + P_{DCR} + P_{ACR} \quad (16)$$

#### 2.4. Capacitor Losses

Capacitors are major storage elements in power electronic converters and their typical non-idealities are shown in Figure 8.

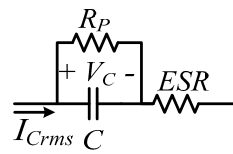


Figure 8. Capacitor model with non-idealities.

Two major power losses in the capacitor are those in its AC and DC resistances [33].  $P_{ac}$  is:

$$P_{ac} = I_{Crms}^2 ESR \quad (17)$$

while  $P_{dc}$  is:

$$P_{dc} = \frac{V_C^2}{R_P} \quad (18)$$

Total power loss of the capacitor is thus:

$$P_{loss(Capacitor)} = P_{ac} + P_{dc} \quad (19)$$

$P_{dc}$  is small as compared to  $P_{ac}$  as capacitors are mainly used to pass current ripple, thus  $P_{dc}$  it is frequently ignored.



### 3.1.3. Inductor Losses

$P_{CORE}$ ,  $P_{DCR}$  and  $P_{ACR}$  can be calculated as:

$$P_{CORE} \approx \frac{(V_{out} - V_{in} - I_{in}DCR - V_F)^2}{R_C} \quad (28)$$

$$P_{DCR} = I_{in}^2 DCR \quad (29)$$

$$P_{ACR} = \frac{\Delta i^2}{12} ACR \quad (30)$$

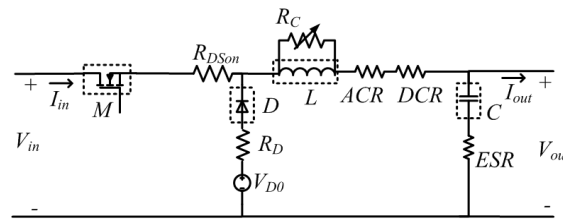
### 3.1.4. Capacitor Losses

$P_{loss(Capacitor)}$  is obtained using Equation (17) as:

$$P_{loss(Capacitor)} = \frac{\Delta i^2}{12} ESR \quad (31)$$

## 3.2. Buck Converter in CCM

A typical non-ideal buck converter is shown in Figure 10.



**Figure 10.** Buck converter topology for power loss model.

### 3.2.1. MOSFETs Losses

$P_{CM}$  is obtained from Equation (1) and can be estimated [30] as:

$$P_{CM} = R_{DS(on)} D \left[ I_{out}^2 + \frac{\Delta i^2}{12} \right] \quad (32)$$

To calculate  $P_{SW}$ ,  $I_{Don}$  and  $I_{Doff}$  can be obtained from Figure 7 and  $V_{DS}$  as in Equation (23). Thus,  $P_{ON}$  and  $P_{OFF}$  are calculated as:

$$I_{Don} = I_{out} - \frac{\Delta i}{2} \quad (33)$$

$$I_{Doff} = I_{out} + \frac{\Delta i}{2} \quad (34)$$

$$P_{ON(M)} = \frac{1}{2} V_{in} \left( I_{out} - \frac{\Delta i}{2} \right) t_r f_{sw} \quad (35)$$

$$P_{OFF(M)} = \frac{1}{2} V_{in} \left( I_{out} + \frac{\Delta i}{2} \right) t_f f_{sw} \quad (36)$$

### 3.2.2. Diode Losses

$P_{CD}$  and  $P_{SWD}$  are obtained by referring Equations (7) and (10) as:

$$P_{CD} = V_{D0}(1 - D)I_{out} + R_D(1 - D)I_{out}^2 \quad (37)$$

$$P_{SWD} = \frac{1}{2} Q_{rr} (V_{out} + I_{out} DCR) f_{sw} \quad (38)$$

### 3.2.3. Inductor Losses

$P_{CORE}$ ,  $P_{DCR}$  and  $P_{ACR}$  can be calculated as:

$$P_{CORE} \approx \frac{(V_{in} - V_{out} - I_{in} R_{DSon} - I_{out} DCR)^2}{R_C} \quad (39)$$

$$P_{DCR} = I_{out}^2 DCR \quad (40)$$

$$P_{ACR} = \frac{\Delta i^2}{12} ACR \quad (41)$$

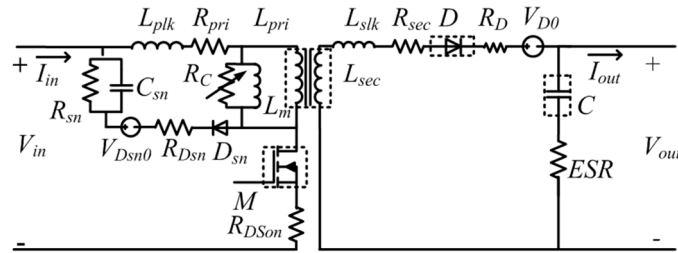
### 3.2.4. Capacitor Losses

$P_{loss(Capacitor)}$  is obtained using Equation (17) as:

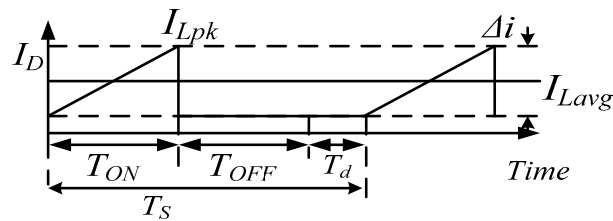
$$P_{loss(Capacitor)} = \frac{\Delta i^2}{12} ESR \quad (42)$$

## 3.3. Flyback Converter in DCM

Flyback converters are widely used in DCM. A non-ideal flyback converter in DCM is shown in the Figure 11. For the sake of illustration, the MOSFET switching period was considered as  $T_{ON} + T_{OFF} = 0.8T_S$  as shown in Figure 12.



**Figure 11.** Flyback converter model with its non-idealities.



**Figure 12.** MOSFET switching waveform.

### 3.3.1. MOSFET Losses

$$T_{ON} = \frac{0.8T_S (V_{out} + V_F)}{V_F} \quad (43)$$

$$V_{DS} = V_{in} + nV_{out} \quad (44)$$

$P_{CM}$  in the flyback converter is described in [30,35] as:

$$P_{CM} = R_{DSon} \left( \frac{V_{in}}{(L_m + L_{pri}) f_{sw}} D \sqrt{0.26 \left( 1 + \frac{V_{out}}{V_F} \right)} \right)^2 \quad (45)$$

For a flyback converter in DCM,  $I_{Don}$  is zero but  $I_{Doff}$  and  $P_{SW}$  are determined using [35,36] and Figure 13 as:

$$I_{Doff} = \frac{0.9 V_{in} D}{2 (L_m + L_{pri}) f_{sw}} \quad (46)$$

$$P_{SW} = P_{OFF(M)} = (V_{in} + n V_{out}) \left[ \frac{0.9 V_{in} D}{2 (L_m + L_{pri})} \right] \frac{t_f}{2} \quad (47)$$

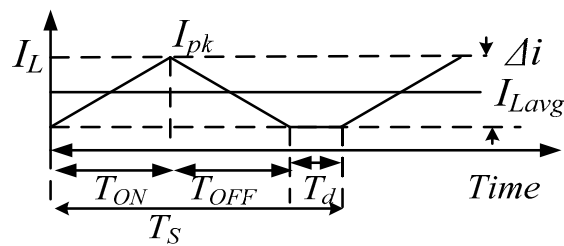


Figure 13. Inductor switching waveform.

### 3.3.2. Diode Losses

$P_{CD}$  and  $P_{SWD}$  of the flyback diode are calculated as:

$$P_{CD} = V_{D0}(1 - D)I_{out} + R_D(1 - D) \left[ \frac{0.52n V_{in} D}{(L_m + L_{pri}) f_{sw}} \right]^2 \quad (48)$$

$$P_{SWD} = \frac{1}{2} Q_{rr} V_{out} f_{sw} \quad (49)$$

### 3.3.3. Flyback Coupled-Inductor/Transformer Losses

$P_{CORE}$  is given in [20,34,36] as:

$$P_{CORE} = K_{fe} B_{AC}^\beta A_C L_m \quad (50)$$

where:

$$B_{AC}^\beta = \frac{L_m \Delta i}{N_{pri} A_C} \quad (51)$$

Primary  $P_{Rpri}$  and secondary  $P_{Rsec}$  resistive power losses are calculated [21] as:

$$P_{Rpri} = \left( \frac{0.4 V_{in} D}{(L_m + L_{pri}) f_{sw}} \right)^2 R_{pri} \quad (52)$$

$$P_{Rsec} = \left( \frac{0.4n V_{in} D}{(L_m + L_{pri}) f_{sw}} \right)^2 R_{sec} \quad (53)$$

### 3.3.4. Capacitor Losses

Form Equation (17),  $P_{loss(Capacitor)}$  is calculate as:

$$P_{loss(Capacitor)} = \left\{ \left[ \frac{0.52nV_{in}D}{(L_m + L_{pri})f_{sw}} \right]^2 - I_{out}^2 \right\} ESR \quad (54)$$

### 3.3.5. Snubber Circuit Losses

The main components in the snubber branch are  $R_{sn}$ ,  $C_{sn}$  and  $D_{sn}$ .  $R_{sn}$  and  $C_{sn}$  form a clamp unit.  $P_{clamp}$  is represented as [35]:

$$P_{clamp} = \frac{(V_{clamp})^2}{R_{sn}} = \frac{(0.9V_{DSBR} - V_{in})^2}{R_{sn}} \quad (55)$$

or:

$$P_{clamp} = \frac{1}{2}f_{sw}L_{pri}\Delta i^2 \left( 1 + \frac{V_{in}}{0.9V_{DSBR} - 2V_{in}} \right) \quad (56)$$

Snubber diode conduction loss  $P_{CDsn}$  is obtained from Equation (7) as:

$$P_{CDsn} = V_{Dsn0}(1 - D)nI_{out} + R_{Dsn}(1 - D)nI_{Srms}^2 \quad (57)$$

while  $P_{SWDsn}$  is obtained as:

$$P_{SWDsn} = \frac{1}{2}Q_{rrsn}V_{in}f_{sw} \quad (58)$$

Total snubber circuit power loss is the summation of snubber diode power loss and power loss in the clamp unit. Therefore, all power loss equations for the three different converter examples are derived based on datasheet information and converter ratings. Results that validate the derived models are shown in Section 5 where experimental prototypes are used to measure the total loss in the converter.

## 4. Major Component Cost Models

A large database of cost information for multiple elements was compiled from common manufacturers' and suppliers' data. The two main sources of this data were Digikey [37] and Mouser Electronics [38], where searches were performed for MOSFETs, diodes, capacitors, and inductors of specific rating ranges. Search filters were applied to achieve such range limits, and the database is compiled and available for public use [39]. Since multiple options exist for different power, voltage, current, and/or device value rating (e.g., inductance and capacitance), the average cost for each component at a certain rating combination was found by considering these multiple options. This database was input to MATLAB to create interpolated graphs and find a mathematical relationship between cost and component ratings. Cost per quantity was also considered. The impact of time on cost is not considered due to availability of present prices only. Some other costs such as costs resulting from auxiliaries, heat sinks, fan/clod plates, etc are also not considered because they are beyond the scope of this work, where the focus is mainly on methodology.

### 4.1. MOSFETs

SiC and GaN type semiconductor cost is still varying rapidly due to continued production improvements, thus to demonstrate the methodology we focus on Si. To create a MOSFET cost model  $Cost_M$ , a large database was prepared using  $V_{DS}$ ,  $I_D$  and cost.  $\alpha_i$  coefficients are as listed in Table 1, but it should be noted that these coefficients vary across a certain range and the values shown are

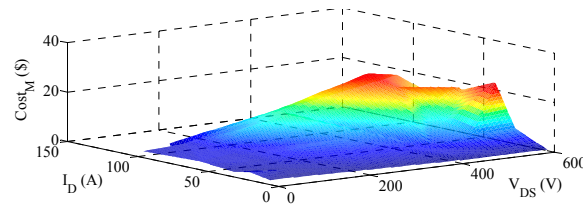


selected to achieve the best fit for specific components used in Section 5. Figures 14 and 15 show the mathematical relationship for this database.  $Cost_M$  is represented as:

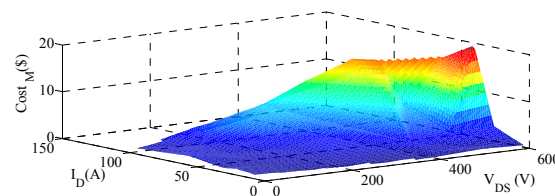
$$Cost_M(V_{DS}, I_D) = \sum_{i=0}^{i=15} \alpha_i V_{DS}^{\beta_i} I_D^{\gamma_i} \quad (59)$$

**Table 1.** Coefficients for the MOSFET cost model equation.

Coefficient	Value	Range	$\beta_i$	$\gamma_i$
$\alpha_0$	0.8091	(−17.52, 19.14)	0	0
$\alpha_1$	0.01964	(−0.06058, 0.09985)	1	0
$\alpha_2$	−0.1375	(−2.465, 2.19)	0	1
$\alpha_3$	$-3.497 \times 10^{-5}$	(−0.0001393, $6.939 \times 10^{-5}$ )	2	0
$\alpha_4$	−0.00323	(−0.0106, 0.004137)	1	1
$\alpha_5$	0.01736	(−0.08388, 0.1186)	0	2
$\alpha_6$	$1.3 \times 10^{-8}$	( $-1.6 \times 10^{-6}$ , $1.6 \times 10^{-6}$ )	3	0
$\alpha_7$	$5.022 \times 10^{-6}$	( $-4.517 \times 10^{-6}$ , $1.456 \times 10^{-5}$ )	2	1
$\alpha_8$	$9.087 \times 10^{-5}$	( $-9.87 \times 10^{-5}$ , 0.0002804)	1	2
$\alpha_9$	−0.0005698	(−0.002582, 0.001443)	0	3
$\alpha_{10}$	$-8.033 \times 10^{-8}$	( $-2.976 \times 10^{-7}$ , $1.37 \times 10^{-7}$ )	2	2
$\alpha_{11}$	$-9.716 \times 10^{-7}$	( $-2.976 \times 10^{-6}$ , $1.032 \times 10^{-6}$ )	1	3
$\alpha_{12}$	$7.185 \times 10^{-6}$	( $-1.183 \times 10^{-5}$ , $2.62 \times 10^{-5}$ )	0	4
$\alpha_{13}$	$3.17 \times 10^{-10}$	( $-1.034 \times 10^{-9}$ , $1.668 \times 10^{-9}$ )	2	3
$\alpha_{14}$	$4 \times 10^{-9}$	( $-5.126 \times 10^{-9}$ , $1.313 \times 10^{-8}$ )	1	4
$\alpha_{15}$	$-3.103 \times 10^{-8}$	( $-1.006 \times 10^{-7}$ , $3.851 \times 10^{-8}$ )	0	5



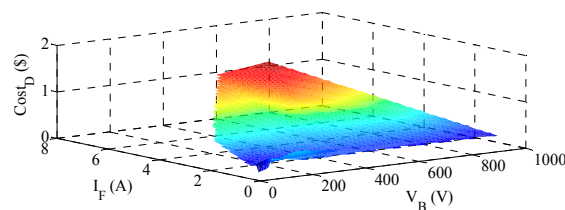
**Figure 14.** MOSFET cost model for one unit.



**Figure 15.** MOSFET cost model for 1000 units.

#### 4.2. Diodes

A diode cost database was prepared using  $V_B$ ,  $I_F$  and cost where Figures 16 and 17 show the interpolated cost surfaces while the mathematical model is shown in Equation (60) and its coefficients are shown in Table 2.



**Figure 16.** Diode cost model for one unit.

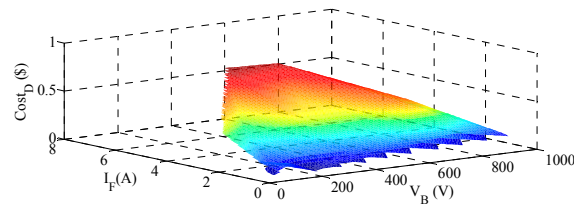


Figure 17. Diode cost model for 1000 units.

$$Cost_D(V_B, I_F) = \sum_{j=0}^{j=2} \delta_j V_B^{\theta_j} I_F^{\kappa_j} \quad (60)$$

Table 2. Coefficients for the diode cost model equation.

Coefficients	Value	Range	$\theta_j$	$\kappa_j$
$\delta_0$	0.22	(0.1, 0.3)	0	0
$\delta_1$	$7 \times 10^5$	$(-2.6 \times 10^{-4}, 1.2 \times 10^{-4})$	1	0
$\delta_2$	0.1	(0.08, 0.13)	0	1

#### 4.3. Inductors

Inductor cost data is compiled based on  $L$ ,  $I_L$  and cost. Figures 18 and 19 show the interpolated cost surfaces while the mathematical model is shown in Equation (61) and its coefficients are where  $x = 9.67$ ,  $\mu = 61.64$ ,  $\phi = -8.246$ ,  $v = 4.495$ ,  $\omega = -0.08658$ .

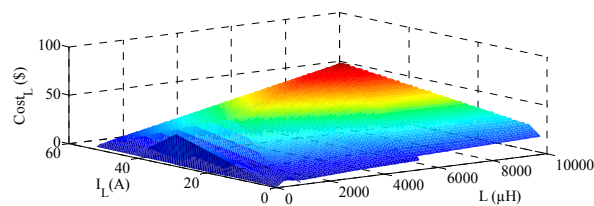


Figure 18. Inductor cost model for one unit.

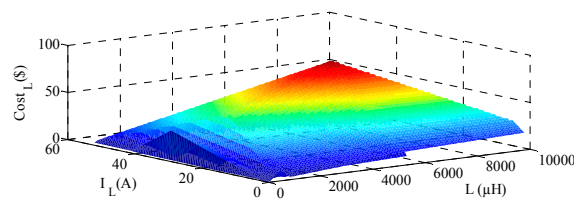


Figure 19. Inductor cost model for 1000 units.

$$Cost_L(L, I_L) = \chi + \mu \sin(v\pi L I_L) + \phi e^{-(\omega I_L)^2} \quad (61)$$

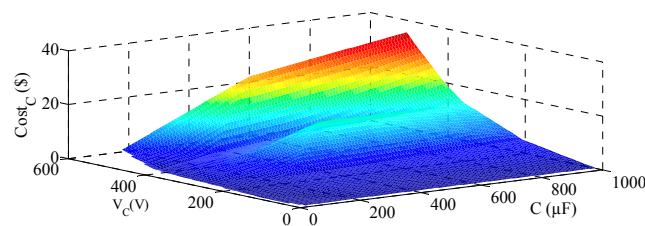
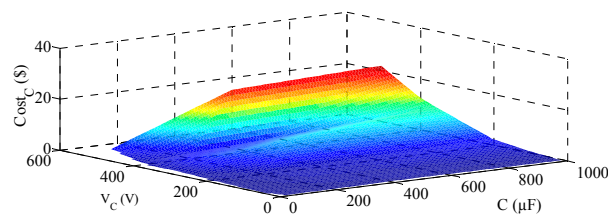
#### 4.4. Capacitors

A capacitor cost ( $Cost_C$ ) database for electrolytic capacitors was prepared using  $C$ ,  $V_C$  and cost where Figures 20 and 21 show the interpolated cost surfaces while the model is shown in Equation (62) and its coefficients are shown in Table 3. Different material of capacitor will lead to different cost, but electrolytic capacitor is chosen as an example to illustrate the methodology:

$$Cost_C(C, V_C) = \sum_{z=0}^{z=8} \eta_z C^{\sigma_z} V_C^{\xi_z} \quad (62)$$

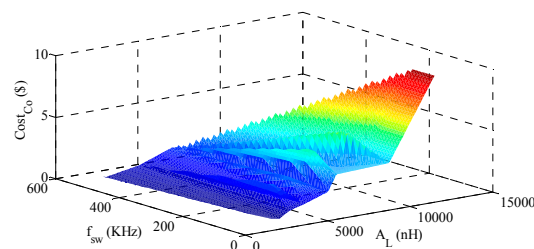
**Table 3.** Coefficients for the capacitor cost model equation.

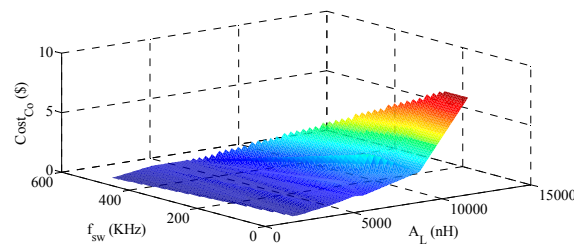
Coefficients	Value	Ranges	$\sigma_z$	$\xi_z$
$\eta_0$	-0.5651	(-4.043, 2.913)	0	0
$\eta_1$	$7.98 \times 10^{-4}$	(-0.017, 0.019)	1	0
$\eta_2$	0.03	(-0.022, 0.082)	0	1
$\eta_3$	$5.35 \times 10^{-7}$	( $-1.6 \times 10^{-5}$ , $1.74 \times 10^{-53}$ )	2	0
$\eta_4$	$3.2 \times 10^{-5}$	( $-5 \times 10^{-5}$ , 0.0001139)	1	1
$\eta_5$	$-1.72 \times 10^{-4}$	( $-4 \times 10^{-4}$ , $5.9 \times 10^{-5}$ )	0	2
$\eta_6$	$-4.81 \times 10^{-8}$	( $-1.1 \times 10^{-7}$ , $1 \times 10^{-8}$ )	2	1
$\eta_7$	$1.6 \times 10^{-7}$	( $4.2 \times 10^{-8}$ , $2.8 \times 10^{-7}$ )	1	2
$\eta_8$	$2.5 \times 10^{-7}$	( $-5.5 \times 10^{-8}$ , $5.6 \times 10^{-8}$ )	0	3

**Figure 20.** Capacitor cost model for one unit.**Figure 21.** Capacitor cost model for 1000 units.

#### 4.5. Flyback Coupled-Inductor Core

Typical core materials include silicon steel, iron powder and ferrites. A ferrite material core is used in the selected transformer to demonstrate the methodology. Two types of cores, gapped and ungapped, are considered in the proposed cost model with a frequency range between 50 KHz and 500 KHz. High frequency cores which are used for radio or telecommunications application are excluded. The cost core cost model was prepared using  $f_{sw}$ ,  $A_L$  and cost. Figures 22 and 23 show the interpolated  $Cost_{CO}$  surfaces while the mathematical model is shown in Equation (63) and its coefficients are shown in Table 4.

**Figure 22.** Flyback core cost model for one unit.



**Figure 23.** Flyback core cost model for 1000 units.

$$Cost_{Co}(A_L, f_{sw}) = \sum_{m=0}^{m=4} \tau_m A_L^{\psi_m} f_{sw}^{\rho_m} \quad (63)$$

**Table 4.** Coefficients for the core cost model equation.

Coefficients	Value	Ranges	$\psi_m$	$\rho_m$
$\tau_0$	1.204	(0.6736, 1.735)	0	0
$\tau_1$	1.625	(1.31, 1.939)	1	0
$\tau_2$	0.1432	(−0.6245, 0.9078)	0	1
$\tau_3$	−0.007604	(−0.467, 0.4518)	1	1
$\tau_4$	−0.1744	(−0.6827, 0.344)	0	2

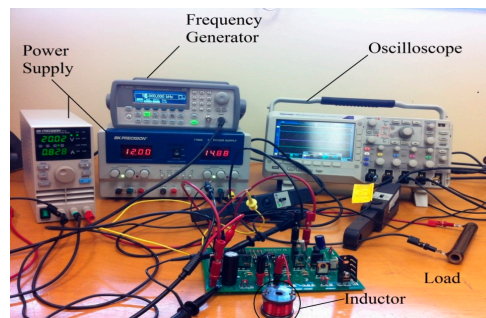
Cost models presented here were evaluated based on two criteria. The first criterion is that an analytical form is available for the cost model, i.e., polynomial, trigonometric, exponential, etc. in order to integrate this model with other mathematical and optimization tools. The second criterion is that the  $R^2$  value for each model, which is a measure between 0 and 1 of how well does the model match discrete data points, is acceptable. An  $R^2$  value that is closer to 1 is desired. The second criterion is essential when dealing with cost modeling of power electronic devices since their ratings are not available as continuous options; for example, MOSFET ratings of 50 V and 100 V exist, but not necessarily at 63.5 V, and the surface fit provided applies to the continuous range. All  $R^2$  values of the proposed models are shown in Table 5, and are all acceptable except for MOSFETs whose cost model's  $R^2$  value is low. To mitigate this case, a locally weighted scatterplot smoothing (LOWESS) model was established to achieve an  $R^2 = 0.9436$  for  $Cost_M$  but does not have an explicitly model equation like the polynomial one. Also, note that that exact cost estimates of specific components can be obtained if coefficients are changed within the specified ranges shown in Tables 1–4.

**Table 5.** Surface fitting evaluation of cost models.

Cost Model	$R^2$ Value (0 to 1)
$Cost_M$ (Polynomial, presented here)	0.6717
$Cost_M$ (LOWESS, no analytical expression)	0.9436
$Cost_D$	0.8899
$Cost_C$	0.8274
$Cost_L$	0.7014
$Cost_{CO}$	0.9365

## 5. Results

Basic boost, buck and flyback converters were experimentally developed to test the power loss and cost models presented here. Bus bar losses are not considered since the experimental prototype is at a power level that does not require bus bar. More bus bar losses information can be found in [40]. All parasitic elements and specific test condition examples are given in Table 6. Figure 24 shows the board housing both the boost and buck converters (flyback converter not shown).



**Figure 24.** Experimental setup for the buck and boost converters.

**Table 6.** Example testing conditions and parasitic elements in experimental prototypes.

Parameter	Boost	Buck	Flyback
$V_{in}$	19.3 V	60 V	12.1 V
$I_{in}$	3.18 A	1.04 A	0.434 A
$V_{out}$	75.2 V	24.1 V	25.7 V
$I_{out}$	0.794 A	2.39 A	0.151 A
$\Delta i$	1.1 A	2.95 A	0.89 A
$f_{sw}$	50 KHz	50 KHz	100 KHz
$D$	0.75	0.4	0.7
$ESR$	0.603 $\Omega$	0.603 $\Omega$	0.603 $\Omega$
$V_{D0}$	1 V	1 V	1 V
$R_D$	7 m $\Omega$	7 m $\Omega$	7 m $\Omega$
$DCR/R_{pri}$	0.06 $\Omega$	34 m $\Omega$	0.09
$ACR/R_{sec}$	0	1.5 $\Omega$	0.58
$Q_{rr}$	195 nC	195 nC	195 nC
$Q_{gs}$	64 nC	13 nC	13 nC
$R_{DSon}$	0.029 $\Omega$	0.18 $\Omega$	0.18 $\Omega$
$t_r$	100 nsec	51 nsec	51 nsec
$t_f$	63 nsec	36 nsec	36 nsec
$\approx R_c$	3325 $\Omega$	-	-
$L_m, L_{pri}$	-	-	59.4 $\mu$ H, 3.5 $\mu$ H
$B$	-	3400 mT	42.42 mT
$V_e/A_C$	-	0.24 cm <sup>3</sup>	0.97 cm <sup>3</sup>

Parasitic elements shown in Table 6 are extracted from datasheets of the components used in the experimental setup and which are IRFP4332PBF MOSFET, AIRD-03-101K inductor, MURF860G diode, and EEU-EB2D221 capacitor in the boost converter and IRFP240 MOSFET, AIRD-03-101K inductor, MURF860G diode, and EEU-EB2D221 capacitor in buck converters, and IRFP240 MOSFET, Q4338-BL flyback transformer, EGP10G Diode, and EEU-EB2D221 capacitor are used in the flyback converter.

### 5.1. Power Loss Model Verification

To validate the power loss models derived in Section 3, each of the three converters was tested under the conditions shown in Table 6, along with various output voltages and currents varied with the duty ratio. Power losses were measured by deducting the output power of the converter from its input power. Gate drive losses can be measured, but were not considered since the gate drive power supply was separate in the experimental setup and the gate drive losses do not contribute to the experimental system-level verification. Voltage divider and current sensor in the prototype consume much less power than main power losses, thus they are not taken into consideration. Figures 25–27 show experimental results of each converter at the specified test conditions in Table 6. Input and output voltage and current were measured to obtain totally converter loss to verify converter scope-level power loss. All measurements are under zero offset condition and using calibrated probes to ensure measurement accuracy.

Tables 7–9 show power loss estimates of each converter under different duty ratios. It is clear from Tables 5–7 that the error in estimating power losses using the derived models is less than 8%

leading to more than 92% accuracy. More accurate measurements and models would still be of very high value for rapid prototyping, but the achieved model-based estimation error is very satisfactory for evaluating various design options. Among the sources of estimation error are approximations, e.g.,  $R_C$  (when not in a datasheet), and limited measurement accuracy.

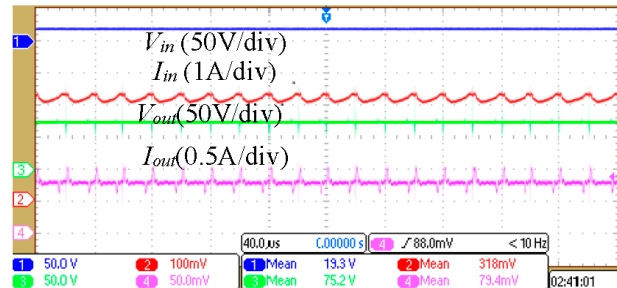


Figure 25. Boost converter experimental results for  $D = 75\%$ .

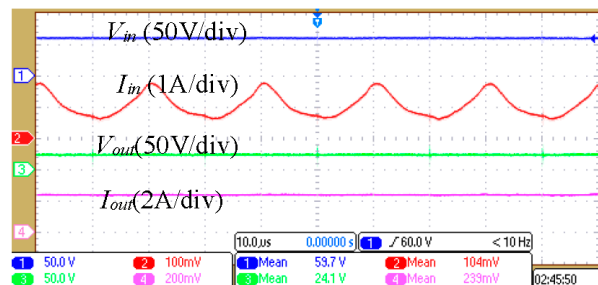


Figure 26. Buck converter experimental results for  $D = 40\%$ .

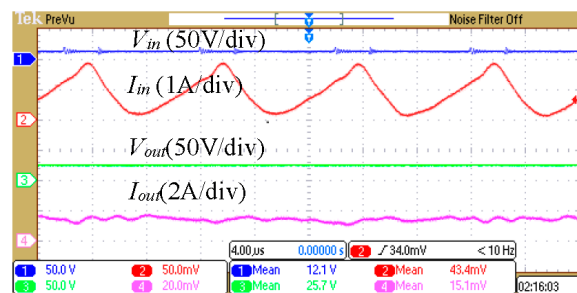


Figure 27. Flyback converter experimental results for  $D = 50\%$ .

Table 7. Estimated and measured power loss in boost converter.

Duty Ratio	$P_{Measured}$ (W)	$P_{Estimated}$ (W)	Error %
30%	0.6	0.56	−6.6%
40%	0.78	0.72	−7.69%
50%	0.97	0.92	−5.15%
60%	1.36	1.37	0.74%

Table 8. Estimated and measured power loss in buck converter.

Duty Ratio	$P_{Measured}$ (W)	$P_{Estimated}$ (W)	Error %
20%	2.54	2.49	−1.96%
30%	3.76	3.78	0.53%
40%	4.8	5.04	5%
50%	7.05	6.55	−7.09%

**Table 9.** Estimated and measured power loss in flyback converter.

Duty Ratio	$P_{Measured}$ (W)	$P_{Estimated}$ (W)	Error %
20%	0.32	0.31	−3.13%
30%	0.55	0.56	1.81%
40%	0.85	0.82	−4.7%
50%	1.32	1.27	−3.78%

## 5.2. Cost Model Verification

In order to validate the cost models proposed in Section 3, prices of the parts used were compared to prices generated from the mathematical models for the MOSFET, diode, inductor, and capacitor utilized. The flyback coupled inductor model was split into wire and cores due to their abundant information, thus similar core and wire to the Q4338-BL model are used for cost validation. Cost figures of these components were generated based on Equations (59)–(63), and results are compared to estimated prices in Table 10.

**Table 10.** Detailed cost comparison for power components.

Component	Actual Cost	Estimated Cost	Error %
MOSFET (IRFP4332PBF)	\$4.33	\$4.37	−0.92%
Inductor (AIRD-03-101K)	\$5.97	\$5.95	0.33%
Diode (MURF860G)	\$0.99	\$1.03	−4.04%
Capacitor (EEU-EB2D221)	\$0.723	\$0.752	−4.01%
Core (B66421G0000X187)	\$0.69	\$0.724	−4.93%
Wire (Belden 22AWG)	\$49.03	\$48.03	2.039%

Results in Table 10 are shown to have less than 5% error and thus the cost models established prove that the results are more than 95% accurate. The accuracy of the cost model was improved with the help of interpolated graphs and surface fitting tools. Since cost of components changes with technology and manufacturing trends, the methodology presented here can be applied for future technologies or with a refined, more comprehensive database.

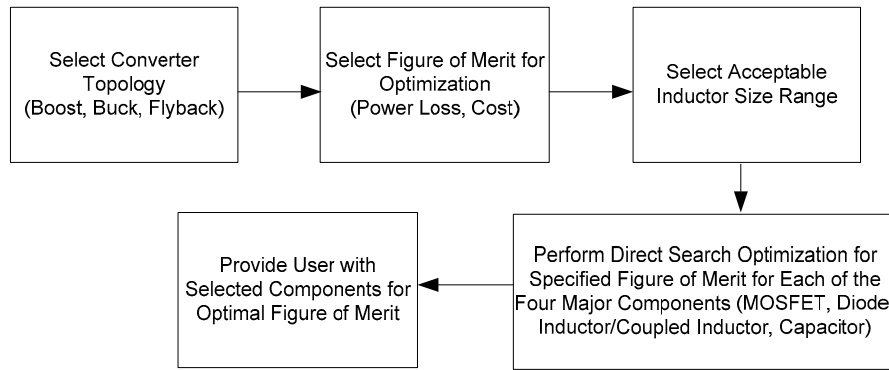
## 6. Optimization of Converter Designs for a Specific Figure of Merit

### 6.1. Optimal Design Selection Approach

The main objective of establishing power loss models in Sections 3 and 4 is to achieve the capability of selecting the “right components” in a converter. Such components can be selected based on a figure of merit, or an optimization objective function. These figures of merit include two main factors which are (1) minimum power loss; and (2) minimum cost. While co-optimizing for both can establish a Pareto front for acceptable local minima of cost and power loss, the next sections optimize for either power loss or cost, independently. Co-optimization is left for future work and is a natural next step of this paper.

In order to find component combinations that can optimize a figure of merit, a direct search optimization is performed with priority given to the component with most influence on the figure of merit being optimized. In both power loss and cost optimizations, inductors are given priority—(1) In power loss optimization, the impact of inductors on ripple and other components’ power losses is very significant; (2) in cost optimization, inductors tend to be the most expensive components. Figure 28 demonstrates the overall high-level direct search optimization performed. Sections 6.2 and 6.3 present approaches for two different figures of merit being power loss and cost, respectively.





**Figure 28.** High-level block diagram of proposed figure of merit optimization.

## 6.2. Minimum Power Loss Designs

Power loss models developed here are combined with converter ratings to automatically produce system-level minimum power loss and select the right components. This procedure reduces the manual effort in calculating component power losses to select a combination of components that minimizes power losses. Components are selected in the order that affects selection of other components—For example, selecting the inductor in a boost converter comes as a priority as it affects the losses in semiconductors and capacitor as the inductor determines the input current ripple. In order to search for components with compatible voltage and current ratings which are set by the designer, minimum inductance and capacitance values in addition to MOSFET and diode ratings for boost and buck converters in CCM are calculated based on [41,42], while component ratings are double the converter ratings even though this factor can be modified. The resulting minimum power loss does not guarantee low cost but selects components leading to a minimum converter power loss from the available database. A pseudo-code is shown below as an example for inductor selection for minimum inductor power loss and similar logic is applied to other components. Figure 29 shows a flowchart for the minimum power loss rapid prototyping tool.

---

### Start

Get input and output parameters;

$I_L = I_{in}$ ;

$L = ((V_{in} \times D \times (1 - D)) / (2 \times f_{sw} \times I_{out}))$ ;

$L_{max} = 2 \times L$ ;

Read inductor.xls file and get the entire database;

for  $i = 1$  to all database

if  $L \leq$  inductor values in database &&

$L_{max} >$  inductor values in database

if  $I_L \leq$  inductor current values in database

Extract ACR, DCR and RC values from the database;

end if;

end if;

$i = i + 1$ ;

end if;

Calculate  $P_{ACR}$ ,  $P_{DCR}$  and  $P_{CORE}$  as described in power loss model

$P_{loss\_inductor} = P_{ACR} + P_{DCR} + P_{CORE}$ ;

Print component name;

---

The procedure shown in Figure 29 is integrated into a user-friendly GUI developed in MATLAB for rapid-prototyping. The user enters the converter type, currently boost or buck converter, and sets

the operating points and basic specifications of the converter such as desired output voltage ripple and switching frequency, then receives suggested components based on the minimum combined power loss. This GUI is shown in Figures 30 and 31 for buck and boost optimal component selection, respectively.

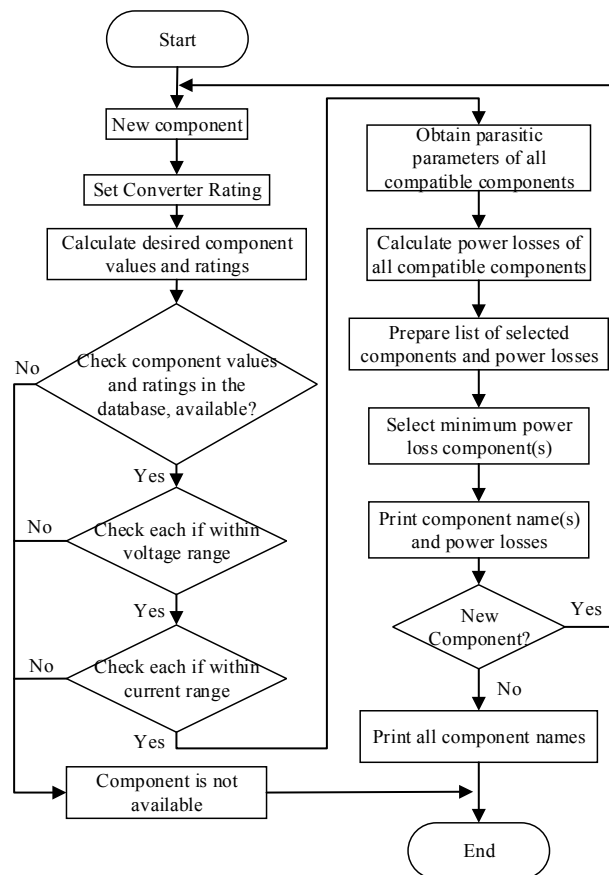


Figure 29. Flowchart of the minimum power loss tool.

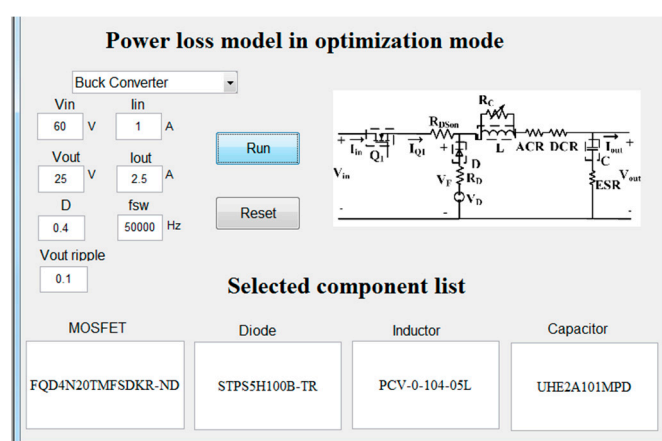
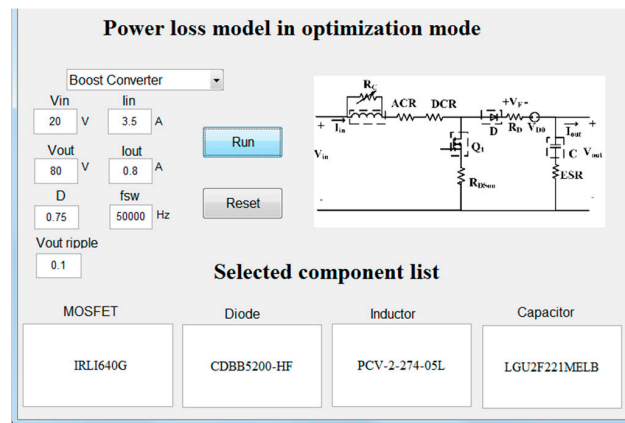


Figure 30. Minimum power loss selection (optimization mode) for a buck converter example.

In order to validate the optimal component selection based on minimum converter power losses, all selected components based on compatible ratings were evaluated manually. Power losses highlighted as gray background in Tables 11 and 12 are those for minimum power loss components and confirm results shown in Figures 30 and 31. Other examples are shown in the Appendix B.



**Figure 31.** Minimum power loss selection (optimization mode) for a boost converter example.

**Table 11.** Component options for the buck converter minimum power loss example where shown components have values and/or ratings satisfy converter operating points.

MOSFET		Diode	
Suitable Components	$P_{Loss}$ (W)	Suitable Components	$P_{Loss}$ (W)
FQD4N20TMFSCT-ND	5.03508831	SK35A-LTP	2.878
FQD4N20TMFSDKRND	5.03508831		
Capacitor		STPS5H100B-TR	
Suitable Components	$P_{Loss}$ (W)	B350A-13-F	2.881
UHE2A101MPD	0.005741826	SS35	2.877
ESH107M200AM7AA	1.07828776	CDBC5100-G	2.464
UVZ2F101MHD	0.014467593	SB550-E3/54	2.397
UPT2G101MHD6	0.014467593	SK55L-TP	2.464
Inductor		SB550	2.255
Suitable Components	$P_{Loss}$ (W)	CDBC580-G	2.458
PCV-0-104-01L	0.940523683	SS5P10-M3/86A	2.301
PCV-0-104-03L	0.35827212	SB580-T	2.213
PCV-0-104-05L	0.274278036	HSM580G/TR13	2.464
		RGP30B-E3/73	3.186
		SK310A-LTP	2.890
		CDBA3100-G	2.734
		B3100-13-F	2.586

**Table 12.** Component options for the boost converter minimum power loss example where shown components have values and/or ratings satisfy converter operating points.

MOSFET		Capacitor	
Suitable Components	$P_{Loss}$ (W)	Suitable Components	$P_{Loss}$ (W)
RDN100N20FU6-ND	3.436527778	EEU-EB2D221	0.000223251
RDN100N20-ND	3.436527778	LGU2F221MELB	0.000223251
IRLI640GPBF	1.898888889	ECO-S2GB221EA	0.0271
IRLI640G	1.898888889	Inductor	
FQP9N30	4.466997222	Suitable Components	$P_{Loss}$ (W)
STP12NK30Z	3.76386	PCV-0-274-10L	2.983
3.763864198		PCV-2-274-03L	
		PCV-2-274-05L	
		PCV-2-274-10L	3.3021
		PCV-2-394-05L	
Suitable Components	$P_{Loss}$ (W)	PCV-2-274-05L	1.172
CDBB5200-HF	1.495	PCV-2-274-10L	1.528
		PCV-2-394-05L	3.299

Note that a separate GUI has also been developed for component-specific evaluation as shown in Figure 32, where the effect of specific parameters and component choices can be visualized in terms of power loss.

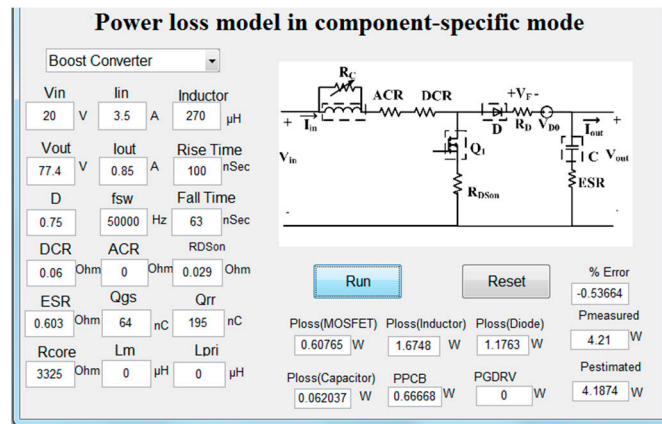


Figure 32. Component-specific power loss model for a boost converter example.

### 6.3. Minimum Cost Designs

Another rapid prototyping tool is developed to achieve minimum cost of essential components for boost and buck converters as example applications. Component selection for minimum cost is done sequentially for different components based on converter ratings only. A short list of components that satisfy the converter ratings and values for inductance and capacitance is established, and components with minimum cost are selected. This selection is not necessarily optimal in terms of efficiency but ensures minimum cost based on the available database. The optimal-cost component selection pseudo-code is below and the flowchart is shown in Figure 33.

#### Start

Get input and output parameters;

$$L = ((V_{in} \times D \times (1-D)) / (2 \times f_{sw} \times I_{out})); L_{max} = 2 \times L;$$

Read inductor.xls file and get all the database;

for  $i = 1$  to all database

if  $L \leq \text{inductor values in database} \ \&\& \ L_{max} > \text{inductor values in database}$

Extract ACR, DCR and RC values from database;

Extract unit costs and multiple unit costs data base;

end  $i = i + 1$ ;

end

Find minimum cost of the component

Print minimum cost of the component for unit quantity;

Calculate  $P_{ACR}$ ,  $P_{DCR}$  and  $P_{CORE}$  as described in power loss model;

$$P_{loss\_inductor} = P_{ACR} + P_{DCR} + P_{CORE};$$

Print component name; Print component cost;

Two GUIs were developed to implement rapid prototyping based on cost models with one GUI targeting minimum converter cost and the other targeting component-specific cost models. Screenshots of the tool designed for rapid prototyping to achieve minimum converter cost are shown in Figures 34 and 35 for buck and boost converters, respectively. Tables 13 and 14 show manual validation of these results based on the short list of components that meet the converter specifications

in the available database. Results in Figures 34 and 35 are highlighted in Tables 13 and 14 for minimum cost. The component-specific GUI is shown in Figure 36.

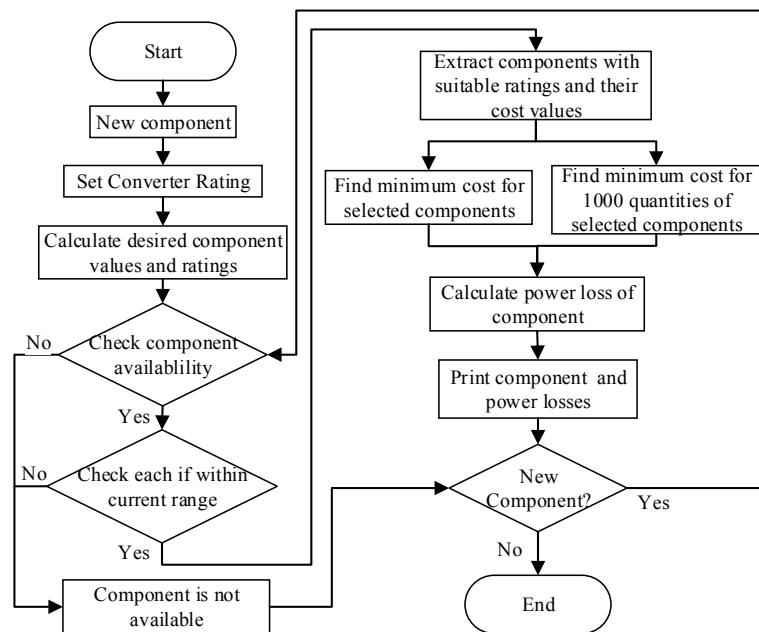


Figure 33. Optimization technique implementation for cost model.

As can be seen in the GUI screenshots and manual validations, the rapid prototyping tools holding all power loss models and cost models from Section 2 are very valuable for practicing engineers and researchers. These GUIs can be conveniently adjusted to include different component types, various technologies for specific components, and a growing database of component with adjustable cost and prices. While models running behind the GUIs may not be all inclusive of all losses in buck and boost converters, the presented methodology and MATLAB platform is very scalable and flexible. Engineers, designers, and researchers can iteratively and manually study the effect of different component parameters, e.g., MOSFET  $R_{DS,on}$ , on converter efficiency using the component-specific mode, or can rely on built in minimum cost or loss searches in the optimization mode.

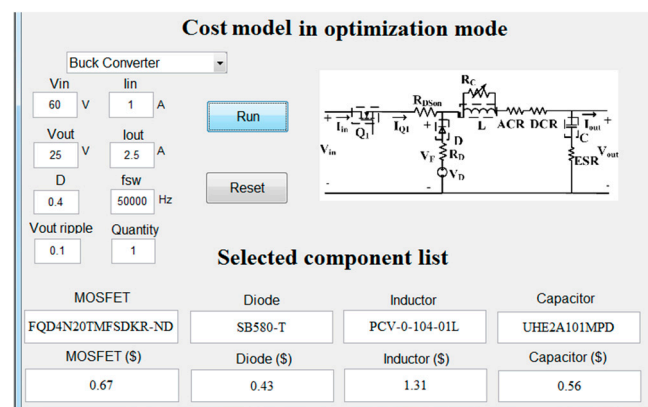


Figure 34. Minimum cost selection (opt. mode) for a buck converter.

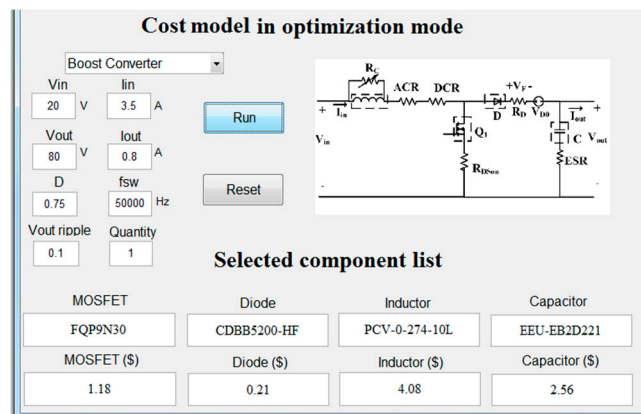


Figure 35. Minimum cost selection (opt. mode) for a buck converter.

Table 13. Component options for the buck converter optimal cost example where shown components have values and/or ratings satisfy converter operating points.

MOSFET		Diode	
Suitable Components	Cost (\$)	Suitable Components	Cost (\$)
FQD4N20TMFSCT-ND	0.67	SK35A-LTP	0.57
FQD4N20TMFSDKR-ND	0.67	STPS5H100B-TR	1.4
Capacitor		B350A-13-F	0.46
Suitable Components	Cost (\$)	SS35	0.63
UHE2A101MPD	0.56	B550C-13-F	0.95
ESH107M200AM7AA	1.02	SB550-E3/54	0.61
UVZ2F101MHD	1.85	SK55L-TP	0.49
UPT2G101MHD6	2.68	SB550	0.56
Inductor		CDBC580-G	0.74
Suitable Components	Cost (\$)	SB580	0.59
PCV-0-104-01L	1.31	SB580-T	0.43
PCV-0-104-03L	1.48	HSM580G/TR13	1.34
PCV-0-104-05L	2.37	RGP30B-E3/73	0.476
		SK310A-LTP	0.57
		CDBA3100-G	0.63
		B3100-13-F	0.68
		CDBC5100-G	0.74
		SS5P10-M3/86A	0.77
		SB5100-T	0.74

Table 14. Component options for the boost converter optimal cost example where shown components have values and/or ratings satisfy converter operating points.

MOSFET		
Suitable Components	Cost (\$)	$P_{Loss}$ (W)
RDN100N20FU6-ND	2.73	3.436
RDN100N20-ND	2.73	3.436
IRLI640GPBF	2.88	1.898
IRLI640G	2.88	1.898
FQP9N30	1.18	4.467
STP12NK30Z	1.95	3.763864198
Diode		
Suitable Components	Cost (\$)	$P_{Loss}$ (W)
CDBB5200-HF	0.21	1.495

Table 14. Cont.

Inductor		
Suitable Components	Cost (\$)	$P_{Loss}$ (W)
PCV-0-274-10L		
PCV-2-274-03L		
PCV-2-274-05L		
PCV-2-274-10L		
PCV-2-394-05L		
PCV-2-274-03L	4.15	3.302
PCV-2-274-05L	4.56	1.172
PCV-2-274-10L	7.39	1.528
PCV-2-394-05L	5.1	3.299
Capacitor		
Suitable Components	Cost (\$)	$P_{Loss}$ (W)
EEU-EB2D221	2.56	0.000223251
LGU2F221MELB	7.022	0.000223251
ECO-S2GB221EA	4.68	0.0271

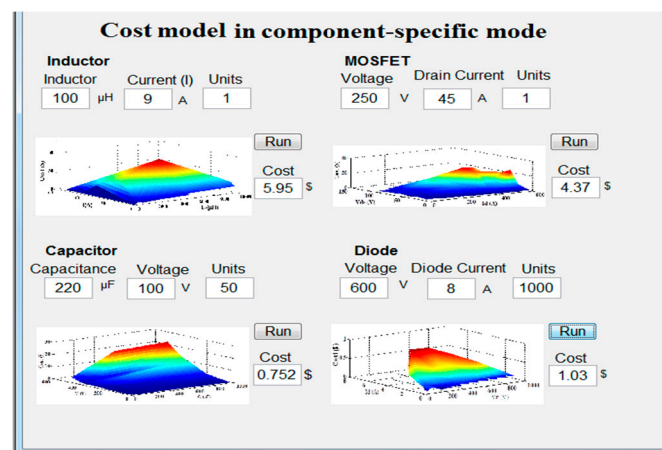


Figure 36. GUI for component cost estimates in component-specific mode.

## 7. Conclusions

This paper presents power loss and cost models of major power electronic components which can be further aggregated into power electronic converters. The proposed models are expected to aid designers in making preliminary useful estimates which help to decide specific components that can achieve desired system power loss and cost. Cost models are found based on an extensive survey of commercial devices followed by cost surface fitting. Power loss models are based on generalized forms that are reformulated to reach converter-specific models. Power loss models presented here are based on non-idealities and parasitic elements including PCB and gate drive losses to develop to achieve higher accuracy. The presented models are shown to be over 93% accurate. All models are integrated into MATLAB-based rapid prototyping tools designed for either minimum power loss or minimum cost component selection. With a large database, hundreds or thousands of various component options can be evaluated in minutes to achieve model-based component selection for optimized converter designs. The implementation of these tools with supplier databases is of major future interest, and extending the models to other applications and converters such as DC/AC inverters and AC/DC rectifiers can be achieved using the methodologies proposed here. Future work will include open-access web-based GUIs and possible linking to major supplier databases for up-to-date component lists that eliminate obsolete parts, and up-to-date prices.

**Author Contributions:** Amruta V. Kulkarni is the first author of this paper whose Master's thesis work focused on the topic of the paper; she performed the literature review to find all related cost and loss model equations, applied



these equations to specific converter topologies, and built the rapid prototyping tools; she also established the original component database. Weiqiang Chen helped to perform the hardware validation of models and double checked the accuracy of cost and loss models in addition to database data; he was responsible for paper submission and revision. Ali M. Bazzi provided the original idea for this paper, and provided guidance and mentoring on how to achieve the rapid prototyping tools; he was the research and academic advisor of Amruta V. Kulkarni and the advisor of Weiqiang Chen.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

$A$	Plate area in $\text{mm}^2$
$A_C$	Core cross-sectional area
$A_L$	Inductance factor
$ACR$	Inductor ac resistance
$B$	The peak flux density
$B_{AC}^{\beta}$	AC component of flux density
$\Delta B^m, \Delta B_{max}$	Maximum peak flux density
$C$	Capacitance value
$C_{gs}$	MOSFET gate-to-source capacitance
$Cost_C$	Capacitor cost model
$Cost_{CO}$	Core cost model
$Cost_D$	Diode cost model
$Cost_L$	Inductor cost model
$Cost_M$	MOSFET cost model
$Cost_W$	Wire cost model
$C_{sn}$	Snubber capacitor
$C_{stray}$	PCB stray capacitance
$d$	Plate separation in mm
$D$	Duty ratio
$DCR$	Inductor DC resistance
$D_{sn}$	Snubber diode
$E_r$	Dielectric constant for air
$ESR$	Equivalent series resistance
$f$	Inductor Current frequency
$f_{sw}$	Switching frequency
$G$	Wire gauge
$H$	Height of PCB trace
$\Delta i$	Inductor ripple current
$I_{Crms}$	Capacitor RMS current
$I_{Drms}, I_D$	Drain-to-source RMS current
$I_{Don}, I_{Doff}$	MOSFET on- and off-current
$\Delta I_F$	Change in diode forward current
$I_{Favg}, I_{Frms}$	Diode avg. and RMS fwd. current
$I_{Dsn(avg)}$	Snubber diode average current
$I_{Dsn(rms)}$	Snubber diode RMS current
$I_{in}$	Converter input current
$I_L$	Inductor current
$I_{Lavg}, I_{Lrms}$	Inductor average and RMS current
$I_{out}$	Converter output current
$I_{QBS}, I_{QCC}$	Gate drive quiescent currents
$I_{Srms}$	Snubber branch RMS current
$I_{trace}$	PCB trace current
$K_1$	Inductor core material constant
$K_{fe}$	Inductor current material constant at $f_{sw}$
$L$	Inductance value in
$L_e$	Length of PCB trace
$L_m$	Mutual inductance
$L_{pri}$	Primary inductance
$L_{sec}$	Secondary inductance
$L_{stray}$	PCB stray inductance
$n$	Transformation ratio
$N_{pri}$	Primary windings number of turns
$N_{sec}$	Secondary windings number of turns

$P_{ac}$	Capacitor AC loss
$P_{ACR}$	Inductor AC resistance loss
$P_{BT}$	Power dissipated at the bootstrap pin
$P_{CD}$	Diode conduction loss
$P_{CDsn}$	Snubber diode power loss
$P_{clamp}$	Power loss in the clamp unit
$P_{CM}$	MOSFET conduction loss
$P_{CORE}$	Inductor or flyback transformer core loss
$P_{Cstray}$	PCB stray capacitance loss
$P_{dc}$	Capacitor DC loss
$P_{DCR}$	Inductor DC resistance loss
$P_G$	MOSFET gate loss
$P_{GDRV}$	Gate drive power loss
$P_{loss(Capacitor)}$	Total capacitor power loss
$P_{loss(Diode)}$	Total diode power loss
$P_{loss(Inductor)}$	Total inductor power loss
$P_{loss(MOSFET)}$	Total MOSFET power loss
$P_{ON(M)}$	MOSFET turn-on loss
$P_{OFF(M)}$	MOSFET turn-off loss
$P_{PCB}$	Total PCB power loss
$P_{Rpri}$	Flyback transformer primary power loss
$P_{Rsec}$	Flyback transformer secondary power loss
$P_{stray}$	PCB stray inductance power loss
$P_{SW}$	MOSFET total switching losses
$P_{SWD}$	Diode switching loss
$P_{SWDsn}$	Snubber diode switching loss
$P_{Total}$	Total converter power loss
$P_{trace}$	PCB trace power loss
$P_{VCC}$	Power drawn through the gate drive supply pin
$Q_g$	Bootstrap capacitor charge
$Q_{gs}$	Gate-to-source charge
$Q_{rr}$	Diode reverse recovery charge
$R_C$	Effective core impedance
$R_{Dsn}$	Snubber diode on-resistance
$R_D$	Diode on-resistance
$R_{DSon}$	Drain-to-source resistance
$R_{Load}$	Output load resistor
$R_{sn}$	Snubber resistor
$R_p$	Capacitor parallel resistor
$R_{pri}$	Primary DC resistance
$R_{sec}$	Secondary DC resistance
$R_{trace}$	PCB trace resistance
$t_r, t_f$	MOSFET rise and fall times
$V_B$	Diode DC blocking voltage
$V_{BT}$	Gate drive IC Bootstrap voltage
$V_C$	Capacitor voltage
$V_{clamp}$	Clamp voltage rise
$V_{CC}$	Gate drive IC Supply voltage
$V_d$	Voltage difference between dielectric material
$V_{D0}, V_{Dsn0}$	Diode initial state voltage
$V_{Dmax}, V_{Dtyp}$	Diode maximum and typical fwd. voltage
$V_{DS}, V_{ds}$	Drain to source voltage
$V_{DSBR}$	Drain to source breakdown voltage
$V_e$	Effective core volume
$\Delta V_F$	Change in diode fwd. voltage
$V_{in}$	Converter input voltage
$V_L$	Inductor voltage
$V_{out}$	Converter output voltage
$\Delta V_{out}$	Converter output voltage ripple
$V_{rr}$	Reverse recovery voltage
$V_{supply}$	Supply voltage
$W$	Width of PCB trace
$x, y$	Core loss coefficients

## Appendix A

Examples of optimal component selection are shown here with highlighted values matching results of the rapid prototyping tools. Table A1 shows the example cases of boost and buck converter specifications, the parameters shown in Table A1 are the bases of the calculation of power loss and cost. Afterwards, the minimum power loss and cost can be found and optimal components can be selected. Tables A2–A7 show the optimal component selection for power loss minimization and Tables A8–A13 show the optimal component selection for cost minimization.

**Table A1.** Example cases of boost and buck converter specifications.

Parameters	Boost Converter			Buck Converter		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
$V_{in}$ (V)	50	40	20	50	200	200
$I_{in}$ (A)	4	2.1	2	0.5	2	1.5
$V_{out}$ (V)	120	80	130	25	160	120
$I_{out}$ (A)	2.1	0.9	0.3	1	2.5	2.5
Duty	0.6	0.5	0.85	0.5	0.8	0.6
$f_{sw}$ (KHz)	100	100	50	50	50	100
$V_{outripple}$ (V)	0.1	0.1	0.1	0.2	0.1	0.2

**Table A2.** Boost converter minimum loss results for case 1.

MOSFET		Diode	
Suitable Components	$P_{Loss}$ (W)	Suitable Components	$P_{Loss}$ (W)
FQP9N30	6.05	RD0504T-TL-H	3.63
STP12NK30Z	4.19	BY229B-400HE3/45	5.53
IRF740PBF	5.87	STTH5L04DEE-TR	3.26
IRF740STRLPBF	5.87	<b>Capacitor</b>	
SiHB10N40D	6.14	Suitable Components	$P_{Loss}$ (W)
<b>Inductor</b>		LGU2F221MELB	0.00022
Suitable Components	$P_{Loss}$ (W)	ECO-S2GB221EA	0.027
PCV-2-274-03L	4.42		
PCV-2-274-05L	1.60		
PCV-2-274-10L	2.05		

**Table A3.** Boost converter minimum loss results for case 2.

MOSFET		Inductor	
Suitable Components	$P_{Loss}$ (W)	Suitable Components	$P_{Loss}$ (W)
FQD7N20LTMDKR	2.47	PCV-2-394-05L	1.32
BUZ73AL H-ND	1.86		
JAN2N6798U-MIL	1.28	<b>Capacitor</b>	
FQD7N30TMTR-ND	2.027	Suitable Components	$P_{Loss}$ (W)
<b>Diode</b>		EEU-ED2C470	0.00022
Suitable Components	$P_{Loss}$ (W)	UPB2E470MHD1TO	0.00022
S320	1.77	ECO-S2GA470BA	0.022
PDS3200-13	1.66	380LX470M500H012	0.0055
GI912-E3/73	2.01		

**Table A4.** Boost converter minimum loss results for case 3.

MOSFET		Diode	
Suitable Components	$P_{Loss}$ (W)	Suitable Components	$P_{Loss}$ (W)
FQD7N30TMTR-ND	2.51	UVZ2F101MHD	0.00019
IRF730PBF	3.46	UPT2G101MHD6	0.00019
IRF730STRRPBF	3.46	<b>Inductor</b>	
STP7NK40Z	3.45	Suitable Components	$P_{Loss}$ (W)
STD9NM40N	2.72	PCV-2-564-02L	12.71
STD6NK50ZT4	4.16	PCV-2-564-06L	8.05
FDD6N50FTM	4.00	PCV-2-564-08L	4.25
NDF05N50ZH	5.17	DO5040H-684KLB	37.93
<b>Diode</b>			
Suitable Components	$P_{Loss}$ (W)		
RGP30G-E3/73	0.64		

**Table A5.** Buck converter minimum loss results for case 1.

MOSFET		Inductor	
Suitable Components	$P_{Loss}$ (W)	Suitable Components	$P_{Loss}$ (W)
FQT7N10LTFCT-ND	0.43	PCV-2-223-05L	0.05
FQT7N10LTFDKR-ND	0.43	PCV-2-223-10L	0.049
FQT7N10TFTR-ND	0.30	RFB1010-221L	3.48
ZXMN20B28KTCCTN	0.66	CV-0-224-03L	0.14
ZXMN20B28KTCDKR	0.66		
<b>Diode</b>		<b>Capacitor</b>	
Suitable Components	$P_{Loss}$ (W)	Suitable Components	$P_{Loss}$ (W)
SS15	0.95	EEU-FC2A220	0.074
GF1A-E3/67A	1.096	EKXG401ELL220	0.25
SS15E-TP	0.89	EEU-EB2D220	0.16
SK15-13-F	0.91	UPJ2F220MHD1TN	0.21
SS18-TP	0.84		
SS18	0.95		
B180-13-F	0.92		
CDBA180-G	0.96		
RS1B-E3/5AT	1.17		
CDBM1100-G	0.96		
SS110-TP	0.84		
SB1100	0.96		

**Table A6.** Buck converter minimum loss results for case 2.

MOSFET		Diode	
Suitable Components	$P_{Loss}$ (W)	Suitable Components	$P_{Loss}$ (W)
IRF730PBF	7.084	RGP30G-E3/73	1.16
IRF730STRRPBF	7.084	RD0504T-TL-H	1.037
STP7NK40Z	7.038	STTH5L04DEE-TR	0.87
STD9NM40N	5.47	BYC5DX-500,127	1.062
STD6NK50ZT4	8.63	RGP30J-E3/73	1.075
FDD6N50FTM	8.41	CN649	0.98
NDF05N50ZH	10.47	LXA03B600	1.75
STP8N80K5	6.94	BYV25D-600,118	0.98
SPD06N80C3	6.73	LQA05TC600	1.28
IXTH6N80A	10.77	<b>Capacitor</b>	
<b>Inductor</b>		Suitable Components	$P_{Loss}$ (W)
Suitable Components	$P_{Loss}$ (W)	UPT2G101MHD6	0.013
PCV-2-223-05L	0.19		
PCV-2-223-10L	0.17		
PCH-27X-223_LT	136.30		
PCV-0-224-03L	1.048		

**Table A7.** Buck converter minimum loss results for case 3.

MOSFET		Diode	
Suitable Components	$P_{Loss}$ (W)	Suitable Components	$P_{Loss}$ (W)
IRF720	9.74	RGP30G-E3/73	2.27
IRF720SPBF	9.74	RD0504T-TL-H	2.018
IRF720STRRPBF	9.74	STTH5L04DEE-TR	1.74
IRF730PBF	5.83	<b>Inductor</b>	
IRF730STRRPBF	5.83	Suitable Components	$P_{Loss}$ (W)
STP7NK40Z	5.74	PCV-0-104-01L	4.63
STD9NM40N	4.36	PCV-0-104-03L	1.75
STD6NK50ZT4	7.26	PCV-0-104-05L	1.34
FDD6N50FTM	7.24	<b>Capacitor</b>	
NDF05N50ZH	8.43	Suitable Components	$P_{Loss}$ (W)
STP8N80K5	5.95	UPB2E470MHD1TO	0.021
SPD06N80C3	5.96	ECO-S2GA470BA	2.058
IXTH6N80A	9.883333333	380LX470M500H012	0.520833
		380LX470M500H012	

**Table A8.** Boost converter minimum cost results for case 1.

MOSFET		Diode	
Suitable Components	Cost (\$)	Suitable Components	Cost (\$)
FQP9N30	1.18	RD0504T-TL-H	1.05
STP12NK30Z	1.95	BY229B-400HE3/45	1.03
IRF740PBF	1.63	BYC5DX-500,127	0.35
IRF740STRLPBF	1.63	BYV25D-600,118	0.848
SiHB10N40D	1.79	LQA05TC600	1.41
<b>Inductor</b>		MURF860G	0.99
Suitable Components	Cost (\$)	LQA08TC600	1.93
PCV-2-274-03L	4.15	QH08TZ600	1.85
PCV-2-274-05L	4.56	<b>Capacitor</b>	
P CV-2-274-10L	7.39	Suitable Components	Cost (\$)
		LGU2F221MELB	7.022
		ECO-S2GB221EA	4.68

**Table A9.** Boost converter minimum cost results for case 2.

MOSFET		Diode	
Suitable Components	Cost (\$)	Suitable Components	Cost (\$)
FQD7N20LTMDKR-ND	0.98	GI912-E3/73	0.48
BUZ73AL H-ND	1.26	RGP30G-E3/73	0.45
JAN2N6798U-MIL	4.34	RD0504T-TL-H	1.05
RDN100N20FU6-ND	2.73	<b>Capacitor</b>	
RDN100N20-ND	2.73	Suitable Components	Cost (\$)
IRLI640GPBF	2.88	EEU-ED2C470	0.72
IRLI640G	2.88	UPB2E470MHD1TO	1.67
FQD7N30TMTR-ND	1.04	ECO-S2GA470BA	1.31
FQP9N30	1.18	380LX470M500H012	5.41
STP12NK30Z	1.95	<b>Inductor</b>	
		Suitable Components	Cost (\$)
		PCV-2-394-05L	5.1

**Table A10.** Boost converter minimum cost results for case 3.

MOSFET		Inductor	
Suitable Components	Cost (\$)	Suitable Components	Cost (\$)
FQD7N30TMTR-ND	1.04	PCV-2-564-02L	3.78
FQP9N30	1.18	PCV-2-564-06L	6.46
STP12NK30Z	1.95	PCV-2-564-08L	10.79
IRF730PBF	1.26	<b>Capacitor</b>	
IRF730STRRPBF	1.51	Suitable Components	Cost (\$)
STP7NK40Z	1.56	UVZ2F101MHD	1.85
STD9NM40N	1.67	UPT2G101MHD6	2.68
IRF740PBF	1.63	<b>Diode</b>	
IRF740STRLPBF	1.63	Suitable Components	Cost (\$)
SiHB10N40D	1.79	LQA05TC600	1.41
STD6NK50ZT4	1.18	RGP30G-E3/73	0.45
FDD6N50FTM	1.1	RD0504T-TL-H	1.05
NDF05N50ZH	0.94	BYC5DX-500,127	0.35
TK10A50D	1.89	RGP30J-E3/73	0.495
STP11NK50ZFP	1.93	LXA03B600	0.81
IPA50R350CP	1.12	BYV25D-600,118	0.848
FDPF12N50UT	1.73		

**Table A11.** Buck converter minimum cost results for case 1.

MOSFET		Inductor	
Suitable Components	Cost (\$)	Suitable Components	Cost (\$)
FQT7N10LTFCT-ND	0.54	PCV-2-223-05L	2.12
FQT7N10LTFDKR-ND	0.54	PCV-2-223-10L	2.06
FQT7N10TFTR-ND	0.54	PCH-27X-223_LT	1.91
<b>Diode</b>		RFB1010-221L	0.68
Suitable Components	Cost (\$)	PCV-0-224-03L	1.46
SS18-TP	0.39	<b>Capacitor</b>	
SS18	0.46	Suitable Components	Cost (\$)
B180-13-F	0.82	EEU-FC2A220	0.502
CDBA180-G	0.54	EKXG401ELL220	1.72
RS1B-E3/5AT	0.178	EEU-EB2D220	0.69
CDBM1100-G	0.57	UPJ2F220MHD1TN	1.324
SS110-TP	0.39		
SB1100	0.52		

**Table A12.** Buck converter minimum cost results for case 2.

MOSFET		Diode	
Suitable Components	Cost (\$)	Suitable Components	Cost (\$)
IRF730PBF	1.26	RGP30G-E3/73	0.45
IRF730STRRPBF	1.51	RD0504T-TL-H	1.05
STP7NK40Z	1.56	STTH5L04DEE-TR	1.49
STD9NM40N	1.67	BYC5DX-500,127	0.35
STD6NK50ZT4	1.18	RGP30J-E3/73	0.49
FDD6N50FTM	1.1	CN649	0.45
NDF05N50ZH	0.94	LXA03B600	0.81
<b>Inductor</b>		BYV25D-600,118	0.84
Suitable Components	Cost (\$)	LQA05TC600	1.41
PCV-2-223-05L	2.12	<b>Capacitor</b>	
PCV-2-223-10L	2.06	Suitable Components	Cost (\$)
PCH-27X-223_LT	1.91	UPT2G101MHD6	2.68
PCV-0-224-03L	1.46		

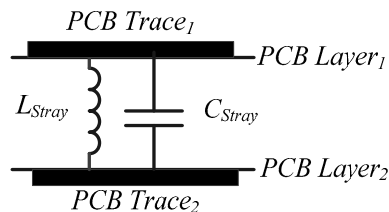
**Table A13.** Buck converter minimum cost results for case 3.

MOSFET		Diode	
Suitable Components	Cost (\$)	Suitable Components	Cost (\$)
IRF720	3.18	RGP30G-E3/73	0.45
IRF720SPBF	1.51	RD0504T-TL-H	1.05
IRF720STRRPBF	1.51	STTH5L04DEE-TR	1.49
IRF730PBF	1.26	<b>Inductor</b>	
IRF730STRRPBF	1.51	Suitable Components	Cost (\$)
STP7NK40Z	1.56	PCV-0-104-01L	1.31
STD9NM40N	1.67	PCV-0-104-03L	1.48
STD6NK50ZT4	1.18	PCV-0-104-05L	2.37
FDD6N50FTM	1.1	<b>Capacitor</b>	
NDF05N50ZH	0.94	Suitable Components	Cost (\$)
		UPB2E470MHD1TO	1.67
		ECO-S2GA470BA	1.31
		380LX470M500H012	5.41
		380LX470M500H012	5.41

## Appendix B

### Appendix B.1 PCB Losses

It is important to consider PCB power losses to achieve accuracy in the power loss modeling. Stray inductances and capacitances are usually observed in multilayer PCBs [18–20] and are illustrated in Figure B1.

**Figure B1.** PCB equivalent model.

Trace power loss  $P_{trace}$  [17] is calculated as:

$$P_{trace} = I_{trace}^2 R_{trace} \quad (B1)$$

while the stray inductance loss  $P_{Lstray}$  is obtained [25] as:

$$P_{Lstray} = I_{trace} L_{stray} \left( \frac{di}{dt} \right) \quad (B2)$$

where  $L_{stray}$  can be estimated in  $\mu\text{H}$  as:

$$L_{stray} = 2 \times 10^{-4} L_e \left[ \ln \left( \frac{2L_e}{W + H} \right) + 0.2 \left( \frac{W + H}{L_e} \right) + 0.5 \right] \quad (B3)$$

As presented in [17], stray capacitance is estimated as:

$$C_{stray} = \frac{0.085 E_r A}{d} \quad (B4)$$



and  $P_{Cstray}$  is:

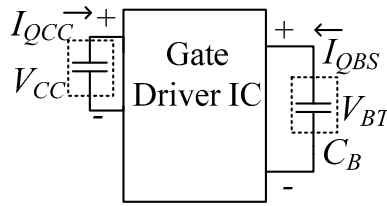
$$P_{Cstray} = \frac{1}{2} V_d^2 C_{Stray} f_{sw} \quad (B5)$$

The total PCB power loss  $P_{PCB}$  is thus:

$$P_{PCB} = P_{trace} + P_{Lstray} + P_{Cstray} \quad (B6)$$

## Appendix B.2 Gate Drive Losses

Major power loss in the gate drive circuit is normally observed across its supply and bootstrap capacitor pins. Figure B2 shows a typical high-side gate drive IC connection. Gate drive losses shown in this paper mainly focused on self-oscillating ICs or dedicated application ICs.



**Figure B2.** Gate drive ICs equivalent model.

$P_{GDRV}$  is calculated as in [21] to be:

$$P_{GDRV} = P_{VCC} + P_{BT} \quad (B7)$$

where:

$$P_{VCC} = I_{QCC} V_{CC} \quad (B8)$$

$$P_{BT} = I_{QBS} V_{BT} \quad (B9)$$

The converter total power loss  $P_{Total}$  is thus:

$$P_{Total} = P_{loss(MOSFET)} + P_{loss(Inductor)} + P_{loss(Diode)} + P_{loss(Capacitor)} + P_{PCB} + P_{GDRV} \quad (B10)$$

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