Power Grid Environment and Inductor Design for Power Loss Optimization with Boost Converter by Genetic Algorithm

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Abstract. In this paper, a proposed inductor design method with toroidal powder core is presented to minimize the total power loss of boost converter. Losses in the inductor, capacitor and semiconductors are considered. The total power loss function of the boost converter as an objective function is calculated iteratively by using the genetic algorithm (GA) in MATLAB. Then the optimal core size, permeability and number of turns can be obtained, which minimize the total power loss. Finally, the experimental results verify the proposed inductor design method is feasible by comparing with the general inductor design method in an 800W boost converter operating at 50kHz.

Keywords: Boost converter; inductor design; toroidal powder core; genetic algorithm; power loss.

1. Introduction

The boost converter is widely applied in electronic products and the inductor is usually responsible for an important part of the power loss in boost converter. At present, the research work on the boost converter has been mainly focused on the optimization design of the inductor. Reference[1] introduced an optimization design method of the inductor called “PL product” by separating the output power and inductance needed for a desired inductor ripple current. Though this method made the inductor design easier, it cannot determine whether the desired inductor ripple can get a suitable inductor and lead to a minimum total power loss. Reference[2] presented that by selecting the right inductor ripple current could help optimize the inductor design but the right inductor ripple current selecting method was not mentioned.

The procedure of general inductor design with toroidal powder core[3] is shown as Figure 1. The switching frequency, inductor DC and ripple current, maximum current density and core material are given as specifications. Then the inductance required with DC bias current can be estimated. The appropriate core size and permeability are selected in the core selection chart according to the inductor stored energy ($LI_{DC^2}$). The next is the calculation of the number of turns by using the initial permeance. As we known, for powder core, the increase of magnetizing force occurs the permeability reduction, the suitable number of turns can be got by adjusting the number of turns and calculating the real inductance from permeability vs DC bias curve provided by core manufacturer until the real inductance is satisfy to the required inductance. The last one is the selection of wire size by using the maximum current density.
Figure 1. General inductor design procedure.

Unfortunately, the general inductor design method could lead to a non-optimal inductor design. For a fixed switching frequency, the inductor ripple current determines the inductance. The inductor current ripple ratio (peak to peak) is usually given by 10% to 30% with intuition and experience[4]. The different inductances cause the currents flowing through the converter to be different, resulting in the different losses of semiconductors, inductor, capacitor and total power loss. So the somewhat arbitrarily selected inductor ripple current could lead to more total power loss. Therefore, this paper proposes a new inductor design method of selecting the core size, permeability and number of turns to minimize the total power loss for boost converter with toroidal powder core by using the genetic algorithm. To evaluate the proposed inductor design method, an 800 W boost converter is used with a switching frequency of 50 kHz. The experimental results show the proposed inductor design method can lead to the optimal results.

2. Proposed Inductor Design Method

The genetic algorithm is used in the proposed inductor design method. It is a method for solving both constrained and unconstrained optimization problems based on a natural selection process mimicking the biological evolution. The algorithm repeatedly modifies a population of individual solutions[5]. The evolution flowchart of genetic algorithm is shown in Figure 2. The genetic algorithm begins with a set of randomly generated initial population and uses the population of possible solutions to the search space. Then each solution is encoded in a string called a chromosome. Chromosomes are evaluated for fitness each generation. If there is no fitness value, different chromosomes with a high probability of surviving are chosen as parents and combined to form child chromosomes. Chromosomes may undergo mutation, then a new generation is formed and the process is repeated. By reproduction, crossover and mutation, the genetic algorithm searches the solution space while creating more fit solutions over each generation until the optimal solution is obtained.
Figure 2. Genetic algorithm evolution flowchart.

Figure 3 shows the procedure of proposed inductor design method. The starting is the given specifications including the switching frequency, the maximum current density and core material. Different from the general inductor design method, the inductor ripple current is not given as specifications. Then is the wire selection. In the next step, the MATLAB genetic algorithm is used and finally the optimal results are obtained.

Figure 3. Proposed inductor design procedure.

In MATLAB genetic algorithm, the variables are core size, permeability and the number of turns. As the variables, the core size and permeability are indexed. The objective function is the total power loss function. The total power loss of boost converter $P_{\text{loss}}$ contains MOSFET loss $P_Q$, diode loss $P_D$, capacitor equivalent series resistance (ESR) loss $P_C$ and inductor loss $P_L$. Thus, the total power loss function can be expressed as

$$P_{\text{loss}} = P_Q + P_D + P_C + P_L$$

(1)

The constraint function is $1 \leq N \leq N_{\text{max}}$, where, $N$ is the number of turns and $N_{\text{max}}$ is the maximum number of turns corresponding to the different core sizes. The options for the genetic algorithm are generations and populationsize.

The derivation of current equations flowing through the boost converter are summarized in Appendix. The derivation of each loss function at continuous conduction mode (CCM) and discontinuous conduction mode (DCM) which is derived from theoretical aspects by us is shown as below[6]-[11].

2.1. MOSFET Loss

The MOSFET loss contains conduction loss $P_{\text{cond}}$, turn-on switching loss $P_{\text{on}}$, turn-off switching loss $P_{\text{off}}$, discharging loss $P_{\text{qloss}}$ and driving loss $P_{\text{drive}}$. It can be expressed as

$$P_Q = P_{\text{cond}} + P_{\text{on}} + P_{\text{off}} + P_{\text{qloss}} + P_{\text{drive}}$$

(2)

The MOSFET conduction loss is provided as

$$P_{\text{cond}} = I_{\text{on}}^2 R_{\text{on}}$$

(3)
where $I_{Q_{rms}}$ is MOSFET rms current and $R_{on}$ is MOSFET drain-source on-resistance. The MOSFET turn-on switching loss is given as

$$P_{Q_{on}} = \begin{cases} \frac{1}{2} (I_{L_{dc}} - \Delta I_{l}) V_{o} t_{on} f_{s} & \text{at CCM} \\ 0 & \text{at DCM} \end{cases}$$

where $I_{L_{dc}}$ is inductor DC current, $\Delta I_{l}$ is inductor ripple current (half of peak to peak), $V_{o}$ is output voltage, $t_{on}$ is MOSFET turn-on rise time and $f_{s}$ is switching frequency. The MOSFET turn-off switching loss is written as

$$P_{Q_{off}} = \begin{cases} \frac{1}{2} (I_{L_{dc}} + \Delta I_{l}) V_{o} t_{off} f_{s} & \text{at CCM} \\ \Delta I_{l} V_{o} t_{off} f_{s} & \text{at DCM} \end{cases}$$

where $t_{off}$ is MOSFET turn-off fall time. The discharging loss of MOSFET output capacitance $C_{oss}$ for all CCM and DCM is given as

$$P_{Q_{oss}} = E_{oss} f_{s}$$

where $E_{oss}$ is MOSFET output capacitance energy. The gate drive loss for all CCM and DCM is provided as

$$P_{Q_{drive}} = V_{gs} Q_{g} f_{s}$$

where $V_{gs}$ and $Q_{g}$ are MOSFET gate source voltage and total gate charge.

### 2.2. Diode Loss
The diode loss contains conduction loss $P_{D_{cond}}$ and switching loss $P_{D_{sw}}$. It can be expressed as

$$P_{D} = P_{D_{cond}} + P_{D_{sw}}$$

The diode conduction loss is obtained as

$$P_{D_{cond}} = I_{D} V_{D} + I_{D_{rms}} R_{D_{on}}$$

where $I_{D}$ and $I_{D_{rms}}$ are output and diode rms current, $V_{D}$ is diode forward voltage drop and $R_{D_{on}}$ is diode on-resistance. The diode switching loss occurs during the switching of the MOSFET, when diode continues to conduct in opposite direction until the reverse recovery charge is discharged. This loss is equal to zero when the converter operates in discontinuous conduction mode, since the current through diode falls to zero before the transistor switches off. So the diode switching loss is provided as

$$P_{D_{sw}} = \begin{cases} V_{D} \left[ (I_{L_{dc}} - \Delta I_{l}) t_{r} + Q_{r} \right] f_{s} & \text{at CCM} \\ 0 & \text{at DCM} \end{cases}$$

where $t_{r}$ and $Q_{r}$ are diode reverse recovery time and reverse recovery charge. When the silicon carbide (SIC) Schottky diode is used, the capacitive charge $Q_{c}$ instead of $Q_{r}$ is used and $t_{r}$ is 0.

### 2.3. Capacitor ESR Loss
The capacitor ESR loss can be summarized as

$$P_{C} = I_{C_{rms}}^{2} R_{c}$$

where $I_{C_{rms}}$ is capacitor rms current and $R_{c}$ is capacitor equivalent series resistance.

### 2.4. Inductor Loss
The inductor loss contains core loss $P_{L_{c}}$ and winding loss $P_{L_{w}}$. It can be expressed as
\[ P_L = P_{le} + P_{lw} \] (12)

General Steinmetz Equation (GSE) is commonly used to describe the core loss under sinusoidal excitation. But non-sinusoidal excitation is normal for typical power electronics applications. Simply using the peak value of the flux density would underestimate the core loss. In this paper, the core loss is calculated through the improved General Steinmetz Equation (iGSE) which modifies the original equations while retaining the original coefficients[6]. The inductor core loss density using iGSE model is calculated as

\[ P_{GSE} = \frac{1}{T_s} k_i |\Delta B|^\beta \int_0^{T_s} |\frac{dB(t)}{dt}|^\alpha dt \] (13)

where

\[ k_i = \frac{K_c}{\left(2^{\beta+1} \pi^{\beta-1}\right) \int_0^{\pi} \cos(\theta)^\alpha d\theta} \] (14)

\( K_c, \alpha \) and \( \beta \) are core coefficients that may be found or calculated from manufacturer’s data. \( \Delta B \) is peak to peak flux density ripple and is given as \( \Delta B = V_g D / N A_c f_s \). Substituting \( dB(t)/dt = \Delta B f_s / D \) into Equation (13) and considering the volume \( V_c = A_c l_m \) gives

\[ P_{Le} = k_i D^\beta \left( D^{\alpha-1} + (1-D)^{\alpha-1}\right) l_m A_c^{1-\beta} \left(\frac{V_g}{N}\right)^\beta f_s^{\alpha-\beta} \] (15)

where \( V_g \) is input voltage, \( D \) is duty cycle, \( A_c \) and \( l_m \) are cross-sectional area and magnetic field length of core. The inductor winding loss contains DC winding loss \( P_{wDC} \) and AC winding loss \( P_{wAC} \). It can be written as

\[ P_{lw} = P_{wDC} + P_{wAC} \] (16)

The DC winding loss is expressed as

\[ P_{wDC} = I_{rms}^2 R_{DC} \] (17)

where \( I_{rms} \) is inductor rms current and \( R_{DC} \) is DC winding resistance which is given as \( R_{DC} = N \rho_{cu} l_f / A_{cw} \). \( l_f \) and \( \rho_{cw} \) denote the mean length turn of core and wire resistivity. The calculation of AC winding loss needs AC winding resistance which can be provided by multiplying DC winding resistance by AC resistance ratio \( F_r \). The Dowell’s equation is used to calculate \( F_r \) and is given as[6]

\[ D(i) = \frac{\varphi \sinh(2\varphi) + \sin(2\varphi)}{\cosh(2\varphi) - \cos(2\varphi)} + \frac{2(\varphi^2 - 1) \varphi \sinh(\varphi) - \sin(\varphi)}{3 \cosh(\varphi) + \cos(\varphi)} \] (18)

where \( \varphi \) is the foil height ratio and is given as \( \varphi = h/\delta \). \( h \) is the height of foil. \( \delta \) is the skin depth and \( i \) is the number of layers in one portion.

Figure 4(a) shows the winding structure of inductor with toroidal core. The inner diameter of toroidal core is \( ID \) and \( c_i \) is the perimeter of \( k \)-th inner layer. \( c_i \) can be calculated as

\[ c_i = \pi \left[ ID - (2k-1)\right] \] (19)

where \( w \) is the width of winding considering the spacing factor. Then disassembling the toroidal windings of inner layer in a horizontal axis and assuming the total number of inner layers to be \( m \), we can divide the windings of inner layer into \( m \) portions as shown in Figure 4(b). The number of inner layers in one portion equals to the portion number. The AC resistance ratio of inner layer \( F_{rin} \) can be considered to be the weighted average of the AC resistance ratios from portion 1 to portion \( m \). The
weight of each AC resistance ratio from portion 1 to portion \( m \) can be regarded as the ratio of the length of each portion to the length of the first inner layer in a horizontal axis. Thus the AC resistance ratio of inner layer \( F_{rin} \) can be expressed as

\[
F_{rin} = \sum_{k=1}^{m-1} D(k) \left( \frac{\ell_k - \ell_{k+1}}{\ell_1} \right) + D(m) \frac{N_{m,m}}{\ell_1}
\]  

(20)

Figure 4. Winding structure of inductor.

where \( N_{m,m} \) is the number of turns of \( m \)-th inner layer and can be obtained as

\[
N_{m,m} = N - \sum_{k=1}^{m-1} \text{floor} \left( \frac{\ell_k}{\ell_1} \right)
\]  

(21)

where \( \text{floor}(x) \) rounds the elements of \( x \) to the nearest integers towards minus infinity. The AC resistance ratio of outer layer \( F_{rout} \) can be calculated in the same way. Averaging the AC resistance ratio of inner and outer layer, \( F_r \) can be derived as

\[
F_r = \frac{F_{rin} + F_{rout}}{2}
\]  

(22)

Then the AC winding loss is derived as

\[
P_{wAC} = \Delta I_{rms}^2 F_r R_{DC}
\]  

(23)

where \( \Delta I_{rms} \) is inductor AC rms current.

3. Experimental Results

An 800W boost converter shown in Figure 5 is used in experiment. The switching frequency is set as 50kHz. The MOSFET is IAP60R380P6 with \( R_{on} \) is 0.38 Ohm. The diode is C3D04060A with \( V_D \) is 1.5V. The capacitor is 450MXH with the capacitance is 470\( \mu \)F and \( R_c \) is 0.564 Ohm. The core is HighFlux material with toroidal shape. The maximum current density is given as 700A/cm\(^2\) and the AWG wire size is calculated as 20.
In general inductor design method, the inductor current ripple ratios (peak to peak) of design 1-5 are selected as 10%, 15%, 20%, 25% and 30%, respectively. With the design procedure shown in Figure 1, the inductor design results are shown in Table 1.

Table 1. Inductor design results of general inductor design method.

| Design # | Core part number | Permeability | Number of turns |
|----------|------------------|--------------|-----------------|
| Design 1 | CH572125         | 125μ0        | 151             |
| Design 2 | CH468060         | 60μ0         | 213             |
| Design 3 | CH468060         | 60μ0         | 180             |
| Design 4 | CH468060         | 60μ0         | 159             |

In proposed inductor design method, with the design procedure shown in Figure 3, the inductor design results are shown in Table 2.

Table 2. Inductor design results of proposed inductor design method.

| Design # | Core part number | Permeability | Number of turns |
|----------|------------------|--------------|-----------------|
| Design 6 | CH467125         | 125μ0        | 104             |

The designed six inductors are shown in Figure 6. The total power loss is measured by two power meters and the experimental results are shown in Figure 7.

Figure 5. Experimental equipment.

Figure 6. Inductors used in experiments.

From the experimental results we can see, the total power loss of the proposed inductor design is 14.3W, which is the lowest compared to the general inductor design 1-5. The experimental results validate that the proposed inductor design method can lead to a lower total power loss than the general inductor design method and give an optimal inductor design in the efficiency of the boost converter.

Figure 7. Total power loss of general and proposed inductor design.

4. Conclusions

In this paper, a new inductor design method of selecting the optimal core size, permeability and number of turns with toroidal powder core for the boost converter has been proposed to minimize the total power loss. Different from the general inductor design method, the inductor ripple current is not required as a specification. To obtain the optimal solutions, the genetic algorithm is used. The
experimental results validate the proposed inductor design method is applicable and can lead to the minimum total power loss. The proposed method is also valid for other converter topologies such as buck, buck-boost, PFC boost converter and so on as long as we change the specifications and total power loss functions. Further investigation of boost converter under different core materials and shapes to minimize power loss will be performed in a future work.

5. Appendix
The average and rms values of the current flowing through the boost converter are necessary to calculate the power loss. The current equations are summarized as follows.

5.1. Inductor Current
The inductor ripple current (half peak to peak) is determined as

\[ \Delta i = \frac{V_i D}{2f_s} \]  

where \( L \) is the inductance at full load and can be given as \( L = \mu A N^2 l_m \). \( \mu \) is the effective permeability under dc bias current.

The inductor DC current is given as

\[ I_{Ldc} = \frac{D + D_1}{D_1} I_o \]  

where \( D_1 \) is the duty cycle of diode.

The inductor AC rms current is provided as

\[ \Delta i_{Lrms} = \Delta i \sqrt{\frac{4}{3}(D + D_1) - (D + D_1)^2} \]  

The inductor rms current is calculated as

\[ I_{Lrms} = \sqrt{I_{Ldc}^2 + \Delta i_{Lrms}^2} \]  

5.2. MOSFET Current
The MOSFET rms current is expressed as

\[ I_{Qrms} = \sqrt{\frac{D}{D + D_1}} I_{Lrms} \]  

5.3. Diode Current
The diode rms current is obtained as

\[ I_{Drms} = \sqrt{\frac{D_1}{D + D_1}} I_{Lrms} \]  

5.4. Capacitor Current
The capacitor rms current is written as

\[ I_{Crms} = \sqrt{I_{Drms}^2 - I_o^2} \]  

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