Abstract

In this paper, it is first proposed that genetic algorithm and Taguchi method can be employed in the optimal design of DC-DC converter with LC snubber. The purpose of this optimal design is to lower the spike voltage $V_{ds}$ across power switch and hence reduce the manufacturing cost. For the first step, we investigate the circuit parameters which will affect $V_{ds}$ and subsequently converge the range of circuit parameter value by means of genetic algorithm, and conduct the optimal design of prototype converter with Taguchi method. Compared with spike voltage $V_{ds}$ of non-optimal design circuit, the effect of optimal design is revealed. In suppressing spike voltage, the $V_{ds}$ measured from optimal design circuit is 115V, and is actually 28.1% reduced. Therefore, using genetic algorithm and Taguchi method in the optimal design of converter with LC snubber is a more economic, practical and efficient circuit design, which meanwhile can be easily applied to other electronic circuits and accomplishes the optimal design of various quality characteristics.

Keywords: Optimal design, LC snubber, DC-DC converter, Genetic algorithm, Taguchi method.
1. Introduction

Switching power converters are extensively used in power electronics applications because of their light weight, small volume, and high conversion efficiency. In particular, forward and flyback converters are suitable for low-power and medium-power applications because of their simple circuit structure and easy design [1-4]. Since the switching power converters make use of switching movement to achieve the power conversion, and the parasitic elements existing in the power device will no more be ignore at high frequencies, they cause excessive spike voltage across the power switch, which damages switch elements and leads to a higher power loss, and what is more, adversely reduces conversion efficiency. In order to suppress spike voltage and promote conversion efficiency, it is a common procedure to mount a snubber on the power converters. In practical applications, RCD snubber circuits [5-7] and LC lossless snubber circuits [8-10] are widely utilized. Although RCD snubber can suppress the spike voltage effectively, it does not help to promote the efficiency due to waste energy on resistor. On the contrary, not only can LC snubber suppress the spike voltage of power switch, but also the energy of scatter elements can be sent back to the power source by snubber circuit and the switching efficiency is highly promoted. However, how to select a proper snubber circuit and hence obtain the optimal design will be an issue worthy of investigation.

The merit of genetic algorithm (GA) is the ability to prevent local optimization during the process of optimization. Traditional algorithm starts from a point and gradually approaches to the best solution, while GA presents the solution in the pattern of genes and set off with a great number of possible solutions which complete each other. Through the competition, superior solutions are reproduced and worse ones eliminated, and then new generations are generated by gene recombination. These steps recur until the optimal solution appears [11-14].

However, we are unable to identify precisely the distribution of scatter element on
prototype converter, and in addition, the theoretical values obtained from theoretical analysis are confined to the standard specification of elements, so that the proper element specification cannot be established and the functioning of prototype is far from ideal. Due to these disadvantages, experimentation is extensively adopted to achieve optimal design. Four methods are included to design parameters: (1) trial-and-error method, (2) one-factor-at-a-time method, (3) full-factor experiment, and (4) Taguchi orthogonal array experiment [15-18]. For the last one, Taguchi orthogonal array experiment is able to completely eliminate biases, reduces the trials of experimentation, and simplifies data analysis. This is recognized as more economic, convenient and efficient.

Basically, the entire efficiency of LC lossless snubber is much higher than that of RCD snubber. However, for LC snubbers with the same smaller power, the entire efficiencies of optimal and non-optimal circuits do not make much difference. For these reasons, we conduct the optimal design only on the spike voltage on power switch in order to reduce $V_{dsp}$.

In this paper, we propose the technique of optimal design on DC-DC converter with LC snubber by using GA and Taguchi method. First of all, the voltage $V_{ds}$ across power switch is selected as a cost function, and the optimal theoretical values of circuit elements affecting $V_{ds}$ are calculated by GA. Based on the optimal theoretical values, the control factors and their levels are determined. Eventually, the values of each control factor (circuit elements of the prototype) and the optimal design of DC-DC converter with LC snubber is obtained by Taguchi method.

2. Circuit Parameters Affecting $V_{dsp}$

In 1999, Chuanwen Ji et al. analyzed and discussed the voltage stress across power switch on flyback converter with LC snubber, as shown in Fig. 1. The leakage inductance $L_e$ on the primary of transformer stores energy during the switch-on interval. When the switch is turned off, the clamp capacitor $C_e$ will be charge by $L_e$ and the output side of transformer.
That is [8]

\[ V_{cl} = V_o + I_o \sqrt{L_c / C_c}, \]  

(1)

where \( I_o \) is the instantaneous (max.) current in the primary winding, hence

\[ V_o = V_{cl} - I_o \sqrt{L_c / C_c}. \]  

(2)

Furthermore, according to the law of conservation of energy, \( V_{cl} \) can be obtained:

\[ V_{cl} = \frac{1}{2} V_o + \frac{1}{2} \sqrt{V_o^2 + \frac{4 L_c L_m}{L_m + L_e} V_{in}^2}, \]  

(3)

where \( L_m \) and \( L_e \) are magnetizing and resonant inductors, respectively. Therefore, we can get

\[ V_{ds} = V_{in} + \frac{1}{2} V_o + \frac{1}{2} \sqrt{V_o^2 + \frac{4 L_c L_m}{L_m + L_e} V_{in}^2}. \]  

(4)

From (1) to (4), we have

\[
V_{ds} = V_{in} + \frac{1}{2} \times \left( \frac{4 L_c L_m V_{in}^2}{(L_m + L_e)^2 I_o} - 4 I_o \frac{L_c}{C_c} \right) \times \sqrt{L_c C_c} / 4 L_c + \frac{1}{2} \times \left( \frac{4 L_c L_m V_{in}^2}{(L_m + L_e)^2 I_o} - 4 I_o \frac{L_c}{C_c} \right) \times \frac{1}{4} \sqrt{L_c C_c} + \frac{4 L_c L_m V_{in}^2}{(L_m + L_e)^2} \right)^{1/2}.
\]  

(5)

Under these circumstances, the circuit elements \( L_c, C_c \) and \( L_e \) in Fig. 1 affect \( V_{ds} \).

Therefore, this paper selects \( L_c, C_c \) and \( L_e \) as design parameters and conducts GA and Taguchi method for the optimal design to suppress \( V_{dsp} \).
3. The Optimal Design Procedures and Steps

In this section, we will first calculate the optimal theoretical value of circuit elements by GA, and conduct the optimal design of prototype converter elements with Taguchi method to reduce $V_{dp}$.

3.1 The optimal design of theory value-GA

GA contains powerful operators, of which three fundamental ones are reproduction, crossover and mutation. If reasonable fitness functions can be determined and these operators are appropriately employed, the optimal solution of theoretical value of circuit elements can be obtained. Figure 2 shows the design flowchart and the steps for GA are listed below:

![Design Flowchart for GA](image)

Fig. 2. Optimal design flowchart for GA.
Step 1. Select $V_{ds}$ as a cost function, as in (5).

Step 2. Select circuit elements ($L_C$, $C_i$ and $L_e$) affecting $V_{ds}$ as an initial group.

Step 3. Conduct binary encoding on $L_C$, $C_i$ and $L_e$ to produce parent generation.

Step 4. Calculate the fitness function and judge the optimal fitness function.

Step 5. Reproduce the gene of the optimal fitness function obtained from step 4 and retain to the next generation.

Step 6. Produce new generation through random crossover of parent generation.

Step 7. Randomly select genes from new generation for mutation.

Step 8. Calculate and judge the genes obtained from step 7. If the function reaches convergence, the optimal fitness functions ($L_C$, $C_i$ and $L_e$) and the cost function ($V_{ds}$) are obtained. If it is not, repeat steps 5~8.

3.2. The optimal design of prototype converter-Taguchi method

On the basis of the optimal theoretical value obtained from GA, we select elements from appropriate specifications and conduct the optimal design of prototype converter by Taguchi method [15] for the purpose of reducing $V_{dep}$. According to the control factors and the number of levels, we select an appropriate orthogonal array, and determine the optimal design parameters through experimentation. In so doing, we can reduce both the trials of experimentation and the design cost. Figure 3 reveals the design procedure and steps of the optimal design of DC-DC converter with LC snubber are listed below:

Step 1. Select $V_{ds}$ on power switch as output response.

Step 2. Determine the control factors ($L_C$, $C_i$ and $L_e$) affecting the output response.

Step 3. Determine the numbers of levels for each control factor.

Step 4. Select appropriate Taguchi orthogonal array according to the numbers of control factors and their levels.

Step 5. Evaluate and select the level values of each control factor.
Step 6. Determine the S/N formula of smaller-the-better characteristic according to the output response.

Step 7. Conduct Taguchi experiment according to the selected control factors, level values, and the orthogonal array.

Step 8. Make factor response table and determine the optimal combination of control-factor levels.

Step 9. Evaluate the optimal combination derived from step 8 and judge whether it is necessary to change the level values. If yes, repeat steps 5~9.
Step 10. Obtain the prototype of optimal design from a testing of the confirmation run.

4. Prototype of the Optimal Design

![Fig. 4. DC-DC converter with LC snubber.](image)

In this section, the $V_{dp}$ of a non-optimal design circuit will be first discussed, and then the conduct of the optimal design by using GA and Taguchi method will be presented. Finally, the suppressing effect on $V_{dp}$ of these two kinds of circuits will be compared.

4.1 $V_{dp}$ of the non-optimal circuit

In order to reduce the $V_{dp}$ and hence decrease the production cost, this subsection will take into consideration the circuit of the DC-DC converter with LC snubber, as show in Fig. 4. The $L_c = 16.3 \mu H$, $C_c = 0.0047 \mu F$ and $L_e = 1.82 \mu H$ are randomly selected as elements for the circuit. The specification details of the testing circuit are: $V_{in} = 48V$, $V_o = 5V$, output power $P_o = 30W$, and the switching frequency $f = 50kHz$. Figure 5 shows the measured waveforms, of which $V_{dp} = 160V$. 
4.2 $V_{ds}$ of the optimal design circuit

In this subsection, the design of optimal theoretical values of circuit elements is accomplished by GA. These values are subsequently used to conduct the optimal design of prototype converter elements by Taguchi method. As shown in section 2, $L_e$ can affect the value of $V_{ds}$, and therefore, we choose three types of different transformer windings. Different transformer winding creates different leakage inductor $L_e$. For the first type of winding, primary winding is placed inside and secondary winding is placed outside with $L_e = 1.82 \mu H$. The second type places secondary windings inside and primary windings outside with $L_e = 1.44 \mu H$. For the third method, the first layer is half of the primary winding, the second layer places the secondary winding, and the third layer is another half of the primary winding. This winding type is thus called sandwich windings with $L_e = 1.24 \mu H$.

4.2.1 Optimal design of theoretical circuit element values-GA

Considering the production cost, we determine the range for the circuit elements ($L_e$, $C_t$ and $L_e$). $L_e : [1 \mu H \sim 20 \mu H ]$, $C_t : [1 nF \sim 15 nF ]$ and $L_e : [1.24 \mu H \sim 1.82 \mu H ]$. The population size, crossover probability, and mutation probability of the GA are 36, 0.5, and 0.08, respectively. According to the design procedure (section 3.1), the value for circuit elements is first given by binary encoding of the octal values (parent generation). The best genes are then retained in the next generation for double crossover. New generations are produced, among which we randomly select genes for mutation, step by step, we accomplish
the optimal design of theoretical circuit element values. At the last stage, we have totally 6000 generations of encoding, reproduction, crossover and mutation being run through and the results are obtained. Figure 6 shows that $V_{ds}=88.7\text{V}$ is the lowest cost function value. As such, the optimal theoretical values for circuit elements are $L_c=12.1\mu\text{H}$, $C_c=0.015\mu\text{F}$ and $L_e=1.24\mu\text{H}$.

Fig. 6. The simulation of circuit element by GA.

4.2.2 The optimal design of the prototype converter-Taguchi method

In this subsection, the flowchart and steps described in section 3.2 are pursued and the optimal design is conducted on Fig. 4. First, the $V_{ds}$ is selected as the quality characteristic, then three different specifications of $L_c$, $C_c$ and $L_e$ are adopted. Therefore, a Taguchi orthogonal array is chosen for experimentation, and the control factors and level values are shown in Table 1.

The objective of the optimal design is to suppress the spike voltage across the power switch to 0; and accordingly the S/N formula of smaller-the-better is:

$$S/N = -10 \log |y - y_0| \text{dB}. \quad (6)$$
Table 1. Control factors and level values

<table>
<thead>
<tr>
<th>Control factors</th>
<th>Description</th>
<th>Level 1 (μH)</th>
<th>Level 2 (μH)</th>
<th>Level 3 (μH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Resonant inductor</td>
<td>11.3</td>
<td>13.5</td>
<td>16.3</td>
</tr>
<tr>
<td>B</td>
<td>Clamp Capacitor</td>
<td>0.0047</td>
<td>0.01</td>
<td>0.015</td>
</tr>
<tr>
<td>C</td>
<td>Transformer leakage inductor</td>
<td>1.24</td>
<td>1.44</td>
<td>1.82</td>
</tr>
</tbody>
</table>

Table 2. Orthogonal array $L_0 (3^4)$ and the test data

<table>
<thead>
<tr>
<th>Exp.</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>N/A</th>
<th>y</th>
<th>$y_0$</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>150</td>
<td>80</td>
<td>-18.451</td>
</tr>
<tr>
<td>2</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>130</td>
<td>80</td>
<td>-16.989</td>
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<tr>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>122</td>
<td>80</td>
<td>-16.232</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>156</td>
<td>80</td>
<td>-18.808</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>146</td>
<td>80</td>
<td>-18.195</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>116</td>
<td>80</td>
<td>-15.563</td>
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<tr>
<td>7</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>160</td>
<td>80</td>
<td>-19.031</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>127</td>
<td>80</td>
<td>-16.721</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>121</td>
<td>80</td>
<td>-16.128</td>
</tr>
</tbody>
</table>

Table 3. Responses of the control factors.

<table>
<thead>
<tr>
<th>Control factors</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-17.224</td>
<td>-17.522</td>
<td>-17.293</td>
</tr>
<tr>
<td>B</td>
<td>-18.763</td>
<td>-17.302</td>
<td>-15.974</td>
</tr>
<tr>
<td>C</td>
<td>-16.192</td>
<td>-17.194</td>
<td>-17.254</td>
</tr>
</tbody>
</table>

Of which, $y$ is the peak value of $V_{ds}$, and $y_0$ is the ideal value of $V_{ds}$. The measured outcome for the circuit is shown in Table 2 and the response table for the control factors to S/N can be derived as revealed in Table 3. According to Table 3, the optimal-level combinations $A.B.C.$ are obtained. On the basis of these combinations and Table 1, the optimal element specifications $L_c = 11.3 \mu$H, $C_c = 0.015 \mu$F and $L_e = 1.24 \mu$H are selected and testing is then conducted. The results of the testing is $y=115V$, $y_0 = 80V$; therefore, S/N = -15.441 dB, the prototype of the optimal design circuit and its $V_{ds}$ waveform are shown in
Figs. 7 and 8.

Fig. 7. A prototype of the optimal design circuit.

Fig. 8. $V_{ds}$ of the optimal design circuit ($V_{dp} = 115V$).

From the results, the S/N is -15.441 dB, which is greater than the values for any experimental group in Table 2. This proves the effect of optimalization. For suppressing the spike voltage, compare $V_{dp} = 115V$ derived from the optimal design with the $V_{dp} = 160V$ obtained from non-optimal circuit described in section 4.1, 28.1% is reduced. Therefore, applying GA and Taguchi method to the optimal design of DC-DC converter with LC snubber circuit is an effective and feasible method.

5. Conclusion

Since we are unable to identify precisely the distribution of scatter elements on a converter, and in addition, the theoretical element values obtained from theoretical analysis is
confined to the standard specifications of elements, so that proper element specification cannot be established and the functioning of the prototype is far from ideal. These limitations depreciate the purpose of optimal design. In this paper, we first obtain the optimal theoretical value for circuit elements of a DC-DC converter with LC snubber by GA. These values are then used for optimal design of the prototype converter through Taguchi method. We investigate the circuit parameters affecting $V_{ds}$ and illustrate the procedures and steps for the optimal design by GA and Taguchi method. This method is then used on designing a prototype converter compared with the non-optimal prototype to demonstrate the effect of the $V_{ds}$ across power switch. Comparing with the $V_{dop}$ of non-optimal circuit, the $V_{dop}$ obtained from optimal design is 115V and 28.1% is reduced. For these reasons, the method proposed in this paper is efficient and feasible.
References


