Design of high voltage DC power supply based on LCC resonant converter

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Abstract. The aim of this paper is to design a small size, light weight high frequency high voltage (HFHV) power supply. It presents a comprehensive procedure for designing a high output voltage power supply based on series-parallel (LCC) resonant converter, aiming to realize the soft-switching. Through mathematical calculation based on an extensive of the first harmonic analysis, the paper derives the approach of determining the resonant parameters of the LCC converter. Then, a 35 kV power supply featuring a series-parallel resonant converter topology to compensate the distributed parameter is built to verify the correctness of the theory.

1. Introduction
Nowadays, high voltage DC power supply is widely used in electrostatic precipitation and medical diagnostic. Most of the high voltage power supplies are made up of power frequency step-up transformer directly. Although it has the advantages of simple fabrication process and low failure rate, it cannot meet the portable requirement.

This paper introduces a high voltage DC power supply featured with higher power and efficiency and less volume. As key parts of high voltage power supply, the size of the transformer should be as small as possible, but the cooling area will be reduced as the volume decreases, thus the losses of the HFHV transformer becomes more significant [1-2]. Moreover, the leakage inductance and the distributed capacitance of the transformer will cause high peak voltage and large charging current, increasing heat, inevitably affecting the normal operation. In this paper, LCC resonant converter is introduced to take advantage of the distributed parameters of the transformer to realize soft-switching within a wide input and load range.

2. Overview of the system
The block diagram of the system is shown in figure 1. It mainly consists of two parts: the power circuit and the control circuit. The power circuit contains a HFHV transformer, a full-wave rectifier, a switching unit, and a low pass filter. The shaded part is the control circuit containing the microcontroller mainly for creating bipolar PWM control signals.

The input for the system is 220 V/50Hz. After rectifier and inverter, a high frequency voltage is increased by HFHV step-up transformer. The high voltage rectifier and the high voltage capacitor are used to reduce ripple or noise of the DC voltage. The specifications of the HFHV power supply are as follows:

Input voltage: 220 V ± 20%.

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Maximum working voltage: 35 kV.
Maximum operating current: 100 mA.

3. Design of the LCC resonant converter

As known to all, the distributed parameter can greatly increase the loss of HFHV transformer, even damaging the switch components [3-4]. Thus how to decrease the adverse impact of the distributed parameters is a key point in designing the power supply. The most widely used and effective method is LCC resonant technique [5-6]. In order to facilitate analysis, the full-bridge LCC resonant converter with capacitance-type filter is given in figure 2.

In figure 2, \(C_s\) and \(L_s\) are series resonant capacitor and inductor, \(C_p\) is the parallel resonant capacitor; \(L_o\) is the leakage inductance while \(C_t\) is distribution capacitance including the equivalent distributed capacitance referred to the primary side. In order to achieve zero-voltage switching (ZVS), the circuit is operating above resonance so that the current delivered to the resonant circuit is lagging the voltage applied to the resonant circuit. Each leg has a snubber capacitor directly paralleled across the IGBT [7].

![Figure 1](image1.png)

**Figure 1.** The block diagram of the whole system.

![Figure 2](image2.png)

**Figure 2.** LCC resonant converter with capacitive output filter.

The fundamental voltage of AB in figure 2 is determined by equation (1), where \(D\) is the duty cycle:

\[
U_{AB} = \frac{4}{\pi} \cdot U_{DC} \cdot \sin\left(\frac{D \cdot \pi}{2}\right)
\]

In which, \(U_{DC}\) is the DC input voltage of the inverter, \(D\) is the duty cycle.

After the Fourier transform of the transformer’s primary voltage and current, the transformer, rectifier, output filter and load can be equivalent to a capacitive two-Port network which is represented by a RC parallel circuit as shown in figure 3 [8].
Figure 3. AC equivalent circuit of LCC resonant converter.

Considering the effect of duty cycle, using the extensive of first harmonic analysis, we can get the voltage gain $M$:

$$M = \frac{U_o}{U_i} = 4 \cdot \frac{k_{21}}{k_v} \cdot \sin(D \cdot \frac{\pi}{2}) \cdot n$$  

(2)

In which, $n$ is the turns ratio of the transformer, $k_v$ is a coefficient describing the relationship between output voltage and input voltage, its value is determined as follow:

$$k_v = 1 + 0.27 \cdot \sin \left( \frac{\theta}{2} \right)$$  

(3)

$\theta$ is the normalized value of the conducting angle of the rectifiers, its value is determined by:

$$\theta = 4 \cdot \text{arctan} \left( \frac{2 \cdot \pi \cdot Q \cdot n^2}{f_{sN} \cdot \alpha} \right)$$  

$$Q = \left( \frac{L_s}{C_s} \right)^{1/2} / R_e$$  

(4)

$f_{sN} = f_s \cdot f_o$ is the normalized value for the switching frequency, $f_o$ is the resonant frequency of the $C_s$ and $L_s$, $f_s$ is the switching frequency.

$$k_{21} = \left[ 1 - \alpha (f_{sN} - 1)^2 \left( 1 + \frac{\tan(\beta)}{\omega C_p R_e} \right)^2 \right] \left[ \alpha (f_{sN}^2 - 1)^2 \cdot \frac{1}{\omega C_p R_e} \right]^{-1/2}$$  

(5)

In which, $\beta = -0.4363 \sin(\theta)$ is phase difference between fundamental voltage and fundamental current of transformer. $\alpha$ is determined as $C_p / C_s$ and $\omega C_p R_e = \pi k_e^2 / [4 \tan(\theta/2)^2]$. Therefore, the relationship between $D$ and other parameters can be obtained:

$$D = 1 - \frac{2}{\pi} \cdot \text{arctan} \left( \frac{1}{\omega C_p R_e} \cdot \alpha \cdot \left[ f_{sN}^2 - \left( 1 + (\omega C_p R_e + \tan(\beta)^2) \right) - 1 \right] - \left[ \omega C_p R_e + \tan(\beta) \right] \cdot \left[ 1 + \left( 1 + \frac{\tan(\beta)}{\omega C_p R_e} \right) \right] \right)$$  

(6)

According to equation (2)-(6), the relationship between voltage gain and switching frequency under different load (according to equation (4), $Q$ is proportional to $R_e$) is shown in figure 4 (taking $\alpha=2$). By adjusting the parameters of the resonant component properly, appropriate gain and the switching frequency range can be obtained. Figure 4 provides the basis curve for the selection of switching frequency under different loads.

Based on the characteristics of figure 4, the adjustment range of $f_{sN}$ is large when the load changes from light-load to full-load. On the other hand, the resonant frequency $f_o$ is fixed with the determined resonant components. Hence, the range of switching frequency $f_s$ is very large which is difficult to achieve due to the design of resonant components.
Figure 4. Relationship between voltage gain $M$ and $f_{SN}$ under different load.

Normally, the load changes from full-load to light-load. Therefore, in this paper, phase-shifted control is also adopted to adjust duty cycle at the same time. In this way, the LCC converter can achieve soft-switching over the entire load range with a small adjustment of the switching frequency. Taking the distribution parameters of the transformer into the consideration, an equivalent simplified model of LCC is described in figure 5[9].

Figure 5. Simplified model of LCC considering the distribution parameters.

Therefore, the actual values of LCC resonant parameters need to be modified as follows:

$$\begin{align*}
L_p &= L_s - L_t \\
C_p' &= C_p - C_i
\end{align*}$$

(7)

As known to all, transformer design is another key point. The volume of the transformer is small so the effective insulation distance is limited. Therefore, we design a special insulation is adopted in this paper. The distribution parameters of the HFHV transformer are $L=75.4$ uH and $C=44.23$ nF.

When we choose $Q=3$, $\alpha=2$ and the working frequency is $20$ kHz, according to equation (4), the calculated results are $L_s=186.7$ uH and $C_s=307.7$ nF. Combining equation (7), we get $C_p=153.85$ nF, $C_p'=19.62$ nF and $L_p=111.3$ uH.

4. Experiment and results

Based on the parameters above, the voltage of the series resonant capacitor and the current of the resonant inductor at full load are illustrated in figure 6. As shown, the series resonant inductor current $i_{Ls}$ and resonant capacitor voltage $u_{Cs}$ are sinusoidal, so the switch can achieve ZVS and the switching
stress of the IGBTs is reduced. The resonant inductor current leads the voltage across the resonant capacitor, thus the converter is inductive. The output voltage waveform is shown in figure 7. According to figure 7, we can find that the output DC voltage reaches 35 kV and has low output ripple and noise.

5. Conclusion
This paper gives the specific procedure of determining parameters of high voltage DC power supply based on the LCC resonant converter. Considering the influence of transformer distributed parameters, the extended fundamental approximation is adopted to ensure soft switching. The switching stress of the IGBTs is reduced, improving the efficiency of the converter. Compared with the traditional method, the proposed method is simple and more practical. The paper verified the correctness of the theory and design process through a 35 kV high voltage DC power supply. The efficiency of the DC power supply reached 95%, and the mass of the power supply is about 6 kg.

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